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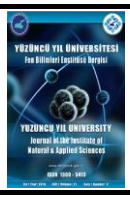
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Research Article

Effects of Pharmaceuticals Used Against COVID-19 on HDAC Activity and Inflammation in Cell Line Obtained from a Colorectal Adenocarcinoma Patient

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Abstract: Different doses of various drugs were used in the treatment of the Coronavirus Disease 2019 (COVID-19) pandemic that affected the whole world. Since these drugs are not directly related to COVID-19, it was very important to elucidate their effects. Studies have shown that COVID-19 is closely related to colorectal cancer. Our study examines the effects of Lopinavir/ritonavir, hydroxychloroquine, favipiravir, and oseltamivir, as well as their active ingredients used during COVID-19 treatment, on the histone deacetylase enzyme (HDAC) in colorectal cancer cells. Thus, it is aimed to provide a different perspective on the relationship between pandemic and colorectal cancer. In this study, the effects of the applied drugs on cell viability were evaluated with 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) analysis, acridine orange/propidium iodide (AO/PI) staining and histone deacetylase enzyme activity was evaluated in colorectal adenocarcinoma cell line (Caco-2) with HDAC assay. Using an enzyme-linked immunosorbent assay (ELISA), the inflammatory effects on the cells due to the application were assessed based on the expression levels of interleukin 10 (IL-10), interleukin 6 (IL-6), and tumor necrosis factor alpha (TNF-α). Experimental groups showed continued cell viability, and an increase in HDAC enzyme activity was observed. This increase was found to effectively influence the IL-6 expression, which is believed to enhance inflammation.

Keywords: Favipiravir, HDAC, Hydroxychloroquine, Lopinavir/ritonavir, Oseltamivir, Valproic acid

COVID-19'a Karşı Kullanılan Farmasötiklerin Kolorektal Adenokarsinom Hastasından Elde Edilen Hücre Dizisinde HDAC Aktivitesi ve Enflamasyon Üzerindeki Etkileri

Öz: Koronavirüs Hastalığı 2019 (COVID-19) pandemisinin tedavisinde çeşitli ilaçların farklı dozları kullanıldı. Bu ilaçlar doğrudan COVID-19 ile ilişkili olmadığından oluşturacakları etkilerin aydınlatılması oldukça önem taşımaktaydı. Yapılan araştırmalarla COVID-19'un kolorektal kanser ile yakından ilişkili olduğu ortaya konulmuştur. Gerçekleştirdiğimiz çalışmada kolorektal kanser hücre soyunda (Caco-2), COVID-19 tedavisinde kullanılan lopinavir/ritonavir, hidroksiklorokin, favipiravir, oseltamivir ilaç ve etken maddelerinin histon deasetilaz enzimi (HDAC) üzerindeki etkinlikleri ve enflamasyona katkıları araştırılmıştır. Böylece pandeminin kolorektal kanserle ilişkisine farklı bir bakış açısı kazandırmış olmak hedeflenmiştir. Bu çalışmada, uygulanan etken maddelerin Caco-2 hücrelerinin hücre canlılığı üzerindeki etkileri; 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromid (MTT) analizi, akridin turuncusu/propidyum iyodür (AO/PI) boyaması kullanılarak belirlendi ve histon deasetilaz enzim aktivitesi HDAC testi ile saptandı. Ayrıca enflamatuvar etki, enzim bağlantılı immünosorbent testi (ELISA) kullanılarak interlökin 10 (IL-10), interlökin 6 (IL-6) ve tümör nekroz faktörü alfa (TNF-α) ekspresyon seviyelerinde meydana gelen değişiklere göre değerlendirildi. Uygulama yapılan gruplarda hücre canlılığı devam ederken, HDAC enzim aktivitesinde artış meydana geldi. Bu artışın IL-6 ekspresyonu üzerinde etkili olduğu gösterilerek enflamasyona neden olduğu düşünülmektedir.

Anahtar Kelimeler: Favipiravir, HDAC, Hidroksiklorokin, Lopinavir/ritonavir, Oseltamivir, Valproik asit

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1. Introduction

Since appeared on December 31, 2019, coronavirus-2 syndrome (SARS-CoV-2), referred to as COVID-19, has rapidly evolved into an expanding pandemic (Page et al., 2021). Drugs repurpose is the technique of using an existing drug or drug candidate for a new treatment or medical condition for which it was not indicated before (Kulkarni et al., 2023). According to this principle, many existing antiviral drugs, such as Lopinavir/ritonavir (Lop/r) (Cao et al., 2020), chloroquine (Wang et al., 2020), hydroxychloroquine (Gautret et al., 2020), and favipiravir (Cai et al., 2020), which were previously used to treat Severe Acute Respiratory Syndrome (SARS), Middle East Respiratory Syndrome (MERS), Human Immunodeficiency Virus (HIV/AIDS), and malaria, have been considered potentially effective in treating COVID-19 and approved for use in patients. Some of these drugs are still in the clinical trial phase (Li & De Clercq, 2020; Sanders et al., 2020).

Lop/r is an antiretroviral agent. *In vivo* studies have shown that it may be effective against MERS, and there is limited evidence that it may also be effective in MERS/SARS patients. In Singapore, 2 out of 5 COVID-19 patients who began treatment with Lop/r deteriorated, suggesting that using a low dose of Lop/r may be effective (Young et al., 2020). In a retrospective analysis of 134 cases COVID-19 in China, 52 patients were given Lop/r, 34 patients were given arbidol, and 48 patients were considered controls; as a result, no differences were observed between the groups regarding symptom improvement and viral load reduction. (Yao et al., 2020).

The positive effects of chloroquine/hydroxychloroquine in the treatment of the SARS-CoV pandemic in 2002-2003 made it a candidate drug for use in the treatment of SARS-CoV-2. Hydroxychloroquine is thought to act through various mechanisms, prevents the virus from binding to the host cell by disrupting the terminal glycosylation of the angiotensin-converting enzyme-2 (ACE-2) receptor, which is the receptor of the SARS-CoV-2 virus that has accumulated there by increasing the pH of the endosomes and lysosomes. An evaluation of data from 100 patients who participated in multicenter clinical trials receiving chloroquine treatment in China indicated that chloroquine phosphate was more effective than the control group in suppressing pneumonia exacerbations, enhancing lung imaging findings, and reducing the duration of the disease (Gao et al., 2020). In a study conducted in France; hydroxychloroquine was given to 20 patients diagnosed with COVID-19 and compared with 16 patients control, who did not receive treatment. The patients' nasopharyngeal samples were examined by polymerase chain reaction (PCR) for daily nasopharyngeal virus detection, and it was found that the negative PCR test rate on days 3, 4, 5, and 6 of treatment in the hydroxychloroquine group was significantly different from that of control patients (Gautret et al., 2020).

Favipiravir inhibits ribonucleic acid (RNA)-dependent RNA polymerase of RNA viruses and prevents the virus from multiplying. This agent, previously used in the treatment of resistant influenza and Ebola virus infection, has also been used in coronavirus infection due to its mechanism of action (Jordan et al., 2018; Shiraki & Daikoku, 2020; Shiraki et al., 2022). In Shenzhen, 35 patients treated with favipiravir achieved negative results in a median of 4 days, while the duration of the disease in the control group of 45 patients who did not receive favipiravir lasted 11 days. The study conducted in 2021 showed that the probability of clinical recovery was 24% higher when favipiravir was administered within the first seven days of hospitalization; However, there was no statistically significant reduction in mortality in hospitalized patients (Hassanipour et al., 2021; Swift et al., 2021).

Oseltamivir is a neuraminidase inhibitor approved for the treatment and prophylaxis of influenza A and B (Agrawal et al., 2020; Yousefi et al., 2021). In a cohort study involving 285 patients COVID-19, the severity of the disease was greater in patients treated with oseltamivir compared to the control group (5.02 vs. 4.2, $p = 0.01$). Additionally, both recovery time and hospital stay were significantly shorter for patients in the oseltamivir group (4.9 vs. 6.6 days, $p < 0.001$). Similarly, the mortality rate was lower in the oseltamivir group (1.7% vs. 6.7%, $p = 0.06$) (Zendehdel et al., 2022).

HDACs are essential in numerous biological processes in living organisms, including transcription, chromatin remodeling, the cell cycle, signal transduction, and gene expression regulation. The regulation of gene expression occurs via the acetylation and deacetylation of transcription factors. Histone tails carry a positive charge due to the presence of amine groups in the amino acid lysine and arginine, facilitating interaction with the negatively charged phosphate groups in the DNA backbone. Histone acetylation, performed by histone acetyltransferases, neutralizes this positive charge by

converting amines to amides, thereby reducing the electrostatic interaction between histones and deoxyribonucleic acid (DNA), which allows chromosomes to undergo transcription more readily (Khangura et al., 2017). Given these properties, they present potential as drug targets. HDAC inhibitors bind to the active sites of HDAC enzymes, resulting in histones remaining in their acetylated form and altering gene expression. These inhibitors impact fundamental cellular processes such as cell division, apoptosis, and differentiation, and are being explored for the treatment of various diseases. HDAC inhibitors have gained prominence in studies focused on treating diverse disease groups, particularly cancer, spinal muscular atrophy, Alzheimer's disease, diabetes, psychiatric disorders, and parasitic infections. Valproic acid, one of the HDAC inhibitors utilized in clinical practice, inhibits HDAC activity both in vitro and in vivo, leading to histone modification (Kucukoglu, 2013). It has been demonstrated to significantly reduce tumor growth and metastasis in animal studies. Consequently, valproic acid may serve as an effective therapeutic agent for cancer treatment.

In this study, conducted with cell line Caco-2, the effects of Lop/r, hydroxychloroquine sulfate, favipiravir, oseltamivir on the activity of HDAC, which play a role in various cellular regulatory processes such as gene transcription, cell growth, apoptosis, necrosis, survival, and cellular proliferation, were investigated (Gallinari et al., 2007). Some drugs that target HDAC enzymes affect various cellular events, and compounds that inhibit these enzymes are used in treatment protocols by participating in these processes (Singh et al., 2018; Tsai et al., 2020).

In the actual literature, there are no studies evaluating the effects of Lop/r, hydroxychloroquine, favipiravir, oseltamivir pharmaceuticals on the activation and inhibition of HDAC, which plays an important role in epigenetic mechanisms in Caco-2 cells. In our study, we investigated the effects of Lop/r, hydroxychloroquine (HYC), favipiravir (FAV), oseltamivir (OSM) active ingredients on HDAC activity by applying them to Caco-2 cell line for 24, 48, 72 hours. To determine the viability of Caco-2 cells, MTT analysis, AO/PI staining were performed.

HDAC activity was measured in cell lysates obtained using NETN solution with the Bio Vision HDAC Activity Colorimetric Assay Kit. Additionally, valproic acid (VPA), a HDAC inhibitor, served as the control group of our study. This approach allowed us to evaluate the cellular activities of the drugs on HDAC at specific time intervals.

Enterocytes regulate intestinal maintenance and defense by secreting and responding to inflammatory mediators and regulating intestinal epithelial permeability. The expression and secretion of cytokines such as IL-6, IL-10 and TNF-α, which play an important role in inflammatory processes, in Caco-2 cells are closely related to intestinal inflammation, inflammatory bowel diseases and colon cancer. In inflammatory effects, IL-6 and TNF-α aggravate inflammation, while IL-10 has an inflammatory effect. Its effectiveness on the intestinal barrier depends on the overproduction of these cytokines. In colon cancer, IL-6 and TNF-α pro-inflammatory cytokines have been shown to be at high levels. These cytokines may play a crucial role in processes such as tumor growth, metastasis, and angiogenesis. The expression and secretion of IL-6, IL-10 and TNF-α cytokines in Caco-2 cells have a very complex regulatory network. This regulation is affected by intracellular transcription factors, epigenetic regulations, microRNAs, extracellular bacterial products, viral infections, other cytokines, oxidative stress, nutritional factors. In our study, we evaluated the relationship between the inflammatory effects on the cells resulting from the application and the HDAC enzyme activity according to the IL-10, IL-6 and TNF-α expression levels using ELISA method (Vitkus et al., 1998; Kany et al., 2019).

2. Material and Methods

2.1. Cell culture

Caco-2 (HTB-37) cells (from ATCC) were cultured in DMEM (Sigma) medium supplemented with 15% FBS (Fetal Bovine Serum, Sigma Aldrich), 2 mM L-glutamine (Multicell), and 100 U/mL penicillin-streptomycin (Gibco) at 37 °C in a 5% CO_2 environment. A total of 3.2 x 10^4 Caco-2 cells per well were seeded in 96-well culture dishes for MTT assay, AO/PI staining, HDAC activity assessment and ELISA analysis. The experimental procedures were performed in triplicate.

2.2. Pharmaceuticals application to cell cultures

According to the IC50 doses in the literature, FAV at a final concentration of 62 µM (4 mg/ml), VPA at 0.5 mM (10 mg/ml), Lop/r at 400mg/100ml, HYC at 200mg and OSM at 15 µM/ml were applied to Caco-2 cell cultures (Cvetkovic & Goa 2003; Terzioglu et al., 2020; Kaya et al., 2024). The instructions for use of the drugs are extended for a maximum of 5 days for FAV and OSM, and for Lop/r and HYC according to the course of the disease. In our study, we applied the pharmaceuticals to Caco-2 cells at 0h-24h-48h-72h time intervals. This point was chosen because it was the most appropriate period to evaluate the duration of efficacy of the pharmaceuticals in the four groups (Table 1).

Table 1. Experimental groups

Group No	Application	Application Period	Application Amount
1		24 h	
2	HYC	48 h	5 µg/ml
3		72 h	
4		24 h	
5	FAV	48 h	52 µg/ml
6		72 h	
7		24 h	
8	OSM	48 h	0.05 µg/ml
9		72 h	
10		24 h	
11	Lop/r	48 h	6000 µM Lop+1400µM r
12		72 h	
13		24 h	
14	VPA	48 h	43 µM
15		72 h	
16		24 h	
17	Control (No application)	48 h	-
18		72 h	

2.3. Cell viability, toxicity, and proliferation analyses were performed using MTT assay

The experimental groups of changing in cell viability was evaluated using by the Vybrant MTT Cell Proliferation Assay [Catalog No. V13154, Thermo Fisher Scientific, Waltham, MA, USA]. Cellular proliferation and inhibition of proliferation were determined according to the optical density (OD) values of the experimental groups at a wavelength of 540 nm. The OD of the control group was considered as 100% viable and all experimental groups were calculated according to this percentage (Guzelel et al., 2024).

2.4. Cell Staining with AO, PI

Firstly, the surface morphology of Caco-2 cells was examined using an inverted light microscope without any treatment applied to the experimental groups.

To assess the accuracy of MTT data and cell viability, nucleic acid binding dyes were utilized and visualized under a fluorescence microscope (Leica DM2500, DH Life Sciences, USA). Cells were labeled with AO and PI dyes; AO stains all nucleated cells and produces green fluorescence, while PI penetrates cells with disrupted membrane integrity and stains dead cells, producing red fluorescence (Kaya et al., 2020).

2.5. Obtaining cell lysates by NETN solution

At the end of the experimental period, cell supernatants were removed, cell dishes were placed on ice plates and NETN solution [250 mM NaCl, 5 mM ethylene diamine tetra acetic acid (EDTA), 50 mM HCl, 0.5% Octylphenyl polyethylene glycol (IGEPAL), 1X Halt Protease Phosphatase Inhibitor Cocktail] was added. Cells were collected from cell culture dishes by scraping and transferred to test

tubes. After incubation on ice for half an hour, the tubes were centrifuged at 13000g. The supernatant was transferred to new test tubes and cell lysates were obtained.

2.6. Protein quantification

The protein amounts in Caco-2 cellular were determined using the Coomassie (Bradford) Protein Assay Kit. Protein quantification was evaluated with Bovine Serum Albumin (BSA) standart graphs prepared using the Sigma Plot 10.0 program.

2.7. HDAC activity test

The manufacturer's instructions were followed for HDAC activity test (Biovision, HDAC Activity Colorimetric Assay Kit, Catalog no: K331). A protein amount of 4 mg from the quantified cell lysates was used for each test. 10 µl of 10X HDAC Assay Buffer and 5 µl of HDAC colorimetric substrate were added to the wells of the 96-well plate, to which the samples were added. The assay plate was incubated at 37° C for 2 hours. Then, 10 µl of Lysine Enhancer was added to the wells to stop the reaction and the plate was incubated again for 30 minutes at 37° C. After incubation, the OD values of the wells were determined by the plate reader at a wavelength 405 nm.

2.8. Determined IL-10, TNF-α, IL-6 expressions levels with ELISA test

IL-10, IL-6, TNF-α expression levels were determined using a commercial booster ELISA kit (IL-6, catalog no: ek0410; IL-10, catalog no: ek0416; TNF-α, catalog no: ek0525). Analyses were performed according to the manufacturer's instructions. Standard protein curves in the kit were created separately for each protein. IL-10, IL-6, TNF-α expression levels were determined using the supernatants obtained at the end of the culture periods. Evaluation: the value of the control group was accepted as 100% and protein amounts were calculated as percentages by comparing between groups. 100 ml of supernatant sample was added to the ELISA plate wells. The plate was incubated at 37 ˚C for 90 minutes. Then, the content of the wells was discharged and 100 µL of 1× biotinylated antihuman IL-6, IL-10 or TNF-α was added to the relevant wells and incubated at 37°C for 60 min. After incubation, the content of the wells was discharged, and the wells were washed 3 times with 1× wash buffer. 100 µL of 1× avidin biotin peroxidase complex was added, and incubation was carried out at 37°C for 30 min. Then, 100 µL of 1× avidin biotin peroxidase complex was added to the wells that were washed 5 times with 1× wash buffer and the plate was incubated at 37°C for 30 min. At the end of the period, the wells were washed 5 times and 90 µL of color development reagent was added and incubation was carried out at 37°C for 25 min. Finally, 100 µL of stop solution was added to each well and OD values were measured at 450 nm absorbance in an ELISA microplate reader.

2.9. Statistical analysis

Statistical evaluation between the treatment groups of our study; one way ANOVA test, which is used to determine whether the mean differences between three or more groups are significant, dependent t-test, which determines the relationship between the dependent sample and the variable sample, and regression test, which measures the relationship between two or more variables, were used to perform (p value <0.05).

3. Results

3.1 Cell viability analysis

The effects of drugs applied to Caco-2 cells on cell viability were calculated which the control group was accepted as 100% in terms of density depending on time (Table 2).

Table 2. Cell viability (%) of experimental groups

Group No	Application	Application Period	% Cell Viability
1		24 h	111.45
2	HYC	48 h	129.07
3		72 h	107.26
4		24 h	88.76
5	FAV	48 h	76.65
6		72 h	93.39
7		24 h	124.67
8	OSM	48 h	113.87
9		72 h	94.93
10		24 h	96.25
11	Lop/r	48 h	70.70
12		72 h	64.09
13		24 h	111.45
14	VPA	48 h	95.37
15		72 h	124.67
16		24 h	100
17	Control (No application)	48 h	100
18		72 h	100

The cell viability of the drug application groups are as follows: 11.45% increase at 24 hours, 29.07% at 48 hours and 7.06% at 72 hours in HYC group; 11.2% decrease at 24 hours, 23.3% at 48 hours and 6.6% at 72 hours in FAV group; 24.67% increase at 24 hours, 13.87% at 48 hours and 5.06% decrease at 72 hours in OSM group; 3.75% decrease at 24 hours, 29.3% at 48 hours and 35.91% decrease at 72 hours in Lop/r group; in VPA acid group, an increase of 11.45% in 24 hours and 24.64% in 72 hours and a decrease of 4.63% in 48 hours were observed compared to the control group. Although the viability percentages changed between the groups at the end of the application periods, no significant difference was observed in cell viability rates between the groups according to the ANOVA statistical test data. This data revealed that the applied HYC, FAV, OSM, Lop/r drug doses did not have a significant effect on cell viability and the cells continued to proliferate in some groups. AO/PI staining was performed on all samples treated with HYC, FAV, OSM, Lop/r groups determine whether cell survival or death (if any) was apoptotic and the existing relationship with MTT analysis. The experimental groups were morphologically visualized and evaluated at 0, 24, 48 and 72 hours according to the application hours (Figure 1). It was observed that the applied doses of HYC, FAV, OSM, Lop/r, VPA groups did not affect the morphology of Caco-2 cells, and the cells continued to proliferate while maintaining their viability. AO/PI staining shows that dead cells are stained red and live proliferating cells are stained green. Figure 1 is shown respectively, Figure 1.A: control group; Figure 1.B: Unstained Caco-2 cell morphology; Figure 1.C: HYC group 5µg/ml at 24 hours; Figure 1.D: Lop/r group 6000 µM Lop+1400 µM r at 24 hours; Figure 1.E: FAV group 50 µg/ml at 24 hours; Figure 1.F: OSM group 0.05 µg/ml at 24 hours; Figure 1.G: VPA group 43 µM at 24 hours; Figure 1.H: HYC group 5µg/ml at 48 hours; Figure 1.I: Lop/r group 6000 µM Lop+1400 µM r at 48 hours; Figure 1.J: FAV group 50 µg/ml at 48 hours; Figure 1.K: OSM group 0.05 µg/ml at 48 hours; Figure 1.L: VPA group 43 µM at 48 hours; Figure 1.M: HYC group 5µg/ml at 72 hours; Figure 1.N: Lop/r group 6000 µM Lop+1400 µM r at 72 hours; Figure 1.O: FAV group 50 µg/ml at 72 hours; Figure 1.P: OSM group 0.05 µg/ml at 72 hours; Figure 1.R: VPA group 43 µM at 72 hours.

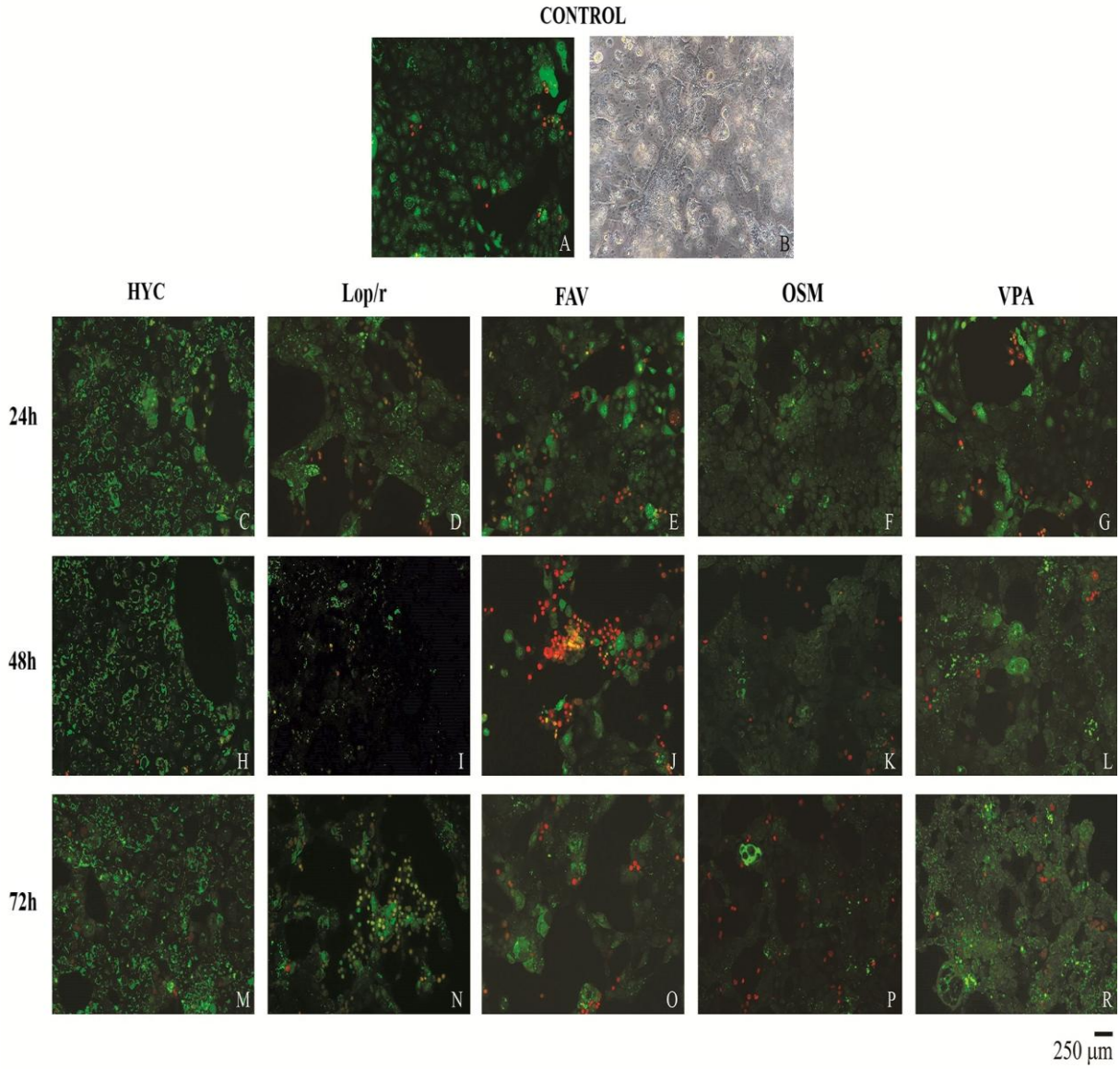


Figure 1. The microphotographs of the AO/PI staining of 0h, 24h, 48h 72h HYC (hydroxychloroquine) 5µg/ml; FAV (favipiravir) 50µg/ml; OSM (oseltamivir) 0.05µg/ml, Lop/r (Lopinavir/ritonavir) 6000 µM Lop+1400µM r; VPA (valproic acid) 43µM application. Dead cells are stained red and live proliferating cells are stained green.

3.2. HDAC activity

The time-dependent effects of drugs on HDAC activity were determined (Table 3). In our study, HDAC activity was evaluated by considering the values of the VPA group, which constituted the technical negative group. In addition, the OD value of the control group without any application was accepted as 100% and the percentage of HDAC activity of other groups was determined. HDAC activity of drug application groups increased by 34.40% in HYC group in 24 hours, 54.77% in 48 hours and 38.83% in 72 hours; 10.87% in FAV group in 24 hours, 77.75% in 48 hours and 83.63% in 72 hours; 7.28% in OSM group in 24 hours, 13.28% in 48 hours and 28.50% in 72 hours; 1.79% increase in Lop/r group in 24 hours, 2.51.91% in 72 hours and 20.03% decrease in 48 hours; In VPA group, a 40.85% decrease was seen in 24 hours, a 37.84% decrease in 48 hours, and a 36.25% increase in 72 hours; all were compared to the control group.

Table 3. HDAC activity (%) of experimental groups

Group No	Application	Application Period	% HDAC Activity
1		24 h	137.40
2	HYC	48 h	154.77
3		72 h	64.17
4		24 h	110.84
5	FAV	48 h	177.75
6		72 h	183.63
7		24 h	107.25
8	OSM	48 h	113.28
9		72 h	128.50
10		24 h	101.79
11	Lop/r	48 h	79.97
12		72 h	102.51
13		24 h	59.15
14	VPA	48 h	62.16
15		72 h	136.25
16		24 h	100
17	Control (No application)	48 h	100
18		72 h	100

Statistical evaluation of HDAC activity between each application group was performed using the ANOVA test. A significant difference was observed between VPA (p=1.89x10^{-12}), OSM (p=0.0014), HYC (p=4.14x10^{-7}), Lop/r (p=3.3x10^{-7}), FAV (p=2.13x10^{-8}) groups. The HDAC activities of different groups at the same application times were statistically evaluated using a paired t-test. There was a statistically significant difference among all groups at 24h (p<0.05) and 48h (p<0.05). However, while OSM group at 72h was not statistically significant compared to the other groups (p=0.384); there was a significant difference between HYC, Lop/r, FAV groups (p<0.05).

3.3 ELISA results

IL-6 expression levels; at 24 h, HYC group approximately 159% and FAV group reached 158% showed a significant increase, VPA control group showed an increase of 223%, OSM group reached 162% and Lop/r group reached 166%. Considering the 24h data, it was shown that there would be an inflammatory response for the drug groups. At 48h, FAV group 205% OSM group 227% increases, Lop/r group reached a peak increase of 451%, indicating a strong inflammatory response in these groups. However, the VPA group showed a lower increase at this point, reaching approximately 127%. At the 72 hours mark, the HYC, FAV, and OSM groups showed varying responses, with HYC group reaching approximately 265%, FAV group reaching 477%, and OSM group 216%. Lop/r group showed persistently high IL-6 levels, while VPA group decreased to approximately 69%, indicating a return to baseline IL-6 levels.

TNF-α expression levels; according to the results of 24h application, HYC group showed a slight decrease to approximately 82%, while FAV group decreased to 42%. However, the OSM group showed an increase to approximately 139%, Lop/r group showed a decrease to 55%, while VPA group reached a peak at 372%, indicating a significant increase in TNF-α levels of the control at this time. 48h, HYC group and FAV group 92% and 43%, respectively, while OSM group increased to 206%. Lop/r group showed a decrease to approximately 46%, and the TNF-α level of VPA group decreased to approximately 255%. At 72h, HYC group and FAV group experienced decreases in TNF-α levels to approximately 61% and 53%. OSM group at 135% and Lop/r group showed 74%. The VPA group showed a decrease to approximately 140%, indicating a return to baseline TNF-α levels. These observations suggest that as TNF-α levels varied between treatments, VPA group consistently showed high TNF-α responses and served as a reliable control for the baseline inflammatory response.

IL-10 expression levels were at 24 hours in HYC group 92%, FAV group 77%, OSM group 115%, Lop/r group 98%, VPA group 125%; at 48 hours in HYC group 88%, FAV group 71%, OSM group 133%, Lop/r group 126%, VPA group 131%; at 72 hours in HYC group 114%, FAV group 108%, OSM group 101%, Lop/r group 131%, VPA control group 143%. IL-10 levels were slightly lower than

the VPA group but remained relatively constant throughout the experiment. The results showed minimal fluctuations in IL-10 levels, suggesting that the HYC group did not significantly affect IL-10 production compared to the VPA control. Statistically, by applying one-way ANOVA test, a significant difference was found between the expression levels of IL-6, IL-10, TNF-α in the Lop/r and OSM application groups ($p<0.05$). This significant difference was determined to be due to the negative correlation between the expression levels of IL-6 and IL-10 in the two groups.

4. Discussion and Conclusion

Many existing antiviral drugs used to treat SARS, MERS, HIV/AIDS, and malaria with the principle of drug repositioning for the management of the COVID-19 pandemic, such as Lop/r (Cao et al., 2020), chloroquine (Wang et al., 2020), HYC (Gautret et al., 2020), and FAV (Cai et al., 2020), were used for potential COVID-19 treatments (Li & De Clerq, 2020; Sanders et al., 2020).

There are no studies in the literature about the epigenetic changes caused by Lop/r, HYC, FAV, OSM pharmaceuticals used worldwide in the treatment of COVID-19 through HDAC activity in intestinal enterocyte cells. This study determined the changes in HDAC activity caused by the application of Lop/r, HYC, FAV, OSM drugs at certain time intervals in Caco-2 cells at the usage doses determined in previous studies. Morphological evaluations, AO/PI staining and MTT analysis results were consistent and showed that the application groups did not cause cytotoxicity. In the presence of the drugs, Caco-2 cells maintained their viability and continued to proliferate. In addition, this study aimed to determine the relationship between cellular responses in cells resulting from the applications and HDAC activation. HDAC activity controls many biological events such as DNA packaging, replication, repair, and gene expression (Zhao & Shilatifard, 2019). Compounds that can inhibit HDAC enzymes (HDAC inhibitors) have been revealed to be effective in suppressing cell division, inducing apoptosis, differentiation, and other biological activities. The effect of these compounds in the treatment of diseases is one of the important areas of pharmacology. Loss of acetylation condenses the chromatin structure and suppresses gene expression. Studies have revealed a direct relationship between DNA methylation and histone modifications (Hu et al., 2020).

Various studies have been conducted on the effects of COVID-19 on cancer patients (Al-Quteimat & Amer, 2020). According to these, cancer was found to be associated with a 2.84-fold increased risk of severe disease and a 2.60-fold increased risk of death in COVID-19 patients. Colorectal cancer ranks second in cancer deaths and is the third most common malignancy in the world. A subgroup analysis based on place of origin showed that Chinese colorectal patients were at significant risk of infection and the burden of COVID-19 infection was 45.1% (Song et al., 2023). This study allowed us to evaluate the epigenetic changes caused by the drugs used in the treatment of COVID-19 (Lop/r, HYC, FAV, OSM) via HDAC activity in the colorectal adenocarcinoma cell line Caco-2, which constitutes the colorectal cancer model. It is well documented in the literature that HDAC activation is high in cancer patients and the importance of using HDAC inhibitors to treat cancer (Roostaee et al., 2015).

Histone deacetylase inhibitors (HDACi) signify a new class of cancer therapies with different effects, such as apoptosis or autophagic cell death. These agents selectively inhibit the activity of HDACs and thereby disrupt the balance of acetylation of histones and other proteins, modifying gene transcription. HDACi can reverse epigenetic abnormalities associated with carcinogenesis and thereby restore intrinsic antitumor responses, such as cell cycle arrest and in vitro cell differentiation. This study shows that HDACi inhibits gene expression in Caco-2 cells.

In our study, the cytotoxic effects of Lop/r, HYC, FAV, OSM pharmaceuticals on Caco-2 cell culture, their effects on HDAC activity, and the changes in proinflammatory IL-6, TNF-α, and anti-inflammatory IL-10 expression caused by this effect were determined. The data we obtained at the end of our study are consistent with the literature, and the application of Lop/r, HYC, FAV and OSM drugs in individuals with colorectal cancer increased HDAC activation. It has been shown that HDACi (VPA) used as the control group decreased HDAC activation in groups without application. A significant difference was observed between the VPA ($p=1.89x10-12$), OSM ($p=0.0014$), HYC ($p=4.14x10^{-7}$), Lop/r ($p=3.3x10^{-7}$) and FAV ($p=2.13x10^{-8)}$ groups. A statistically significant difference was found between all groups at 24 hours ($p<0.05$) and 48 hours ($p<0.05$). In the current study, a specific HDAC family member was not targeted. Instead, we evaluated total HDAC activity and found that the application of the HDAC inhibitor VPA group suppressed HDAC activity in these cells, while all other

drug applications changed HDAC activity in the cultures. As a result, it was revealed that the increase in HDAC activation was applied to Caco-2 cells may have caused some epigenetic changes.

The effectiveness of the application groups on inflammation; in the HYC group, an increase in IL-6 expression was also observed in the 24–48-hour applications. In the FAV group, it was determined that the increase in HDAC activation depending on the application hours was related to the increase in IL-6 levels. In the OSM group, it was statistically determined that the increase in HDAC activation at the 24 and 48 hours caused a significant difference between the expression levels of IL-6, IL-10 and TNF-α ($p<0.05$). In the Lop/r group, difference was found between the expressions of IL-6 and IL-10. Therefore, it was shown that the increase in HDAC enzyme activity in the Lop/r and OSM groups was effective on the inflammatory response. In all groups, the change in IL-10 expression did not affect cell viability and continuous proliferation was achieved. While TNF-α levels showed variable values among all applications, high TNF-α responses were obtained in the VPA group. This suggests that the VPA group serves as a reliable control for the baseline inflammatory response.

This is the first study to provide evidence to determine the effects of HYC, FAV, OSM, Lop/r groups on Caco-2 cell viability, HDAC activity, and inflammatory response. The effects of changes in HDAC enzyme levels on inflammation have been revealed. Thus, a new perspective has been gained on the effectiveness of HYC, FAV, OSM, Lop/r drugs on Caco-2 cells.

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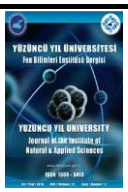
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Research Article

Analysis of Flora and Vegetation Data by R Software Packages: A Case Study from Southern Türkiye

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Abstract: Similarity and dissimilarity indices have been used to statistically compare flora and vegetation research. R software environment is one of the current and popular approaches to doing statistical analysis and graphical visualizations in ecology and many other disciplines. In the study, floristic studies of eight areas in southern Türkiye were compared by beta diversity indices, and some R packages for numerical ecology and taxonomic applications are mentioned and discussed for more detailed analysis. A unified taxa list was compiled based on all the taxa that are detected in compared areas and then a presence/absence data were prepared. Beta diversity indices were calculated to compare the eight floristic fields. Similarity and dissimilarity dendrograms and heatmaps of UPGMA (Unweighted Pair-Group Method using arithmetic Averages) methods were shown in two different main groups. The obtained cluster dendrograms and heat maps of floristic fields allow easy comparison and quantitative differentiation of areas in flora and vegetation studies. The R packages are used to analyze, manage, and manipulate data with publication quality graphics for free in flora and ecology fields like many other disciplines.

Keywords: Diversity indices, Plant ecology, R software, Vegan package

Flora ve Vejetasyon Verilerinin R Yazılım Paketleri ile Analizi: Türkiye'nin Güneyinden Bir Örnek Çalışma

Öz: Flora ve vejetasyon araştırmalarını istatistiksel olarak karşılaştırmak için benzerlik ve farklılık indeksleri kullanılmaktadır. R yazılım ortamı, ekoloji ve diğer birçok disiplinde istatistiksel analiz ve grafiksel görselleştirme yapmak için kullanılan güncel ve popüler yaklaşımlardan biridir. Bu çalışmada, Türkiye'nin güneyindeki sekiz alanın floristik çalışmaları beta çeşitlilik indeksleri ile karşılaştırılmış ve numerik ekoloji ve taksonomik çalışmalarda kullanılan bazı R paketlerinden bahsedilmiş ve tartışılmıştır. Karşılaştırılan alanlarda tespit edilen tüm taksonlar baz alınarak birleşik takson listesi oluşturulmuş ve var/yok verileri hazırlanmıştır. Sekiz floristik alanı karşılaştırmak için beta çeşitlilik indeksleri hesaplandı. UPGMA (Aritmetik Ortalamaları Kullanan Ağırlıksız Çift-Grup Yöntemi) yöntemlerinin benzerlik ve farklılık dendrogramları ile ısı haritaları iki farklı ana grubun olduğunu gösterdi. Floristik alanlardan elde edilen küme dendrogramları ve ısı haritaları, flora ve vejetasyon çalışmalarında alanların kolay karşılaştırılmasını ve nicel farklılaşmasını ortaya koyar. R paketleri diğer birçok disiplinde olduğu gibi flora ve ekoloji alanlarında da ücretsiz olarak yayın kalitesinde grafiklerle verileri analiz etmek, yönetmek ve manipüle etmek için kullanılmaktadır.

Anahtar Kelimeler: Bitki ekolojisi, Çeşitlilik indeksleri, R yazılım ortamı, Vegan paketi

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1. Introduction

Biodiversity or biological diversity defined as the variation of biological life at every hierarchical level on Earth. It mainly includes three levels: genetic, species and ecosystem diversity. The concept also covers interactions among these elements with each other and with their environment (Cipullo, 2016; Niesenbaum, 2019). Biodiversity is not equally distributed over the world. Therefore, the richest area of the world should be determined at every hierarchical level of biodiversity to conserve and sustainable use (Conord et al., 2012; Tantipisanuh & Gale, 2018; Watson et al., 2020).

There are numerous indices and equations designed to measure biodiversity at all levels. The most used measurement is to calculate the species richness. Ecologists have been calculating three different species diversity components: local (alpha), regional (gamma) and differentiation (beta) diversity (Koleff et al., 2003; Baselga, 2010). Ecologists have been using various software programs such as MATLAB, SAS, JUICE, TURBOVEG, CANOCO and STATISTICA to analyze ecological data. Most of that software is not free and not effective for all analysis and graphical visualization (Jansen, 2019; Lai et al., 2019). One of the most powerful and commonly used popular program in science and ecology nowadays is R software environment program (Lai et al., 2019).

R program is an open-source and publicly available free software environment. It is a programming language being used for statistical analysis, data computation, modeling, and graphical applications (Crawley, 2013). R project was created by Ross Ihaka and Robert Gentleman in the 1990s and had rapidly increasing usage and popularity in science and ecology over the last ten years (Bollmann et al., 2017; Lai et al., 2019). The current R software environment is derived from a collaborative effort with contributions of R Development Core Team and volunteer R users from all over the world. The users can download and get more information about R program from its website and related links (R package, 2022a). R program has a simple own graphic user interface (RGui) and some more comprehensive integrated development environments (IDEs) such as RStudio, Tinn-R, Rattle and Eclipse (Valero-Mora & Ledesma, 2012).

R software environment has many packages (at present more than 21.650) for various statistical and graphical applications (R package, 2022b). The packages are the fundamental units of R software environment and contain data, related functions, documents about using package codes (Oksanen et al., 2019; Dray et al., 2020). The packages can be general such as for data analysis (Wickham, 2018; 2019) and graphical visualization (Sarkar, 2018), and/or specific such as for genetic data analysis (Zhang et al., 2017) and ecological modeling (Petzoldt, 2019). This enormous number and subject variation of packages is one of the main reasons that R program is so popular and powerful software environment according to other software programs (Crawley, 2013; Lai et al., 2019).

In this study, floristical diversities of eight research fields based on presence/absence data from southern Türkiye were statistically compared by employing appropriate R software packages. Also, some R packages for numerical ecology and taxonomic applications are mentioned and discussed for more detailed analysis.

2. Material and Methods

2.1. Studied sites

In this study, floristic and/or species diversity of eight areas mostly from southern Türkiye were statistically compared by employing appropriate R software packages. The floristic areas are; Altınbeşik Cave National Park (İbradı-Akseki/Antalya), Bozburun Mountain and Its Environs (Antalya-Isparta-Burdur), Köprülü Kanyon National Park (Antalya-Isparta), Olimpos Beydağları National Park (Antalya), Sütçüler (Isparta), Termessos National Park (Antalya), Tuzaklı, Otluk, Gidefi Mountains and Surroundings (Akseki-Antalya) and the region between Derebucak (Konya)- İbradı and Cevizli (Antalya) (Figure 1 and Table 1).

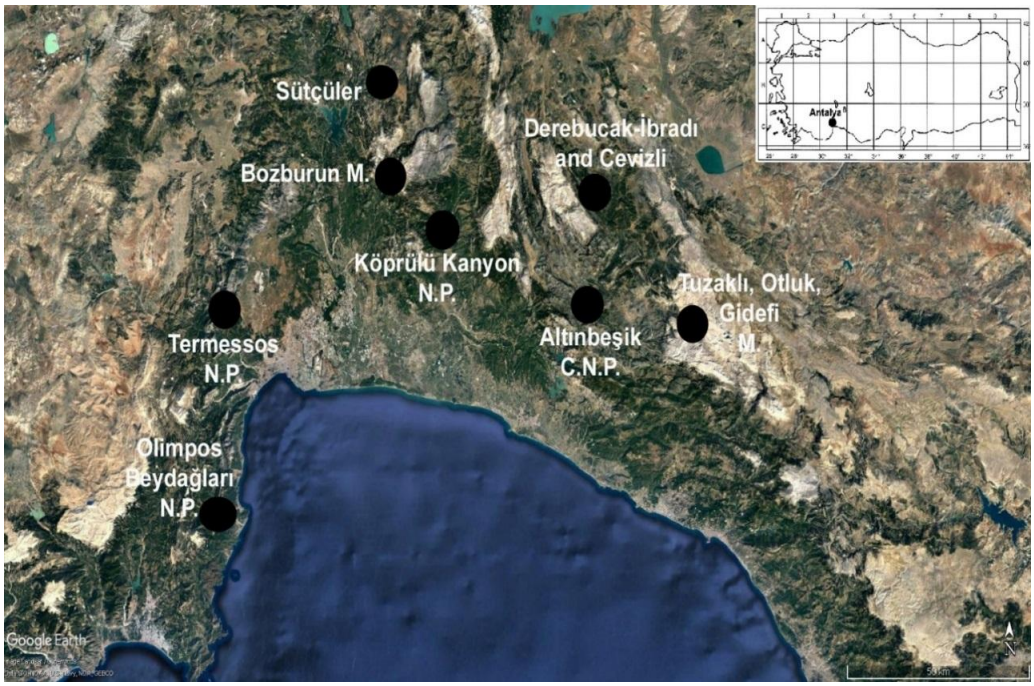


Figure 1. Location of studied areas on southern Türkiye.

The species diversity of sites has been studied in earlier years by different researchers. The sites were chosen because the researchers were familiar with the areas studied and one of the researchers studied the flora and vegetation of one of the relevant sites. Some characteristics of studied sites and related references are presented at Table 1.

Table 1. Some information of the natural areas studied

Name	Altitude (m)	Size (ha)	Total taxon number	References
Altınbeşik Cavern National Park	380-1 165	1 147	605	Cinbilgel & Gokceoglu, 2010
Tuzaklı, Otluk, Gidefi Mountains and Surroundings	500-2 427	17 000	1 023	Duran, 2002
Bozburun Mountains and Its Environs	50-2 505	144 000	645	Fakir, 2006
Termessos National Park	250-1 665	6 702	694	Alçıtepe, 1998
Olimpos Beydağları National Park	0-2 366	68 000	865	Peşmen, 1980
Köprülü Kanyon National Park	110-2 505	36 614	1 027	Özcelik et al., 2006
Flora of Sütçüler	250-2 500	128 700	584	Özcelik & Korkmaz, 2002
The flora of the region between Derebucak-İbradı and Cevizli	450-2 240	120 000	980	Demirelma, 2006

2.2. Data collection and analysis

We first compiled a unified taxa list based on all the taxa that were detected in these areas by various researchers in previous years (Table 1). We then prepared presence/absence data based on the unified list. The statistical computation was performed by calculating similarity and dissimilarity indices. The similarity/dissimilarity coefficients of the two sites were determined from the presence/absence of species. The comparison of the two sites (Grey and White) is shown in Figure 2. Based on binary data format, sites are compared as a pair. In Figure 2, The letter “b” shows the species only belonging to the Grey site while “c” shows the species only found in the White site. The letter “a”

shows the shared species in the two sites. Most of the similarity/dissimilarity indices are calculated by those components (a, b, and c) for beta diversity (Koleff et al., 2003; Anderson et al., 2011; Legendre & Caceres, 2013). The most used beta diversity indices, Jaccard and Sorensen indices, use a / (a + b + c) and 2a / (2a + b + c) formulas to calculate coefficients, respectively. There are many beta diversity formulas in the literature using different combinations of those components of Figure 2 (Koleff et al., 2003; Calderon-Patron et al., 2016).

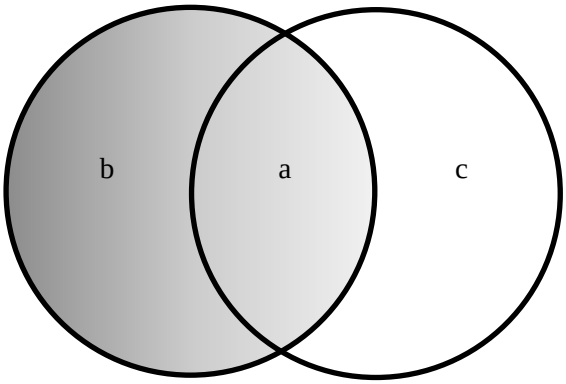


Figure 2. The possible distribution of species in two sites.

An example of the calculation of the studied two sites is shown in Table 2. The Jaccard (a / a + b + c) and Sorensen (2a / 2a + b + c) coefficients were calculated for all paired combinations of studied sites (Chao et al., 2005). According to presence/absence data, the similarity and dissimilarity of each pair of floristic sites were grouped on a common matrix. Thus, 28 area-pair coefficient matrices were obtained for the eight studied sites.

Table 2. Comparison of two sites and obtained coefficients

Studied sites		Olimpos	
		Present	Absent
Termessos	Present	a= 329 shared taxa	c= 365 unigue to Termessos
	Absent	b= 536 unigue to Olimpos	d= 1191 other taxa in the list

The calculation of indices and drawing of dendrograms were done by pertinent packages of R software such as vegan, ade4, betapart, and Stats. Similarity and dissimilarity dendrograms and heatmaps were drawn by using the UPGMA (Unweighted Pair-Group Method using arithmetic Averages) method (Koleff et al., 2003; Lai et al., 2019). This method is used as a clustering technique that uses the unweighed aritmetic averages of the measures of dissimilarity between the related studied variables. The method has been used frequently in ecology, phylogenetic, systematics and numerical taxonomy (Isik et al., 2005).

2.3. Used R packages and codes

All used R packages and their functions in this study are presented below. The R program ignores anything that follows the hashtag (“#”) character. Therefore, hashtags are very useful for adding annotations and comments to codes. Some useful annotations were added to the hashtags after the below codes.

```
> library (ade4) # to load related packages on the user interface.
> library (vegan)
>library (readxl)
>TL <-read_excel ("C:/Users/user1/Desktop/TL.xls",range = "A1:H2751")# to read related excel file. TL is the abbreviation of the taxon list.
>View (TL) # to view the taxon list on the user interface.
>atl<-t (TL) # to transform the dataset in the way the vegan package expects (one column per species and one row per site) in a new data file (atl).
```

>View (atl)

>jatl<- vegdist (atl, method=”jaccard”, binary=T) # to calculate Jaccard dissimilarity coefficients according to vegdist function in a new matrix (jatl).

> head (jatl) # to view only a few rows of jatl matrix.

> head (sqrt(jatl)) # to view only a few rows of square root of jatl vector.

> jatl2<-dist (atl, "binary") # to calculate Jaccard dissimilarity coefficients according to dist function.

> head (jatl2)

> jatl3<-dist.binary (atl, method=1) # to calculate Jaccard dissimilarity coefficients according to dist.binary function.

> head (jatl3)

> satl<-dist.binary (atl, method=5) # to calculate Sorensen dissimilarity coefficients according to dist.binary function.

> head (satl)

> satl2<- vegdist (atl, binary=TRUE)

>cjatl<- hclust (jatl, method =”average”) # to calculate cluster coefficients of jatl matrix according to the average method (UPGMA) of the hclust function.

> csatl<- hclust (satl, method = "average")

> library (cluster)

> library (betapart)

>plot (cjatl, ylab=="Jaccard Dissimilarity") # to draw dissimilarity dendrogram according to Jaccard dissimilarity coefficients.

> plot (csatl, ylab = "Sorensen Dissimilarity")

> cjatl2<- hclust (jatl2, "single")

>plot(cjatl2)

>cjatl3<-hclust(jatl3, "complete")

>plot(cjatl3)

> library (gclus)

> source ("coldiss.R")

> coldiss (jatl, byrank= FALSE, diag=TRUE) # to draw heatmap of Jaccard dissimilarity matrix.

> coldiss (satl, byrank= FALSE, diag=TRUE)

> smatl<- dist.binary (atl, method=2) # to calculate Sokal and Michener coefficients.

>matl<- vegdist (atl, method="manhattan", binary= T)

>cmatl<- hclust (matl, method= "average")

>plot (cmatl, ylab= "Manhattan Dissimilarity")

There are many packages and functions to get the same results as the above calculations. We presented only a few packages and their functions for the same and different indices.

3. Results

There were a total of 2750 taxa in these floristic areas according to the pooled taxa list. Tuzaklı, Otluk, Gidefi Mountains and Surroundings, and the flora of the region between Derebucak (Konya)-İbradı and Cevizli (Antalya) have the highest number of shared taxa (562 species). The lowest number of shared taxa (134) was between Termessos National Park and Sütçüler. Functions of different R packages (such as vegan and betapart) were used to calculate similarity/dissimilarity coefficients based on obtained matrices. Based on the Jaccard similarity and Sorensen dissimilarity values of each pair of floristic areas, the most similar areas were the Tuzaklı-Otluk-Gidefi Mountains and Surroundings, and Derebucak (Konya)-İbradı and Cevizli (Antalya). The most different sites were Termessos N.P. and Sütçüler according to Jaccard and Sorensen coefficients. Also, various similarity and dissimilarity coefficients such as Manhattan and Sokal-Michener were calculated by the same R packages. However, only Sorensen and Jaccard’s results were presented in the results section.

The hierarchical binary cluster dendrograms were drawn by the UPGMA method (Figure 3). According to the dendrogram, there were two different groups/clusters of eight studied sites. Those are the first group with five sites (Derebucak-İbradı-Cevizli, Tuzaklı-Otluk-Gidefi, Altınbeşik Cave N.P., Termessos N.P., and Olimpos-Beydağları N.P.) and the second group with three sites (Bozburun M.,

Sütçüler, and Köprülü Canyon N.P.). Derebucak and Tuzaklı sites were the most similar areas according to Jaccard and Sorensen dissimilarity coefficients (Figure 3). Also, dendrograms were drawn by a single and complete method of the hclust function (see part 2.3. Used R packages and codes). However, the result of the average method (UPGMA) was presented in the results section. Single and complete method dendrograms could be obtained by related functions of part 2.3. of the Material and Methods section.

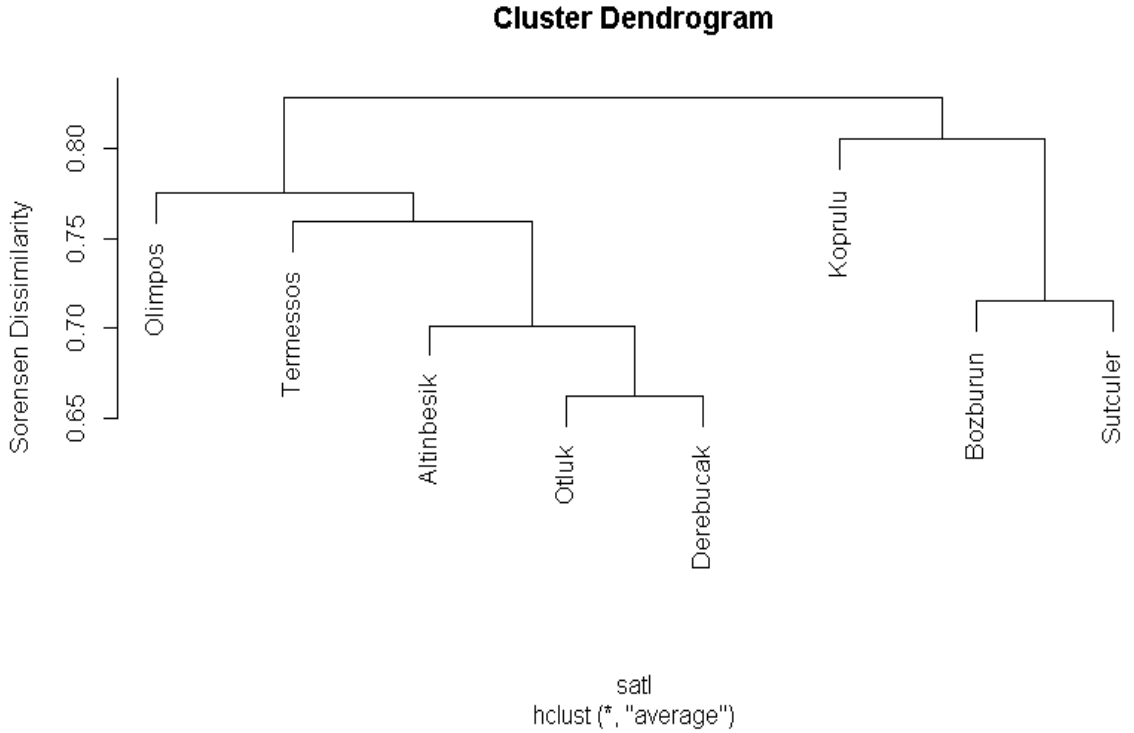


Figure 3. Cluster dendrogram of sites according to Sorensen dissimilarity coefficients.

The heatmap matrix of eight studied areas showed parallelism to the obtained dendrograms (Figures 3 and 4). According to the heatmap, Tuzaklı-Otluk-Gidefi, Derebucak-İbradi-Cevizli and Altınbeşik Cave N.P. were the most similar sites. Termessos N.P. and Olimpos-Beydağları N.P. joined that group. Bozburun, Sütçüler and Köprülü Canyon N.P. were the second group of studied sites (Figure 4). The highest and lowest Jaccard and Sorensen coefficients were also found between Tuzaklı-Otluk-Gidefi M. and Derebucak-İbradı-Cevizli, and between Termessos N.P. and Sütçüler, respectively.

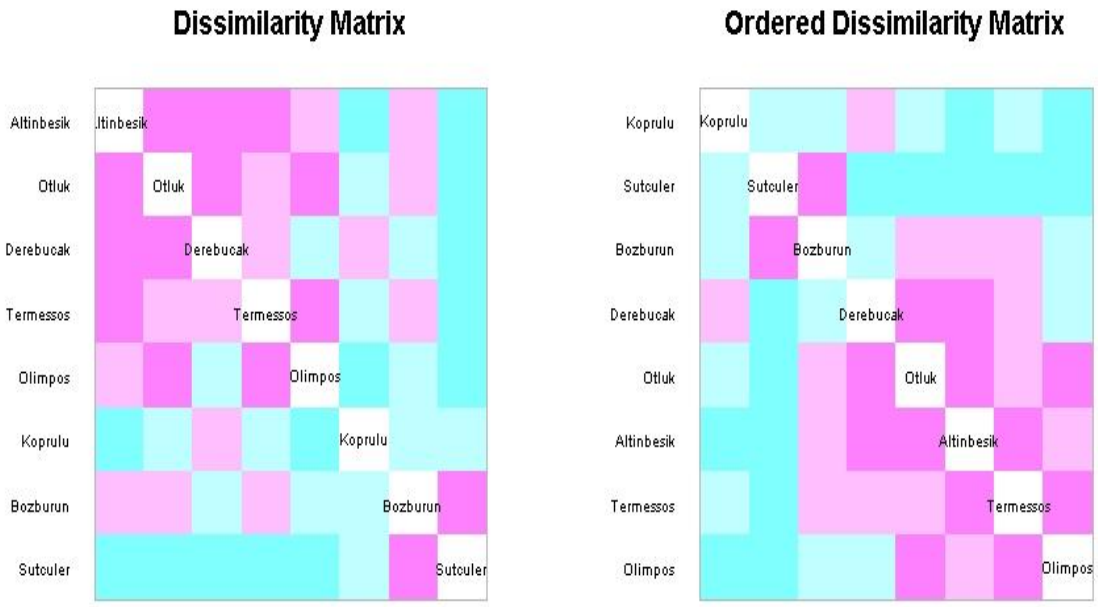


Figure 4. Heatmap matrix of sites according to Jaccard dissimilarity coefficients.

4. Discussion and Conclusion

The flora studies generally present species diversity of related regions with some basic information such as the most frequent life forms (Aldhebiani & Howladar, 2013), the most diverse and/or abundant families/genera (Todou et al., 2017), endemism rate and/or new records (Karagoz & Aslan, 2012), and origin of plants (Zhu et al., 2015 and sites of present study, Table 1). There are commonly no statistical comparisons or analyses in floristic studies. Many indices such as alpha, beta, and gamma have been designed to describe biodiversity (Kindt, 2019; Marcon & Herault, 2020). One of the simplest ways to analyze species diversity of sites is to calculate beta diversity metrics from the presence/absence data of species (Chao et al., 2005). There are numerous similarity and dissimilarity beta indices to statistically compare floristic and vegetational studies in different ecosystems using presence/absence and abundance data of species (Koleff et al., 2003; Baselga, 2010).

Diversity indices such as Jaccard, Manhattan and Sorensen were used to compare eight floristic sites in this study. Tuzaklı-Otluk-Gidefi M. and Derebucak-İbradı-Cevizli were the most similar sites, and Altınbeşik Cave N.P. was the closest site to both sites which are geographically very close to each other (Figure 1). Termessos N.P. and Olimpos-Beydağları N.P. were joined to that group (Figure 3). The similarity of those sites can be attributed to some similar characteristics of them such as having similar ecosystems, vegetation types and climate (Peşmen, 1980; Alçıtepe, 1998; Duran, 2002; Demirelma, 2006; Cinbilgel & Gokceoglu, 2010). Bozburun M., Sütçüler and Köprülü Canyon N. P. were the second group of the dendrogram which are also geographically close to each other (Figure 1) and have similar climate, altitude ranges and ecologic characteristics (Özcelik & Korkmaz, 2002; Fakir, 2006; Özcelik et al., 2006). The dendrograms and heatmaps also show parallelism to geographic and ecologic characteristics of studied sites (Figures 1, 3, 4 and Table 1).

The diversity indices and hierarchical binary cluster dendrograms as applied in a group of floristic sites allow easy definition and quantitative comparison of studied areas instead of some basic information about life forms, common families and origin of plants (Isik et al., 2005; Zhang et al., 2017). The quantitative presentation of floristic data should help various applications about studied sites such as changes of species composition along environmental gradients (Aldhebiani & Howladar, 2013),

degree of association or similarity of sites (Cinbilgel & Gokceoglu, 2010; Todou et al., 2017), and selection of appropriate sites for conservation and management purposes (Zhu et al., 2015).

R software environment program has many advantages to import, manipulate, analyze and export data according to other software programs such as Juice, Canoco, Turboveg and Statistica which are commonly used in ecology (Jansen, 2019; Lai et al., 2019). R program can be downloaded and installed from the CRAN (Comprehensive R Archive Network) website (R package, 2022c) under the terms of the Free Software Foundation's GNU General Public License. The most powerful part of the R program is specialized packages for various analyses in different disciplines (Table 3). There are some disadvantages of the R program such as the time requirement to learn a new language, a character user interface with appropriate syntax and no formal technical support (Crawley, 2013; Paradis et al., 2019).

The R software environment program has more than 21.650 specialized packages for various subjects and/or disciplines. The most used packages in flora and vegetation analysis, maps, and graphics drawing are presented in Table 3. Those packages have many applications such as from basic statistical analysis (BSDA, DescTools, psych, Rmisc) to analysis of ecological data (ade4, BiodiversityR, vegan, vegclust, vegdata), and from managing plant taxonomic names (taxlist, Taxonstand, WorldFlora) to diversity (betapart, ecodist, entropart) and phylogenetics (ape, phylotools) analysis. It should be kept in mind that the R software environment has thousands of packages, and floristic and ecological data analysis packages are much more than the presented packages in Table 3. The application of R software packages is not only suitable to statistically compare floristic and vegetational studies but also usable for faunistical, ecological and genetic studies (Table 3). Therefore, interested researchers should check the R packages repository (R package, 2022d) and select appropriate packages based on research, data type and related analysis (Lortie et al., 2020). Also, all R packages have their sample datasets and reproducible codes about the related subject of the package to show the usage of functions (Baselga et al., 2018; Dray et al., 2020).

One of the most used packages of R in floristic and ecological data is vegan (Oksanen et al., 2019). This package is a community ecology package and provides tools for diversity analysis, ordination methods and multivariate analysis for community and vegetation ecologists (Oksanen et al., 2019). The vegan package contains functions and their arguments on different data types such as vegetation data ("varespec","dune"), tree counts data on plots ("BCI") and bird species occurrence data on islands ("sipoo"). The other packages such as labdsv, BiodiversityR and permute complement the vegan package and provide tools for deeper analysis in various fields of ecology (Table 3). One can easily use and analyze own dataset or example datasets of vegan packages through its user guides and documents (Oksanen et al., 2019). Researchers should check datasets and organize them for related packages. As mentioned in part "2.3. Used R packages and codes" of this study, the related dataset should be arranged according to the way the vegan package expects (i.e. one column per species and one row per site). Then, the functions of interested analysis can be used to get related results.

In conclusion, the popularity and use of R software program have been growing year by year and the number of specialized R packages have been increased day by day due to reproducible codes and open-source characteristics of program. In this study, only a few packages and their a few functions were used to analyse presence/absence data of eight floristic sites and results were easily obtained by reproducible codes for everyone. Therefore, to learn R program and its various packages will help to analyse, manage, and manipulate data with publication quality graphics by free in flora and ecology fields like many other disciplines.

Table 3. Some R packages for ecologic and floristic data analysis

Packages	**Analyse**	**References**
ade4	Analysis of ecological data	(Dray et al., 2020)
ape	Analyses of phylogenetics and evolution	(Paradis et al., 2019)
betapart	Partitioning beta diversity into turnover and nestedness components	(Baselga et al., 2018)
BiodiversityR	Community ecology and suitability analysis	(Kindt, 2019)
BSDA, DescTools, psych, Rmisc,	Basic statistics	(Hope, 2013; Arnholt & Evans, 2017; Revelle, 2019; Signorell et al., 2019)
cluster, prabclus	Cluster and multidimensional analysis	(Maechler et al., 2019; Hennig & Hausdorf, 2020)
cocorresp	Co-correspondence analysis methods	(Simpson, 2009)
conR	Assessment of conservation status	(Dauby, 2019)
dplyr, plyr, reshape, tidyr	Data management and rearrangement	(Wickham, 2018; 2019; Wickham & Henry, 2019; Wickham et al., 2019a)
ecodist	Dissimilarity-based functions for ecological analysis	(Goslee & Urban, 2020)
EcoHydRology	Eco-hydrological interactions	(Fuka et al., 2018)
entropart	Measure diversity	(Marcon & Herault, 2020)
flora	Tools for taxonomic and distribution data	(Carvalho, 2017)
forecast, tseries, zoo	Time series analysis	(Trapletti et al., 2019; Hyndman et al., 2020; Zeileis et al., 2020)
ggmap, ggplot2, gplots, lattice, maps	Graphics and map drawing	(Minka & Deckmyn, 2018; Sarkar, 2018; Kahle et al., 2019; Warnes et al., 2019; Wickham et al., 2019b)
heatmap3, RcolorBrewer, yarrr	Advanced graphics and some statistical presentations	(Neuwirth, 2014; Phillips, 2017; Zhao et al., 2019)
knitr, rmarkdown	Create reproducible reports	(Allaire et al., 2019; Xie et al., 2019)
labdsv	Ordination and multivariate analysis for ecology	(Roberts, 2019)
lme4, MuMIn, nlme, VGAM	Linear and nonlinear mixed effects regression models, multi-model inference	(Barton & Barton, 2019; Yee & Moler, 2019; Bates et al., 2020; Pinheiro et al., 2020)
mefa	Multivariate data handling	(Solymos, 2016)
metacom	Analysis of metacommunity structure	(Dallas & Pulliam, 2020)
pgirmess	Spatial analysis and data mining	(Giraudoux et al., 2018)
phylotools	Phylogenetic tools for eco-phylogenetics	(Zhang et al., 2017)
simecol	Simulation of ecological systems	(Petzoldt, 2019)
spatstat	Spatial point pattern analysis, model-fitting, simulation, and tests	(Baddeley et al., 2020)
taxlist	Managing plant taxonomic lists	(Alvarez & Luebert, 2018)
Taxonstand	Standardization of plant species names	(Cayuela et al., 2019)
TR8	Retrieving plant species traits	(Bocci, 2015)
vegan	Community ecology analysis	(Oksanen et al., 2019)
vegclust, vegdata, vegtable	Clustering and handling vegetation data sets	(De Cáceres, 2019; Jansen, 2019; Alvarez, 2020)
vegetarian	Diversity measures for community data	(Charney & Record, 2012)
WorldFlora	Standardize plant names	(Kindt, 2020)

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Research Article

Spider Diversity on Herbaceous Plants in Samsun Province, Türkiye

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Abstract: In this study, spider diversity on herbaceous plants of Samsun province was investigated. Spider specimens were collected between 2015 and 2018 by using sweeping net, aspirators, and tweezer methods, and stored at -20 ˚C and in 96% ethyl alcohol. Most spiders were found on and around the Asteraceae family. Morphological descriptions are based on the spiders of the Palearctic region and nomenclature is based on the world spider catalog. As a result of the identification, from 397 spider samples belonging to 10 families, 12 genera and 15 species were determined. These are; *Phylloneta impressa* (L. Koch, 1881), *Enoplognatha ovata* (Clerck, 1757), *Heterotheridion nigrovariegatum* (Simon, 1873), *Oxyopes lineatus* Latreille, 1806, *Tetragnatha montana* Simon, 1874, *Tetragnatha extensa* (Linnaeus, 1758), *Pulchellodromus pulchellus* (Lucas, 1846), *Evarcha arcuata* (Clerck, 1757), *Misumena vatia* (Clerck, 1757), *Runcinia grammica* (C. L. Koch, 1837), *Argiope bruennichi* (Scopoli, 1772), *Argiope lobata* (Pallas, 1772), *Neoscona adianta* (Walckenaer, 1802), *Neoscona byzanthina* (Pavesi, 1876), *Araneus quadratus* Clerck, 1757. In the study, findings represent the first detailed spider records from herbaceous plants in the Samsun province.

Keywords: Araneae, Astaraceae, Samsun

Samsun (Türkiye) İli Otsu Bitkiler Üzerindeki Örümcek Çeşitliliği

Öz: Bu çalışma da, Samsun ili otsu bitkileri üzerinde bulunan örümcek çeşitliliği araştırılmıştır. Örümcek örnekleri 2015-2018 yılları arasında atrap, aspiratör ve pens yardımı ile toplanarak -20 ˚C de ve %96'lık etil alkolde muhafaza edilmiştir. Örümcekler çoğunlukla Astaraceae familyası üzerinden ve etrafından toplanmıştır. Morfolojik tanımlamalar Palearktik bölge örümcekleri temel alınarak tanımlanmış ve isimlendirmeler dünya örümcek kataloğuna göre düzenlenmiştir. Teşhisler sonucunda, araştırma bölgesinden toplanan 397 adet örümcek örneğinden 10 familyaya ait 12 cins ve 15 tür tespit edilmiştir. Tespit edilen türler şu şekildedir; *Phylloneta impressa* (L. Koch, 1881), *Enoplognatha ovata* (Clerck, 1757), *Heterotheridion nigrovariegatum* (Simon, 1873), *Oxyopes lineatus* Latreille, 1806, *Tetragnatha montana* Simon, 1874, *Tetragnatha extensa* (Linnaeus, 1758), *Pulchellodromus pulchellus* (Lucas, 1846), *Evarcha arcuata* (Clerck, 1757), *Misumena vatia* (Clerck, 1757), *Runcinia grammica* (C. L. Koch, 1837), *Argiope bruennichi* (Scopoli, 1772), *Argiope lobata* (Pallas, 1772), *Neoscona adianta* (Walckenaer, 1802), *Neoscona byzanthina* (Pavesi, 1876), *Araneus quadratus* Clerck, 1757. Çalışmada elde edilen bulgular Samsun iline ait otsu bitkilerden tespit edilen ilk detaylı örümcek kayıtlarıdır.

Anahtar Kelimeler: Araneae, Otsu bitkiler, Samsun

1. Introduction

Spiders are distributed all over the world and are among the most adaptable animals in nature. Spiders, which mostly live in terrestrial environments, can be found on stony areas, on the soil surface or in the soil, in rocky areas, on herbaceous or woody plants, as well as on leaves or under leaves (Foelix, 2011). Spiders are carnivorous animals, and most of their diet consists of insects. Because of this feature,

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they are also known as biocontrol agents. In many agricultural areas, the predatory properties of spiders are utilised and used in biocontrol studies (Akpınar & Varol, 2019). Research on spiders in the world and in Türkiye continues. Although mostly faunistic studies are carried out, web structure of spiders, venom gland, chitin structure and phylogenetic studies are also available (Kaya et al., 2014; Akpınar & Mammadova, 2020; Hameed et al., 2022; Seyyar & Demir, 2023). There are 51996 species belonging to 135 spider families described so far in worldwide (World Spider Catalog, 2024). In Türkiye, 577 families, 371 genera and 1282 species have been identified (Topçu et al., 2005; Demir & Seyyar, 2017; Danışman et al., 2024).

The aim of the study was to determine the diversity of spiders on herbaceous plants and in herbaceous plant areas in Samsun province. These species, which were previously described in our country, were supported by adding new localities.

2. Material and Methods

The spiders were collected specimens using by aspiratory, sweeping net and with hand from Samsun province of Türkiye on May-August between 2015-2018. Most of the specimens collected by sweeping nets from herbaceous plants (Especially Asteraceae family). Field work was carried out during day and night hours, and the collected spiders (Table 1) were preserved in sample tubes containing 90% ethyl alcohol. Morphological species determinations were made using different references based on the Palearctic region (Oger, 2023; Nentwig et al., 2024; World Spider Catalog, 2024). All species are preserved in the Zoological Museum, Department of Biology, Gaziantep University (GAUNZM).

Table 1. Sampling localities in Samsun province

Sampling dates	Coordinate				
	District/Locality		North	East	Altitude (m)
29.06.2015	Havza	Yenice Village	40°59'	35°45'	680
29.06.2015	Ladik	Center	40°55'	35°50'	925
30.06.2015	Kavak	Kavak Lake	41°03'	35°58'	640
30.06.2015	Atakum	Değirmendüzü	41°15'	36°10'	190
30.06.2015	Atakum	Çakıryalı	41°23'	36°11'	30
30.06.2015	Ondokuzmayıs	Yörükler	41°31'	36°05'	2
30.06.2015	Bafra	Yakıntaş	41°33'	35°57'	25
30.06.2015	Bafra	Dedeli	41°32'	35°51'	50
30.06.2015	Alaçam	Zeytin	41°36'	35°41'	60
30.06.2015	Alaçam	Etyemez	41°37'	35°35'	15
29.07.2015	Ladik	Sarıgazel	40°53'	35°46'	985
29.07.2015	Kavak	Çakallı	41°09'	36°06'	710
29.07.2015	Canik	Avluca	41°10'	36°16'	415
30.07.2015	Alaçam	Taşkelik	41°33'	35°40'	310
30.07.2015	Yakakent	Yeşilköy	41°37'	35°27'	265
31.07.2015	Vezirköprü	Yağınözü	41°10'	35°23'	591
02.05.2016	Havza	Bekdiğin	40°59'	35°46'	675
02.05.2016	Bafra	Doğanca	41°39'	36°00'	10
02.05.2016	Ondokuzmayıs	Emirhasan	41°13'	36°06'	645
02.05.2016	Havza	Taşkaracaören	40°54'	35°38'	682
29.05.2016	Kavak	Kuzalan	41°03'	35°58'	747

Table 1. Sampling localities in Samsun province (continued)

Sampling dates	Coordinate				
	District/Locality		North	East	Altitude (m)
30.05.2016	Çarşamba	Esençay	41°06'	36°35'	115
30.05.2016	Çarşamba	Dikbıyık	41°13'	36°36'	10
30.05.2016	Ondokuzmayıs	Karakavuk	41°22'	36°08'	149
30.05.2016	Bafra	Kolay	41°22'	35°48'	59
31.05.2016	Alaçam	İncirli	41°35'	35°36'	202
31.05.2016	Alaçam	Acem	41°29'	35°34'	921
29.06.2016	Tekkeköy	Hamzalı	41°20'	36°53'	18
29.06.2016	Çarşamba	Arım Köseli	41°21'	36°79'	29
19.05.2017	Terme	Center	41°12'	36°51'	12
14.06.2017	Vezirköprü	Kocakaya	41°18'	35°08'	275
15.06.2017	Vezirköprü	Bakla	41°08'	35°14'	576
17.06.2017	Havza	Çayırözü	40°58'	35°36'	727
17.06.2017	Ladik	Center	40°54'	35°54'	896
17.06.2017	Kavak	Ahırlı	41°04'	35°58'	630
17.06.2017	Tekkeköy	Taşdemir	41°12'	36°34'	9
18.06.2017	Terme	Evci	41°09'	37°03'	5
28.07.2017	Vezirköprü	Türkmen	41°13'	35°26'	275
28.07.2017	Alaçam	Kapaklı	41°30'	35°35'	801
29.07.2017	Bafra	Esençay	41°20'	35°50'	115
29.07.2017	Bafra	Esençay	41°18'	35°50'	223
29.07.2017	Vezirköprü	Güldere	41°17'	35°55'	630
29.07.2017	Havza	Boyalı	41°13'	35°52'	770
29.07.2017	Havza	Çelikalan	41°12'	35°51'	639
29.07.2017	Havza	Dereköy	41°06'	35°42'	564
30.07.2017	Ladik	İbi	40°58'	35°54'	779
30.07.2017	Ladik	Center	40°54'	35°54'	894
18.08.2017	Bafra	Kabaçukur	41°19'	35°50'	123
18.08.2017	Kavak	Akbelen	41°09'	35°53'	910
18.08.2017	Tekkeköy	Ovabaşı	41°12'	36°30'	3
18.08.2017	Çarşamba	Değincek	41°04'	36°38'	120
18.08.2017	Ayvacık	Çamlıkale	40°55'	36°29'	1005
21.06.2018	Vezirköprü	Şentepe	41°14'	35°14'	283
21.06.2018	Vezirköprü	Köprübaşı	41°08'	35°27'	677
21.06.2018	Havza	Ortaklar	41°00'	35°34'	830

3. Results

The spider diversity on herbaceous plants and on the ground in Samsun province in the Central Black Sea region was determined. 398 spider specimens belonging to 10 families were collected from 55 localities (Table 2).

Table 2. Spiders families in the research area

Familya	Female (♀)	Male (♂)	Subadult	Total	%
Araneidae	161	63	71	295	74.12
Thomisidae	8	6	54	68	17.08
Tetragnathidae	2	6	5	13	3.2
Oxyopidae	4	-	-	4	1.00
Salticidae	1	2	2	5	1.25
Theridiidae	2	-	1	3	0.75
Clubionidae	1	-	4	5	1.25
Linyphidae	1	-	1	2	0.50
Zoridae	1	-	-	1	0.25
Philodromidae	1	-	1	1	0.25
Total	182	77	138	397	99.5

As a result of the identification of the adult specimens at species level, 12 genera and 15 species were determined (Table 3).

Tablo 3. Spider species of Samsun province

Familya	Cins	Tür
Araneidae	*Neoscona*	*adianta* (Walckenaer, 1802)
		byzanthina (Pavesi, 1876)
	Araneus	*quadratus* Clerck, 1757
	Argiope	*bruennichi* (Scopoli, 1772)
		lobata (Pallas, 1772)
Theridiidae	*Enoplognatha*	*ovata* (Clerck, 1757)
	Phylloneta	*impressa* (L. Koch, 1881)
	Heterotheridion	*nigrovariegatum* (Simon, 1873)
Philodromidae	*Pulchellodromus*	*pulchellus* (Lucas, 1846)
Thomisidae	*Runcinia*	*grammica* (C. L. Koch, 1837)
	Misumena	*vatia (*Clerck, 1757)
Tetragnathidae	*Tetragnatha*	*montana* Simon, 1874
		extensa (Linnaeus, 1758)
Oxyopidae	*Oxyopes*	*Lineatus* Latreille, 1806
Salticidae	*Evarcha*	*arcuata* (Clerck, 1757)

Identified species in this study were examined in the below.

Family: ARANEIDAE Clerck, 1757
Araneus quadratus Clerck, 1757
Examined material: ♂; Samsun, Kavak, Akbelen, 910 m, 18.08.2017.

Neoscona adianta (Walckenaer, 1802)

Examined material*:* ♂, ♀; Samsun, Havza, Boyalı, 770 m, 29.07.2017; Bafra, Esençay, 115 m, 29.07.2017; Kavak, Akbelen, 910 m, 18.08.2018; Havza, Dereköy, 564 m, 29.07.2017.

Neoscona byzanthina (Pavesi, 1876)
Examined material: ♂, ♀; Samsun, Havza, Boyalı, 770 m, 29.07.2017; Havza, Dereköy, 564 m, 29.07.2017; Samsun, Vezirköprü, Güldere, 630 m, 29.07.2017; Samsun, Kavak, Akbelen, 910 m, 18.08.2017; Çarşamba, Esençay, 115 m, 30.05.2016.

Argiope bruennichi (Scopoli, 1772)
Examined material: ♂; Samsun, Çarşamba, Esençay, 115 m, 30.05.2016; Havza, Boyalı, 770 m, 29.07.2017.

*Argiope lobata (*Pallas, 1772)
Examined material: ♂; Samsun, Kavak, Kuzalan, 747 m, 29.05.2016.

Family: OXYOPIDAE Thorell, 1870
Oxyopes lineatus Latreille, 1806
Examined material: ♀; Samsun, Yakakent, Yeşilköy, 265 m, 30.07.2015.

Family: PHILODROMIDAE Thorell, 1870
Pulchellodromus pulchellus (Lucas, 1846)
Examined material: ♀; Samsun, Havza, Ortaklar, 830 m, 21.06.2018.

Family: SALTICIDAE Blackwall, 1841
Evarcha arcuata (Clerck, 1757)
Examined material: ♂; Samsun, Bafra, Kabaçukur, 123 m, 18.08.2017.

Family: TETRAGNATHIDAE Menge, 1866
Tetragnatha extensa (Linnaeus, 1758)
Examined material: ♂, ♀; Samsun, Bafra, Kabaçukur, 123 m, 18.08.2017; Samsun, Havza, Dereköy, 564 m, 29.07.2017.

Tetragnatha montana Simon, 1874
Examined material*:* ♂; Samsun, Bafra, Kabaçukur, 123 m, 18.08.2017; Samsun, Havza, Dereköy, 564 m, 29.07.2017.

Family: THERIDIIDAE Sundevall, 1833
Enoplognatha ovata Clerck,1757
Examined material: ♂; Samsun, Çarşamba, Arım Köseli, 29 m, 28.06.2016; Havza, Çelikalan, 639 m, 29.07.2017.

Phylloneta impressa (L. Koch, 1881)
Examined material: ♂, ♀; Samsun, Havza, Ortaklar, 830 m, 21.06.2018; 576 m, Vezirköprü, Bakla, 15.06.2017.

Heterotheridion nigrovariegatum (Simon, 1873)
Examined material: ♂; Samsun, Havza, Ortaklar, 830m, 21.06.2018.

Family:THOMISIDAE Sundevall, 1833
Runcinia grammica (C. L. Koch, 1837)
Examined material: ♀, ♂; Samsun, Alaçam, Kapaklı, 801 m, 28.07.2017; Samsun, Havza, Ortaklar, 830 m, 21.06.2018.

Misumena vatia (Clerck, 1757)
Examined material: ♂; Samsun, Havza, Çelikalan, 639 m, 29.07.2017.

4. Discussion and Conclusion

In the study, 397 samples were collected, including 259 adults and 138 juveniles. The adult subadult (juvenile) ratio was calculated as 1:1.86 and the male-female ratio 1:2.36. The ratio of subadult per adult being 0.54 indicates that the subadult in the population mostly become adults. Spiders were generally caught on herbaceous plants, which can be annual or perennial (Asteraceae: *Achillea* spp., *Carduus* spp., *Carthamus* spp., *Centaurea* spp., *Cirsium* spp., *Crepis* spp., *Echinops* spp., *Inula* spp.). Within the scope of the research, spider specimens were mostly caught between June and August, which are the adulting periods. This situation is also observed in the research data; the number of adult specimens was higher than that of juvenile specimens. Since the spiders were generally caught with insect net in the study, many web-building spider specimens (Araneidae, Theridiidae, Tetragnathidae) could be obtained. Samples were also collected from the herbaceous plant ground, and hunting species (Thomisidae and Philodromidae) were obtained. The species identified in the study are similar to the results of previous studies conducted in the Black Sea region (Akpınar et al., 2022).

Spiders are cannibalistic animals, and most of their diet consists of insects. They catch their prey mostly in ambush and waiting in their webs. They also have strong mimicry abilities. The fact that spiders live in all kinds of habitats and ecosystems in terrestrial environments increases the possibility of being found and captured. In addition, different families can be detected due to habitat diversity.

The study captured from vegetation in natural areas. Spraying agricultural areas reduces the number and diversity of insects, making it difficult to catch the spiders that feed on these animals.

No study on spider diversity on herbaceous plants has been found in Samsun before. This study determined the spider diversity of Samsun province for the first time. More studies are needed to contribute to the spider diversity of our country.

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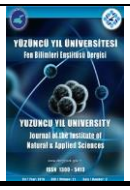
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Research Article

Alteration of Apoptosis-Related Gene Expression by *Pistacia khinjuk* Stocks in Rats Exposed to Ethanol-Induced Toxicity

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Abstract: In this study, it was aimed to determine the effect of *Pistacia khinjuk* Stocks (Bıttım) (Pk), administered through different application methods, on apoptosis-related gene expression in rats subjected to experimental oxidative stress induced by ethanol. The study materials were collected from Siirt-Eruh. The ground samples were macerated in water, and the extracts were used in the experiments after lyophilization. Coffee was prepared from the roasted samples, then filtered and used in the experiments. Dried and powdered Bıttım was mixed into the rats' feed. The rats were divided into five groups: Group I: Normal Control (NC) (n=6), Group II: Oxidative Stress Group (EtOH) (n=6), Group III: Pk: 20% EtOH + Bıttım-based feed (400 mg/kg) (n=6), Group IV: PkE: 20% EtOH + Bıttım water extract (400 mg/kg) (n=6), Group V: PkC: 20% EtOH + Bıttım coffee (400 mg/kg) (n=6). RNA was isolated from the liver and blood, and following cDNA synthesis, gene expression was analyzed using quantitative PCR (qPCR). As a result, this study demonstrated that Pk modulates apoptosis-related gene expression in the liver and blood, in response to ethanol-induced toxicity. Ethanol exposure significantly increased apoptotic markers such as p53 and CASP-3, whereas Pk in feed and extract forms exhibited a protective effect by suppressing apoptotic gene expression, with the feed form being more effective. However, the coffee form showed limited protective capacity. Unexpected fluctuations in gene expression suggest that cellular responses to oxidative stress are complex and influenced by multiple factors.

Keywords: Apoptosis, Bıttım, Hepatotoxicity, *Pistacia khinjuk* Stocks

Etanol Toksisitesine Maruz Bırakılan Ratlarda *Pistacia khinjuk* Stocks Tarafından Apoptozla İlişkili Gen Ekspresyonunun Değişimi

Öz: Bu çalışmada, farklı uygulama yöntemleri kullanılarak verilen Bıttım (*Pistacia khinjuk* Stocks) (Pk) bitkisinin, etanol ile indüklenen deneysel oksidatif strese maruz bırakılan sıçanlarda apoptozla ilişkili gen ekspresyonu üzerindeki etkilerini belirlemek amaçlanmıştır. Çalışma materyali Siirt-Eruh'tan toplanmıştır. Öğütülmüş örnekler su ile maserasyona tabi tutulmuş ve ekstreler liyofilizasyon sonrasında deneylerde kullanılmıştır. Kavrulmuş örneklerden kahve hazırlanmış, ardından süzülüp deneylerde kullanılmıştır. Kurutulup toz haline getirilen Bıttım, sıçanların yemine karıştırılmıştır. Sıçanlar beş gruba ayrılmıştır: Grup I: Normal Kontrol (NC) (n=6), Grup II: Oksidatif Stres Grubu (EtOH) (n=6), Grup III: Pk: %20 EtOH + Bıttım içeren yem (400 mg/kg) (n=6), Grup IV: PkE: %20 EtOH + Bıttım su ekstresi (400 mg/kg) (n=6), Grup V: PkC: %20 EtOH + Bıttım kahvesi (400 mg/kg) (n=6). Karaciğer ve kandan RNA izolasyonu yapılmış ve cDNA sentezinden sonra gen ekspresyonu kantitatif PCR ile analiz edilmiştir. Sonuç olarak, bu çalışma Pk'ın etanol kaynaklı toksisiteye yanıt olarak karaciğer ve kanda apoptozla ilişkili gen ekspresyonunu modüle ettiğini göstermiştir. Etanol maruziyeti, p53 ve CASP-3 gibi apoptotik belirteçleri önemli ölçüde artırırken, Pk'ın yem ve ekstre formları apoptotik gen ekspresyonunu baskılayarak koruyucu bir etki göstermiş, yem formunun daha etkili olduğu belirlenmiştir. Ancak, kahve formunun koruyucu etkisi sınırlı kalmıştır. Gen ekspresyonundaki beklenmedik dalgalanmalar, oksidatif strese karşı hücresel yanıtların karmaşık olduğunu ve birden fazla faktörden etkilendiğini düşündürmektedir.

Anahtar Kelimeler: Apoptoz, Bıttım, Hepatotoksisite, *Pistacia khinjuk* Stocks

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1. Introduction

Alcoholic liver disease is one of the leading causes of morbidity and mortality related to liver disorders and constitutes a significant global health concern. It encompasses a range of liver pathologies, including steatosis (fatty liver), steatohepatitis (inflammation of the fatty liver), fibrosis (scarring of the liver), cirrhosis, and even hepatocellular carcinoma (liver cancer). The main pathological processes involved in ethanol-induced liver damage include oxidative stress, inflammation, apoptosis, and fibrosis (Altamirano & Bataller, 2011).

Long-term excessive alcohol consumption has been found to lead to oxidative stress. This phenomenon can result in the production of reactive oxygen species (ROS) and protein and DNA adducts, which induce inflammatory signaling pathways in the liver, leading to the expression of pro-inflammatory mediators. These mediators can promote hepatocyte apoptosis and necrosis. Apoptosis is the process of programmed cell death; it is triggered by the activation of a mechanism that includes a self-destruction program encoded in the genetic system (Palai & Mishra, 2015). The mitochondrial stress within hepatocytes caused by ROS exposure may also lead to structural and functional mitochondrial complications, increasing the frequency of apoptosis (Karkucinska-Wieckowska et al., 2022). Since apoptosis is one of the main pathological processes involved in ethanol-induced liver damage, it is important to examine apoptosis-related gene expression in rats with this condition.

The most studied genes related to apoptosis are the tumor suppressor gene p53, the anti-apoptotic gene Bcl-2, and the pro-apoptotic gene Bax The p53 gene was first recognized as a tumor suppressor in 1989 and is often referred to as the "guardian of the genome" due to its central role in the DNA damage response (Hafner et al., 2019). In response to chemical damage, p53 is activated to drive stress-specific transcriptional response programs, such as slowing cell division or inducing programmed cell death (Aly et al., 2019). While the Bcl-2 gene protects the cell against death by inhibiting the apoptosis pathway (Song et al., 2014), the Bax gene acts as a regulator of apoptosis (Li et al., 2013). The p53 gene regulates apoptosis by interacting with the Bcl-2 family and providing direct transcriptional activation of the Bax promoter, downregulating the Bcl-2 gene and upregulating Bax gene expression (Song et al., 2014). Caspase-3 is regarded as the most crucial among the executioner caspases and can be activated by any of the initiator caspases, including caspase-8, caspase-9, or caspase-10 (Palai & Mishra, 2015).

Throughout history, humans have utilized plants for various purposes. Herbal remedies are regarded as a prudent approach with minimal side effects for disease prevention. The growing popularity of herbal medicines as alternative therapies reflects rising consumer demand for safer and healthier antitoxic agents (Ghasemzadeh Rahbardar & Hosseinzadeh, 2024). *Pistacia* is a genus belonging to the Anacardiaceae family, comprising about 20 different plants (Bozorgi et al., 2013). The main species belonging to this genus, such as *Pistacia lentiscus*, *Pistacia atlantica*, *Pistacia vera*, *Pistacia terebinthus*, and *Pistacia khinjuk* (Pk), among others, are of particular importance; they have been reported for their potential benefits for both medicinal and commercial purposes (Rauf et al., 2021). *Pistacia khinjuk* (Bıttım) is an important cultural product in Türkiye, particularly in much of Southeastern Anatolia. Traditionally, it is consumed as a special type of coffee and is also used in soap production. As a frequently consumed product in Türkiye, Pk is of great importance in health research due to its bioactive compounds and traditional medicinal uses.

Studies have investigated phytopharmaceuticals affecting the expression of apoptosis-related genes in hepatotoxicity models. In a study, it was aimed to investigate the effect of catechin against D-GalN-induced hepatotoxicity. It was reported that pretreatment with catechin was effective in preventing the disruption of mitochondrial membrane potential, upregulation of p53, Bax, and downregulation of Bcl-2 mRNA levels in the liver of rats (Vasanth et al., 2010). Gedikli & Şengül (2019) investigated the protective effect of quercetin on Cyclophosphamide (CYP)-induced hepatotoxicity in rats. They determined that MDA levels were significantly higher in the CYP group compared to the control group and decreased with quercetin administration. While immunopositivity for Bax and Caspase-3 was higher in the CYP group than in the other groups, Bcl-2 immunopositivity was lower in the CYP group (Gedikli & Şengül, 2019). It was determined that MDA levels were significantly higher in the CYP group compared to the control group and decreased with quercetin administration. In addition, while immunopositivity for Bax and Caspase-3 was higher in the CYP group than in the other groups, Bcl-2 immunopositivity was lower in the CYP group than in the other

groups (Gedikli and Şengül, 2019). Data in the literature indicate that members of the *Pistachio* genus contain the chemicals catechin and quercetin (Rajput et al., 2020).

In light of the information from the literature, the aim of the present study is to investigate the effects of different preparations of *Pistacia khinjuk* on the expression of apoptosis-related genes in rats. While previous studies have reported the hepatoprotective effects of various Pistacia species, no study has specifically examined the impact of *Pistacia khinjuk* on apoptosis-related gene expression in an ethanol-induced liver damage model. Therefore, this study contributes to the literature by exploring the potential influence of *Pistacia khinjuk* on apoptotic pathways in liver tissue.

2. Material and Methods

2.1. Animals and experimental design

The study began with approval from Van Yuzuncu Yil University Experimental Animals Unit Ethics Committee dated 23.02.2023, numbered 2023/05-06. The experimental study was performed on 30 female *Wistar albino* rats. The animals were housed at 22±2˚C in daily light/dark cycle, 60% humidity, and were fed ad libitum in stainless cages. Throughout the study, rats received humane care according to criteria outlined in the ‘’Guide for the Care and Use of Laboratory Animals’ ‘prepared by the National Academy of Science and published by the National Institutes of Health.

Rats were randomly divided into 5 groups (n=6). Before dividing the Wistar rats into groups, an acute toxicity test was conducted on 6 rats, and their behavior was monitored. The test followed the Organization for Economic Co-operation and Development (OECD) guideline 425. Three groups were formed, each with 2 rats, and their weights were measured before placing them in separate cages. One group received 2000 mg/kg Bıttım water extract, another received 2000 mg/kg Bıttım coffee, and the third received pellet feed with 2000 mg/kg Bıttım. The rats were observed for 48 hours. As no deaths occurred, the toxicity test was concluded, and the study began. The groups were then formed as follows:

Group I: Normal Control (NC) (n=6): Rats were given pellet feed and drinking water ad libitum.

Group II: Ethanol Control (EtOH) (n=6): Rats were given 20% ethanol in drinking water and fed with a standard pellet diet ad libitum.

Group III: 20% EtOH + Pk (n=6): Rats were given 20% ethanol in drinking water and 400 mg/kg of Bıttım-based pellet feed.

Group IV: 20% EtOH + PkE (n=6): Rats were given 20% ethanol in drinking water, 400 mg/kg of Bıttım extract via oral gavage, and fed with a standard pellet diet ad libitum.

Group V: 20% EtOH + PkC (n=6): Rats were given 20% ethanol in drinking water, 400 mg/kg of Bıttım coffee via oral gavage, and fed with a standard pellet diet ad libitum.

The experiment was conducted for 60 days. At the end of the study, the animals were anesthetized, blood and tissue samples were taken, and the study was concluded.

2.2. Preparation of *Pistacia khinjuk* (Bıttım)

Pistacia khinjuk Stocks (Pk) was collected from Siirt, Türkiye, and identified by Assoc. Prof. Dr. Süleyman Mesut Pınar. A voucher specimen was deposited at Van Yuzuncu Yil University’s herbarium (VANF) (Herbarium number: 164257). To prepare Bıttım-containing feeds, standard rat feed and Bıttım were powdered. The mixture was moistened with a small amount of water, turned into dough, and shaped into pellets. The prepared pellets were dried in a dark, dry, and cool environment and made ready to be given to experimental animals.

To make water extracts of Pk, 200 grams of the ground plant sample were weighed, placed in a glass beaker, and extracted with 1000 ml of pure water. The beaker was covered with aluminum foil. The mixture, which was homogenized in a shaker at 25 °C for 24 hours, was then placed in a centrifuge. The homogenized mixture was centrifuged at 8000 rpm for 10 minutes. All the supernatants obtained were placed in the same container. Then, the supernatants were partially purified from their solvent at +37 °C with the help of an evaporator. The concentrated extract was stored at -80

°C overnight and then kept in a lyophilization device for 3 days. The lyophilized extracts obtained were stored at –20 °C until the analysis process began.

To prepare the coffee of Pk, the plant was roasted in a pan with continuous stirring until it slightly changed color. The roasted seeds were ground, and coffee was prepared with hot water at a concentration of 400 mg/kg. After cooling and filtering, it was made ready to be administered to animals.

2.3. Gene expression analyses

During dissection, small pieces of liver were taken and placed into RiboSaver solution. The blood was collected into a sterile tube containing heparin. Total RNA from the liver was isolated using the GeneJET RNA Purification Kit (Thermo) according to the manufacturer's instructions. Blood RNA isolation was carried out using the Hydra RNA isolation kit according to the manufacturer's instructions. The concentration of each total RNA sample was quantified using a NanoDrop™ 2000 spectrophotometer (Thermo Fisher Scientific) at 260 and 280 nm. Nuclease-free water (DEPC) was used as a blank, and RNA concentration was calculated from the equation shown below (1):

$$\text{RNA concentration (ng/µL)} = 40 \text{ X } A_{260} \text{ X dilution factor} \quad (1)$$

cDNA synthesis was carried out using the High-Capacity cDNA Reverse Transcription Kit (Thermo) according to the manufacturer's instructions. The quantitative PCR (qPCR) studies in the tissues were performed in a 96-well plate in triplicate, using the Roche LightCycler® 480 real-time thermal cycler. The total reaction volume was 10 µL containing 5 µL SYBR Green, 0.1 µL forward primer, 0.1 µL reverse primer, and 4.8 µL DEPC-treated water. The sequences of the primers are shown in Table 1. The amplification conditions were as follows: initial denaturation at 95 °C for 15 min, followed by 50 cycles of 15 s at 95 °C, 1 min at 50 °C, and 10 s at 72 °C. The expressions of p53, Bax, Bcl-2, and CASP-3 genes in each sample were normalized with the housekeeping gene (β-actin). The expression level was calculated using the $2^{-\Delta\Delta CT}$ method (Livak & Schmittgen, 2001; Schmittgen & Livak, 2008) and expressed as relative expression compared to the control group (NC).

Table 1. Primer sequences used in the experiment

Gene	Forward Primer	Reverse Primer
β-aktin (Housekeeping)	5'-TCTTCCAGCCTTCCTTCCTG-3'	5'-CACACAGAGTACTTGCGCTC-3'
P53 (Housekeeping)	5'-CTCCTCTCCCCAGCAAAAGA-3'	5'-GTAGACTGGCCCTTCTTGGT-3'
Bax (Ramezani et al., 2019)	5'-ACAGGGTTTCATCCAGGATCGAG-3'	5'-AGCTCCATGTTGTTGTCCAGTTC-3'
Bcl-2(Ramezani et al., 2019)	5'-GGATTGTGGCCTTCTTTGAGTTC-3'	5'-AGAGCGATGTTGTCCACCAG-3'
Casp3 (Yardim et al., 2020)	5'-GGAGCTTGGAACGCGAAGAA-3'	5'-ACACAAGCCCATTTCAGGGT-3'

3. Results

Firstly, RNA was isolated from liver and blood samples. After RNA isolation, purity and concentration analyses of the isolated RNAs were conducted (Table 2). The concentrations of RNAs isolated from the liver were considerably higher than those isolated from the blood.

Table 2. Purity and concentration analyses of RNAs

	The Groups	RNA concentration ng/µl		The Groups	RNA concentration ng/µl
Liver	NC	978	Blood	NC	147.62
	ETOH	907.8		ETOH	182.77
	EtOH+Pk	827.8		EtOH+Pk	126.75
	EtOH+PkE	764.63		EtOH+PkE	142,9
	EtOH+PkC	854.47		EtOH+PkC	124.96

In gene expression analysis, β-actin was used as a housekeeping gene. The C_T (cycle threshold) values obtained from the qPCR reactions for β-actin are given in Table 3. The C_T value is the minimum number of cycles at which the fluorescent signal can be detected while the PCR reaction is ongoing (Figure 1-3).

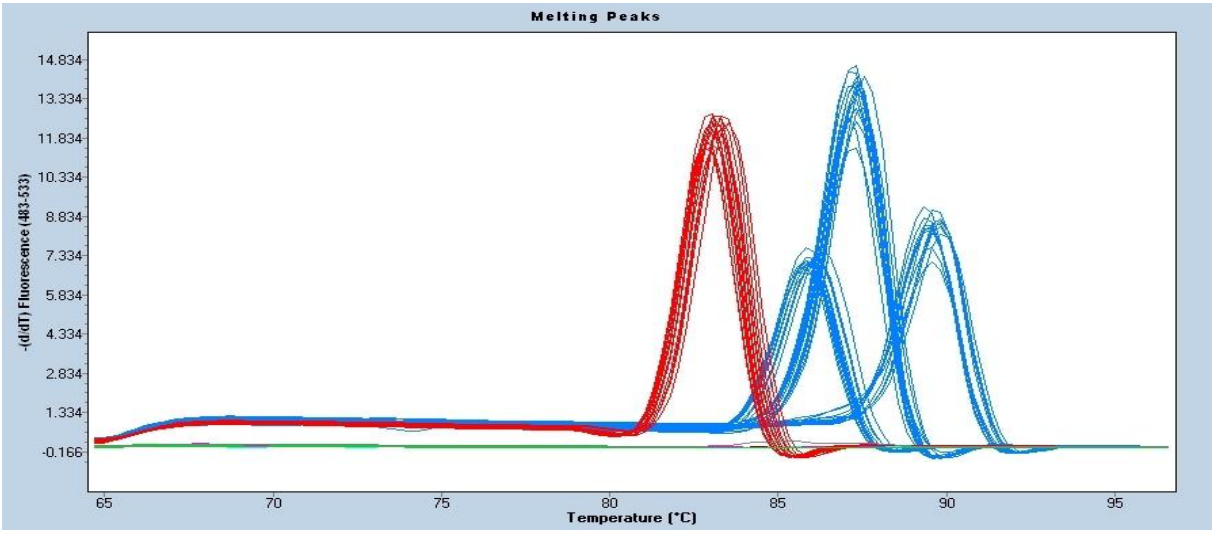


Figure 1. Melting curve analysis of primers by qPCR (1). The figure presents the melting peak analysis, where distinct peaks correspond to specific amplicons. The sharp, well-defined peaks indicate a homogeneous PCR product, while the presence of additional peaks may suggest non-specific amplification or contamination. The temperature at which the peak occurs represents the melting temperature (Tm) of the amplified product, which is influenced by the GC content and sequence composition.

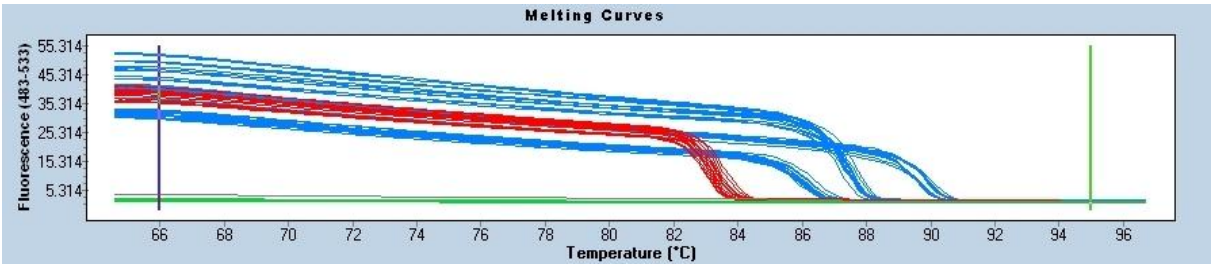


Figure 2. Melting curve analysis of primers by qPCR (2). The figure displays the full melting curve profile, illustrating the gradual denaturation of the PCR product as the temperature increases. A smooth, single transition from a high fluorescence signal to baseline confirms the presence of a single, specific amplicon. Multiple inflection points or irregularities in the curve may indicate primer-dimer formations or non-specific amplifications.

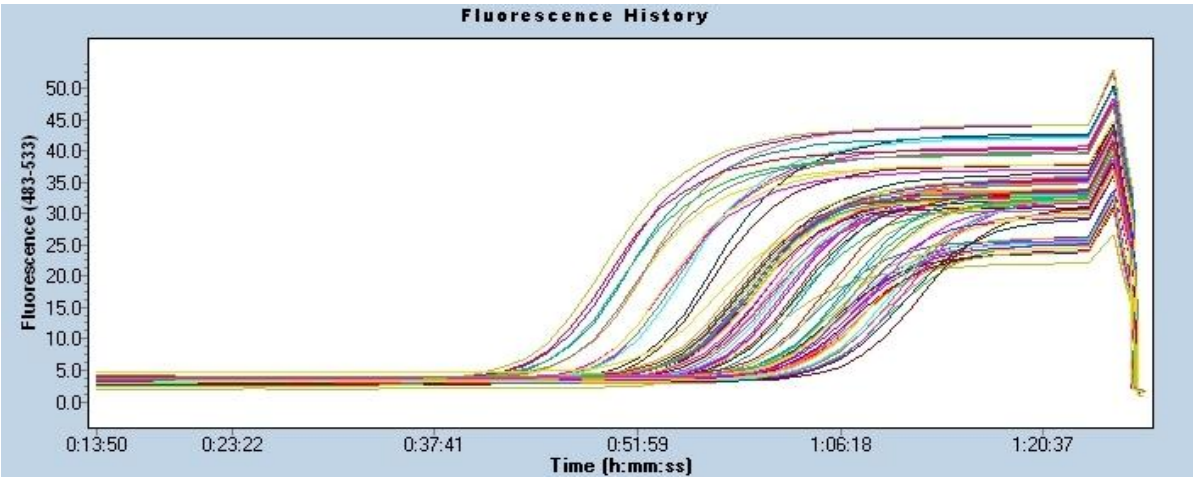


Figure 3. qPCR amplification of all samples. **Baseline Phase (Initial Time Period: 0:13:50 - ~0:50:00):** During the early cycles, fluorescence remains low and stable, indicating that the amount of target DNA is below the detection threshold. **Exponential Amplification Phase (~0:50:00 - 1:10:00)**: A sharp increase in fluorescence occurs as the target DNA undergoes exponential amplification. **Plateau Phase (~1:10:00 - 1:20:37):** The fluorescence signal levels off, indicating that the reaction has reached saturation.

Table 3. C_T Values of β-actin in liver and blood samples from qPCR results

	The Groups	β-aktin C_T±SD		The Groups	β-aktin C_T±SD
Liver	NC	22.89±0.55	Blood	NC	23.25±0.25
	ETOH	24.6±0.64		ETOH	20.44±0.59
	EtOH+Pk	21.04±0.23		EtOH+Pk	20.61±0.66
	EtOH+PkE	20.85±0.49		EtOH+PkE	20.77±0.65
	EtOH+PkC	22.58±0.71		EtOH+PkC	20.12±0.08

After gene expression analysis, $2^{\wedge-\Delta\Delta CT}$ values of p53, Bax, Bcl-2 and CASP-3 genes in the liver are shown in Table 4. As shown in Table 4, values less than 1 indicate a decrease in gene expression compared to the NC group, while values greater than 1 indicate an increase in gene expression compared to the NK group. The expressions of p53, Bax, Bcl-2 and CASP-3 genes in the liver were increased in the EtOH and PkC groups, while they decreased in the EtOH+Pk and EtOH+PkE groups (Table 4, Figure 4).

The $2^{\wedge-\Delta\Delta Ct}$ values for the p53, Bax, Bcl-2, and CASP-3 genes in the blood after gene expression analysis are shown in Table 5. The expressions of the p53 and CASP-3 genes in blood increased in all groups compared to the NC group. Expressions of Bax and Bcl-2 decreased in all groups compared to the NC group (Table 5, Figure 5).

Table 4. Apoptosis-related gene expression in liver tissue

		$2^{-\Delta\Delta Ct}$			
	The Groups	**p53**	**Bax**	**Bcl-2**	**CASP-3**
Liver	NC	1	1	1	1
	ETOH	1.58±0.72	2.32±0.69	3.70±0.97	1.87±0.91
	EtOH+Pk	0.84±0.31	0.51±0.09	0.42±0.09	0.77±0.17
	EtOH+PkE	0.63±0.44	0.47±0.2	0.42±0.13	0.99±0.4
	EtOH+PkC	1.22±0.42	1.18±0.9	1.17±0.51	1.39±0.35

Table 5. Apoptosis-related gene expression levels in blood samples

		$2^{-\Delta\Delta Ct}$			
	The Groups	**p53**	**Bax**	**Bcl-2**	**CASP-3**
Blood	NC	1	1	1	1
	ETOH	2.03±0.85	0.27±0.08	0,43±0.21	1,99±0.32
	EtOH+Pk	3.12±0.72	0.29±0.043	0,61±0.29	1,77±0.45
	EtOH+PkE	3.23±0.6	0.35±0.084	0,54±0.076	2,58±0.98
	EtOH+PkC	4.14±1.04	0.48±0.078	0,63±0.19	2,09±0.78

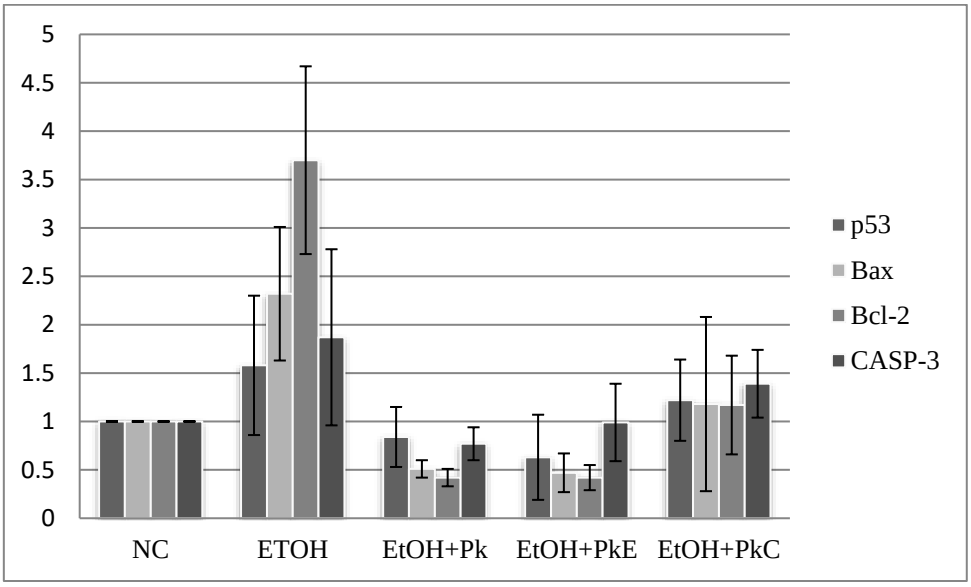


Figure 4. Expressions of apoptosis-related genes in the liver.

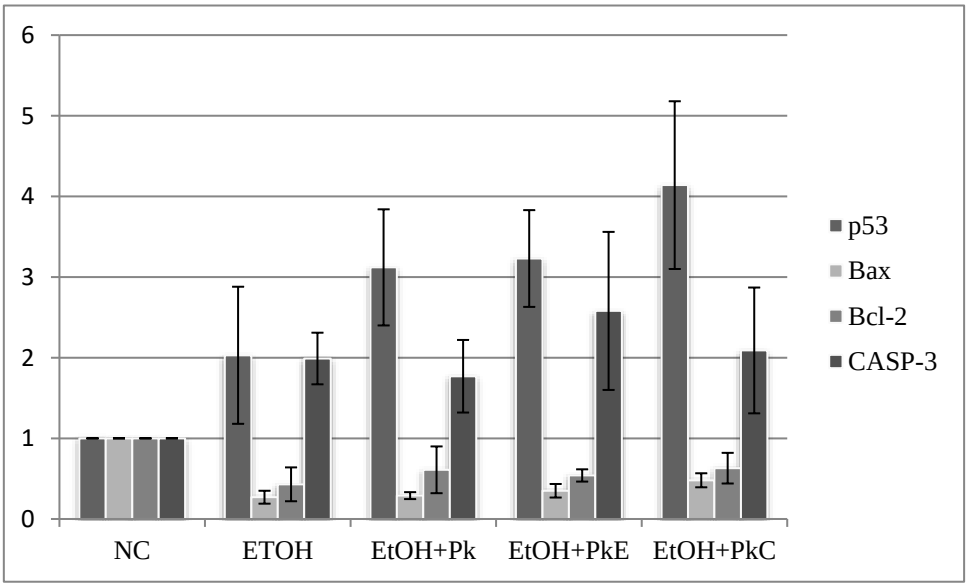


Figure 5. Expressions of apoptosis-related genes in the blood.

4. Discussion

Ethanol is a systemic toxin that can cause damage to various tissues depending on the duration and dosage of exposure. It leads to redox changes in the alcohol dehydrogenase pathway, affecting the metabolism of lipids, carbohydrates, proteins, and purines (Lieber, 2017). The liver is the primary organ responsible for metabolizing ethanol. Oxidative stress plays a significant role in the development of ethanol-related liver disease. This process involves an imbalance between the production of reactive oxygen species (ROS) and the body's ability to detoxify these reactive intermediates or repair the resulting damage (Liu et al., 2021). Chronic alcohol consumption leads to increased oxidative stress, which can cause inflammation, apoptosis, and fibrosis in the liver (Ramos-Tovar & Muriel, 2020). Therefore, in a study that induces liver damage through ethanol exposure, the genes whose expression should be examined are typically associated with pathophysiological processes such as oxidative stress, inflammation, apoptosis, and fibrosis resulting from ethanol. Thus, the aim of the present study was to investigate the effects of oxidative stress that may occur as a result of ethanol metabolism on the expression of apoptosis-related genes, and how these effects could change with the administration of *Pistacia khinjuk* in different forms to rats.

To assess the expression of a specific gene using reverse transcription polymerase chain reaction (RT-PCR or qPCR), the isolation of total RNA and the measurement of ribonucleic acid (RNA) concentration are required. Therefore, the isolation of total RNA represents one of the most critical steps that can significantly influence the outcomes of subsequent experiments. In the present study, RNA concentration obtained from liver tissue was found to be substantially higher compared to that from blood tissue. The samples collected from the liver during dissection were immediately placed in an RNA stabilization solution. In contrast, blood samples were collected in heparinized tubes and stored in liquid nitrogen. Since the 2'OH group in RNA can interact with phosphate groups, RNA is more susceptible to hydrolysis than DNA (Becskei & Rahaman, 2022). These results highlight the importance of using RNA stabilization solutions. There was a significant loss of RNA in the blood samples, likely exacerbated by freeze-thaw cycles, which led to further degradation of RNA. The results showed that specialized collection tubes were necessary for RNA stabilization for blood (Duale et al., 2012).

A melt curve analysis evaluates the separation of double-stranded DNA at high temperatures. When a single DNA type is generated from a particular primer pair, it produces one distinct peak. Conversely, if multiple DNA types or primer dimers are present, the analysis will show two or more peaks which suggest the use of non-specific primers (Adams, 2020). Melt curve analysis is a tool that not only confirms the specificity of the amplified product but also provides valuable information about amplification efficiency and product quality. Researchers can optimize the PCR conditions. For example, if a melt curve indicates the presence of multiple products, adjustments in primer design or annealing temperatures may be warranted (Miao et al., 2020). In the present study, a distinct peak was observed for each pair of primers, indicating that primer specificity had been achieved.

Housekeeping genes, also known as reference genes, are typically selected based on their stable expression levels across various experimental conditions and tissue types (Bustin et al., 2009). The best known housekeeping genes in the literature are glyceraldehyde-3-phosphate dehydrogenase (GAPDH), β-actin, ribosomal proteins (RPL), ubiquitin (UBQ), β-tubulin, 18S ribosomal protein (18S rRNA) and phosphoglycerate kinase (PGK) (Rebouças et al., 2013). In the present study, β-actin was used as a housekeeping gene. The use of β-actin as a housekeeping gene is prevalent due to its stable expression across different cell types; however, it is crucial to validate its stability in specific experimental contexts to avoid misleading conclusions (Rebouças et al., 2013).

The C_T (cycle threshold) value is the minimum number of cycles at which the amount of fluorescent signal can be observed while the PCR reaction is ongoing. A high C_T value indicates that the number of copies is low. This is because the production of enough nucleic acid to give a signal was achieved in later cycles (Gunay et al., 2016). The implications of C_T values extend beyond mere quantification; they also influence the reproducibility and reliability of gene expression analyses. Studies have shown that factors such as primer efficiency, template quality, and the presence of inhibitors can impact C_T values, necessitating rigorous experimental design and controls to ensure accurate data interpretation (Vandesompele et al., 2002; Bustin et al., 2009). Additionally, employing

multiple housekeeping genes for normalization can enhance the robustness of results, particularly in heterogeneous tissues or under varying physiological conditions.

The method of administration of substances to laboratory animals is a critical component of experimental design, as it directly influences the pharmacokinetics of the compounds, including their absorption, distribution, metabolism, and excretion (Turner et al., 2011). Phytopharmaceuticals are naturally present in plants at specific concentrations; however, their levels tend to decrease to some extent after processing. There is limited information on how much of these diminished plant-derived compounds remain available in the body to perform their biological functions. The health benefits of phytopharmaceuticals largely depend on their bioavailability, which includes their absorption, distribution, metabolism, and excretion within the digestive and circulatory systems (Aqil et al., 2013). Based on these considerations, Pk was administered to experimental animals in three different forms: coffee, extract, and feed. In the liver, the results indicate that ethanol exposure significantly upregulated apoptosis-related genes due to oxidative stress. However, this increase was markedly suppressed in the EtOH+Pk and EtOH+PkE groups, suggesting a protective effect of Pk in feed and extract forms. In contrast, the EtOH+PkC group exhibited relatively higher apoptotic gene expression, which may be attributed to changes in bioavailability following the roasting process. These findings highlight that differences in bioavailability play a crucial role in determining the efficacy of Pk in modulating apoptosis.

In the blood, the results suggest changes in apoptotic gene regulation across the different experimental groups, particularly in response to Pk treatments. Ethanol significantly induces apoptosis in blood cells, as evidenced by increased p53 and CASP-3 expression. The feed and extract forms of Pk moderately suppress apoptosis, with the feed form showing slightly greater protective effects. The coffee form unexpectedly exhibits higher apoptotic gene expression, potentially due to alterations in its bioavailability after processing.

In the current study, the expressions of p53, Bax, Bcl-2 and CASP-3 genes in the liver increased in the EtOH and PkC groups, while they decreased in the EtOH+Pk and EtOH+PkE groups compared to the normal control (NC) group. Normally, p53 activation enhances the expression of Bax, which triggers the apoptotic process, while suppressing Bcl-2 expression (Song et al., 2014). However, in this study, all three genes were upregulated. The increased expression of p53, Bax, and Bcl-2 genes together in the experiment could be due to several possible causes. Cells under stress conditions can activate both apoptotic and anti-apoptotic mechanisms. This may reflect an attempt by the cells to survive despite the stress. The increased expression of p53 and Bax may drive apoptosis, but the upregulation of Bcl-2 suggests that the cells are attempting to counteract this process and avoid cell death. This phenomenon has been observed and documented in the literature, where Bcl-2 expression is elevated as a defense mechanism under extreme stress (Vousden & Lane, 2007). High Bcl-2 expression often correlates with an effort to inhibit apoptosis and promote cell survival. Another explanation is timing. Gene expression profiles can change over time as cells respond to damage or stress. In the early stages, p53 and Bax expression increase to initiate apoptosis, but as the process progresses, anti-apoptotic proteins like Bcl-2 may become upregulated to help cells resist apoptosis (Miyashita & Reed, 1995). Also, the liver is an organ composed of heterogeneous cell types. Different cell populations (hepatocytes, stellate cells, Kupffer cells, etc.) may respond differently to ethanol-induced stress. While some cells undergo apoptosis, others may increase Bcl-2 expression to survive (Ramos-Tovar & Muriel, 2020). These aspects could explain the simultaneous increase in all three genes observed in the study, depending on the timing of the experiment.

Expressions of p53 and CASP-3 genes in the blood increased in all groups compared to NC, while Bax and Bcl-2 expressions decreased. Increased CASP-3 expression is commonly observed alongside p53 elevation, as p53 directly or indirectly facilitates CASP-3 activation, marking the final stages of apoptosis. This relationship is well-supported in the literature, where stress-induced activation of p53 often leads to caspase-mediated cell death (Vousden & Lane, 2007). Where p53 is upregulated and apoptosis is actively occurring (as suggested by increased CASP-3 expression), it's common to observe downregulation of Bcl-2 since its anti-apoptotic role is inhibited to allow apoptosis to proceed. But Bax is usually upregulated by p53. One explanation for the downregulation of Bax where p53 is upregulated could be that apoptosis has progressed to a stage where Bax is no longer required or that other pro-apoptotic pathways are taking precedence in inducing caspase activity (Miyashita & Reed, 1995). Another explanation is that apoptosis may be proceeding through

alternative pathways that do not require Bax activation. Previous studies have shown that p53 can trigger apoptosis via caspase-dependent mechanisms without directly inducing Bax expression (Murray-Zmijewski et al., 2006; Vousden & Lane, 2007). Furthermore, the rapid clearance of apoptotic cells in circulation may contribute to the observed downregulation of Bax (Elmore, 2007).

Pistacia khinjuk contains key phytochemicals such as gallic acid, caffeic acid, ellagic acid, quercetin, and catechin (Mohammadi et al., 2019; Merlin et al., 2021). It has been demonstrated that caffeic acid, quercetin, and ellagic acid modulate apoptotic gene expression in human cervical cancer cell lines, with all three compounds increasing p53 expression. Additionally, quercetin upregulates caspase-3, caspase-9, and Bax, while both caffeic acid and quercetin downregulate Bcl-2 (Chang et al., 2010). A study has demonstrated that gallic acid significantly increases the mRNA expression of p53, Bax, and caspase-3 in the MCF-7 breast cancer cell line (Çakır et al., 2023). In the current study, the effects of Pk on gene expressions may be attributed to its bioactive compounds supporting the potential role of *P. khinjuk* as a natural modulator of apoptosis. Similarly, the significant up-regulation of p53 observed in a study suggests that *Pistacia khinjuk* hydroalcoholic extract may activate the mitochondrial (intrinsic) apoptotic pathway by increasing Bax gene expression while decreasing Bcl-2 gene expression, thereby exhibiting potent apoptotic activity against HepG2 cells (Harandi et al., 2022). *Pistacia vera* hull extracts have been shown to inhibit breast cancer cell proliferation through increased expression of Caspase-3, Caspase-8, Bax, and SOD, while downregulating Bcl-2 (Seifaddinipour et al., 2020).

5. Conclusion

This study demonstrated that *Pistacia khinjuk* (Stocks) modulates apoptosis-related gene expression in the liver and blood, in response to ethanol-induced toxicity. Ethanol exposure significantly increased apoptotic markers such as p53 and CASP-3, whereas Pkin feed and extract forms exhibited a protective effect by suppressing apoptotic gene expression, with the feed form being more effective. However, the coffee form showed limited protective capacity. Unexpected fluctuations in gene expression suggest that cellular responses to oxidative stress are complex and influenced by multiple factors.

These findings highlight the potential of Pk-derived bioactive compounds in modulating apoptosis-related pathways, supporting its role as a natural antioxidant with therapeutic potential in ethanol-induced liver damage. However, further mechanistic studies, protein-level validations, and in vivo models are required to confirm these effects and explore their clinical relevance.

This study has certain limitations. The use of six rats per group may limit the statistical power of the findings. The sample size could not be increased due to ethical and financial constraints, which should be considered when interpreting the generalizability of the results. Gene expression analyses in this study relied solely on β-actin as the reference gene. Given that β-actin expression may vary under different experimental conditions, the inclusion of multiple reference genes, such as GAPDH or 18S rRNA, is recommended in future research to enhance the reliability of gene expression normalization. In this study, gene expression analyses were performed using qPCR and significant changes were detected in the relevant genes. However, changes in gene expression levels may not always be directly correlated with protein. Therefore, in future studies, verification of changes in protein levels using techniques such as Western blot or ELISA will provide stronger clinical and translational support for the findings. While this study provides new insights into the role of Pk in oxidative stress regulation, future research should address these limitations to enhance the robustness and applicability of the results.

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Research Article

Comprehensive Analysis of Density of States (DOS), UV-Visible, NMR Spectroscopy, and Molecular Electrostatic Potential (MEP) of RU-486 and its Derivatives (Ph, KOH, NO_2, OH) in Relation to Their Effects on Breast Cancer †

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Abstract: In this study, a comprehensive analysis was conducted on RU-486 (Mifepristone) and its derivatives (Ph, KOH, NO_2, OH), focusing on their potential effectiveness against breast cancer. The analysis included Density of States (DOS) optimization, UV-Visible spectroscopy, Nuclear Magnetic Resonance (NMR) spectroscopy, and Molecular Electrostatic Potential (MEP) mapping. The electronic structures and stabilities of these molecules were examined through DOS, revealing how different functional groups influence their electronic properties. UV-Visible spectroscopy identified shifts in absorption maxima, which correspond to changes in electronic transitions due to functionalization. NMR spectroscopy provided insights into the chemical environments of specific nuclei, offering detailed information on molecular geometry and electronic distribution. MEP analysis mapped the electrostatic potential across the molecular surfaces, pinpointing regions of electrophilic and nucleophilic reactivity. Collectively, these analyses have enhanced the understanding of the electronic properties, reactivity, and potential pharmaceutical applications of RU-486 and its derivatives in breast cancer treatment.

Keywords: DOS, MEP, NMR, Ru-486, UV-Vis

RU-486 ve Türevlerinin (Ph, KOH, NO_2, OH) Yoğunluk Durumu (DOS), UV-Görünür, NMR Spektroskopisi ve Moleküler Elektrostatik Potansiyel (MEP) Üzerine Kapsamlı Analizi ve Meme Kanseri Üzerindeki Etkileri ile İlişkisi

Öz: Bu çalışmada, RU-486 (Mifepriston) ve türevleri (Ph, KOH, NO_2, OH) üzerine meme kanserine karşı potansiyel etkinliklerine odaklanılarak kapsamlı bir analiz gerçekleştirilmiştir. Analiz, Yoğunluk Durumu (DOS) optimizasyonu, UV-Görünür spektroskopisi, Nükleer Manyetik Rezonans (NMR) spektroskopisi ve Moleküler Elektrostatik Potansiyel (MEP) haritalandırmasını içermektedir. DOS aracılığıyla bu moleküllerin elektronik yapıları ve kararlılıkları incelenmiş ve farklı fonksiyonel grupların elektronik özellikler üzerindeki etkileri ortaya konmuştur. UV-Görünür spektroskopisi, fonksiyonelleştirme nedeniyle elektronik geçişlerdeki değişimlere karşılık gelen absorpsiyon maksimumlarında kaymalar belirlemiştir. NMR spektroskopisi, belirli çekirdeklerin kimyasal ortamları hakkında detaylı bilgi sağlayarak moleküler geometrinin ve elektronik dağılımın anlaşılmasına katkıda bulunmuştur. MEP analizi, moleküler yüzeylerdeki elektrostatik potansiyeli haritalandırarak elektrofilik ve nükleofilik reaktivite bölgelerini belirlemiştir. Bu analizler bir araya getirildiğinde, RU-486 ve türevlerinin elektronik özellikleri, reaktiviteleri ve meme kanseri tedavisindeki potansiyel farmasötik uygulamaları hakkındaki çalışmalar artırmıştır.

Anahtar Kelimeler: DOS, MEP, NMR, Ru-486, UV-Vis

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1. Introduction

Breast cancer continues to be a major global health problem, with a significant proportion of cases attributed to reproductive factors, particularly those related to hormonal exposure throughout a woman's life (Obeagu & Obeagu, 2024). Progesterone, a key hormone in female reproductive physiology, is recognized for its role as a major mitogen in breast tissue, promoting the proliferation of breast epithelial cells during the luteal phase of the menstrual cycle (Bartkowiak-Wieczorek et al., 2024). Given the critical role of progesterone in breast tissue dynamics and tumorigenesis, there is increasing interest in the potential of progesterone receptor antagonists as a preventive strategy against breast cancer (Utjés et al., 2024). Mifepristone, a well-known PR modulator, has shown promising results in preclinical and clinical studies due to its ability to counteract the mitogenic effects of progesterone in the breast (Ciebiera et al., 2024). Despite these encouraging findings, the molecular mechanisms underlying the protective effects of mifepristone on normal breast tissue remain poorly understood (Elia et al., 2024). This study contributes to a deeper understanding of the molecular changes induced by progesterone antagonism and highlights the potential of mifepristone as a chemo preventive agent against breast cancer (Iftikhar et al., 2024). It represents the first in vivo examination of the breast transcriptome following mifepristone treatment and provides valuable insight into the early molecular events that may underlie its protective effects (Narwal et al., 2024). Breast cancer is one of the most common malignant tumors worldwide, and metastasis is a leading cause of death among patients (Mustafa et al., 2024). The tumor microenvironment (TME) plays a key role in breast cancer progression, particularly in drug resistance and distant metastasis (Kundu et al., 2024). Within the TME, cancer-associated fibroblasts (CAFs) are activated by tumor cells, leading to the secretion of pro-tumor factors and the production of extracellular matrix (ECM) components that impede drug penetration and facilitate epithelial-mesenchymal transition (EMT) (Zheng & Hao, 2024). In addition, glucocorticoids (GCs) may interact with glucocorticoid receptors (GRs) on breast cancer cells, contributing to immunosuppression and promoting metastasis (He et al., 2024). Recent strategies have focused on combining TME-modulating agents with chemotherapeutic approaches to enhance antitumor efficacy (Zhang et al., 2024a). Natural compounds such as Berberine (Ber) have been shown to inhibit CAF activation and ECM deposition while blocking the TGF-β/Smad2/3-mediated signaling pathway involved in tumor metastasis (Wu et al., 2024). Mifepristone (Ru486), known for its abortifacient properties, has shown antitumor activity by antagonizing GRs and inhibiting GC-GR-mediated metastasis. To overcome the limitations of traditional drug formulations, such as low bioavailability and systemic toxicity, the development of nanosized drug delivery systems has attracted significant attention (Lv et al., 2024). These systems, including liposomes and micelles, can co-deliver multiple drugs with different antitumor mechanisms, thereby enhancing targeted delivery and therapeutic efficacy (Xue et al., 2024). Nanosized carriers modified with hyaluronic acid (HA) show promise in improving drug penetration and targeting tumor cells via CD44 receptor-mediated endocytosis (Chen et al., 2024). The efficacy of these formulations was evaluated in vitro using the "MCF-7/MRC-5" dual-cell model and in vivo using the orthotopic 4T1 cell mouse model (Wu et al., 2024). The results showed that D-HMs and B&R-HLs effectively penetrated tumor tissues, inhibited CAF activation, reduced ECM deposition, and decreased tumor angiogenesis, ultimately leading to significant inhibition of breast cancer metastasis (Sayed et al., 2024). Density Functional Theory (DFT) calculations were performed to analyze the theoretical absorbance spectra, HOMO-LUMO orbitals, density of states (DOS) spectra, and various molecular properties. RU-486 (Mifepristone) and its derivatives are considered promising agents in breast cancer treatment by targeting progesterone and glucocorticoid receptors (Naqvi et al., 2025). Due to their potential to inhibit tumor growth and slow down metastatic processes, research on these compounds for breast cancer prevention and treatment has been steadily increasing (Xiong et al., 2025). Additionally, incorporating nanotechnological drug delivery systems can enhance the efficacy of RU-486, providing a more specific and potent antitumor effect (Mohammad-Jafari et al., 2024).

2. Material and Methods

2.1. Molecular structure Ooptimization

The molecular structures of RU-486 (Mifepristone) and its derivatives (Ph, KOH, NO_2, OH) were optimized using Density Functional Theory (DFT), a quantum mechanical modeling method widely used in computational chemistry to predict molecular geometries and electronic properties with high accuracy. The optimization was carried out using the B3LYP functional combined with the 6-311++G(d,p) basis set, which ensures precise treatment of electron correlation effects and provides reliable structural parameters (Kumar et al., 2024). Once the optimization process was completed, frequency calculations were performed to confirm that each geometry corresponded to a true local minimum on the potential energy surface. This step is crucial because imaginary frequencies would indicate a transition state rather than a stable molecule. The absence of imaginary frequencies verified that the structures obtained were stable conformations (Tegegn et al., 2024). The optimized molecular geometries obtained from this study serve as a foundation for further investigations, including electronic structure analysis (DOS), spectroscopic simulations (UV-Vis, NMR), and Molecular Electrostatic Potential (MEP) mapping, providing valuable insights into the potential applications of RU-486 derivatives.

The Density of States (DOS) analysis was performed to investigate the effects of different functional groups (Ph, KOH, NO_2, OH) on the electronic structures of RU-486 and its derivatives (Middleton et al., 2024). DOS analysis provides critical insight into the distribution of electronic energy levels and how functionalization influences molecular electronic properties (Zaki et al., 2025).

Time-Dependent DFT (TD-DFT) was employed to simulate the UV-Visible absorption spectra of RU-486 and its derivatives (Ghazy et al., 2024). These calculations were conducted in the gas phase at the same B3LYP/6-311++G(d,p) theoretical level, with absorption maxima (λ_max) analyzed to observe the changes in electronic transitions resulting from functionalization of the parent molecule (Aloumko et al., 2024). The NMR chemical shifts of RU-486 and its derivatives were calculated using the Gauge-Independent Atomic Orbital (GIAO) method at the B3LYP/6-311++G(d,p) level (Liu et al., 2024). Proton (^1H) and carbon (^{13}C) NMR spectra were generated, and the chemical environments of specific nuclei were analyzed (Zhang et al., 2024b). The chemical shifts were referenced against Tetramethylsilane (TMS) as an internal standard, providing detailed information about molecular geometry and electronic distribution (Seqqat et al., 2025).

Molecular Electrostatic Potential (MEP) maps were generated to visualize the electrostatic potential across the molecular surfaces of RU-486 and its derivatives (Chatterjee et al., 2024). MEP calculations were performed using the optimized geometries from the DFT calculations at the B3LYP/6-311++G(d,p) level. The MEP maps were analyzed to identify regions of electrophilic and nucleophilic reactivity, which are critical for understanding the interactions of these molecules with biological targets (Şahin, 2023).

The computational data obtained from these analyses were used to compare the electronic properties, chemical reactivity, and potential biological activity of RU-486 and its derivatives. The DOS, UV-Visible spectra, NMR chemical shifts, and MEP maps were collectively examined to draw conclusions regarding the influence of different functional groups on the molecular properties and their effectiveness in breast cancer treatment (Manakkadan et al., 2024).

3. Results

3.1. Geometry optimization

Geometry optimization is a critical process in molecular modeling, aimed at determining the most stable, low-energy configuration of a molecule (Pracht et al., 2024). This process begins with an initial geometry setup, followed by energy minimization, typically performed using advanced quantum chemistry software such as Gaussian 09 (Cao et al., 2024). In this study, the geometry of the RU-486 molecule was optimized in both its pure form and when doped with various functional groups (Ph, KOH, NO_2, OH). These modifications led to distinct molecular conformations, each representing the molecule's lowest energy state (Chaudhuri et al., 2024). Understanding these optimized structures is

essential for analyzing molecular properties, investigating chemical reaction mechanisms, and designing new pharmaceutical compounds. The optimization results, calculated using both DFT and HF approaches, are presented in Figure 1 and Table 1 (Yılmaz & Kebiroglu, 2024).

Table 1. Structural and electronic changes in RU-486 molecule due to various dopants (Ph, KOH, NO_2, OH)

Doped Molecule	Dopant Description	Structural Changes	Electronic Changes
Ph Doped RU-486	Phenyl group (Ph) is a benzene ring attached to RU-486.	Introduces a significant structural component, altering the molecular conformation.	Affects overall geometry and electronic properties of the RU-486 molecule.
KOH Doped RU-486	Potassium hydroxide (KOH), consisting of potassium (purple atom) and hydroxyl (OH) groups.	Causes significant changes in the molecular structure due to interaction with potassium and hydroxyl.	Alters the spatial arrangement and electronic distribution within the RU-486 molecule.
NO_2 Doped RU-486	Nitro group (NO_2), consisting of one nitrogen (blue atom) and two oxygen atoms (red atoms).	Significantly influences the molecular structure, integrating into the RU-486 framework.	Alters conformation and electronic properties of the molecule.
OH Doped RU-486	Hydroxyl group (OH), consisting of one oxygen (red atom) and one hydrogen atom.	Affects the molecular structure and interactions, altering the overall molecular conformation.	Influences the electronic distribution within the molecule.

3.2. Molecular electrostatic potential (MEP) maps

Electrostatic potential maps (MEP) are essential for analyzing the distribution of electronegativity and partial charges within molecules, highlighting regions prone to electrophilic (red) and nucleophilic (blue) attacks (Rajimon et al., 2024). This color-coded visualization helps in understanding molecular interactions, such as bonding with biological molecules, and identifying reactive sites. For the RU-486 molecule and its derivatives, MEP analysis indicates a tendency toward nucleophilic behavior, with green areas representing moderate electron density and potential electrophilic regions (Irfan et al., 2024). These findings, shown in Figure 2 and Table 2, provide valuable insights into the chemical behavior and interaction potential of these molecules. Additionally, the separation between the green and red lines represents the energy difference between the HOMO and LUMO levels for all elements (Çankaya et al., 2024).

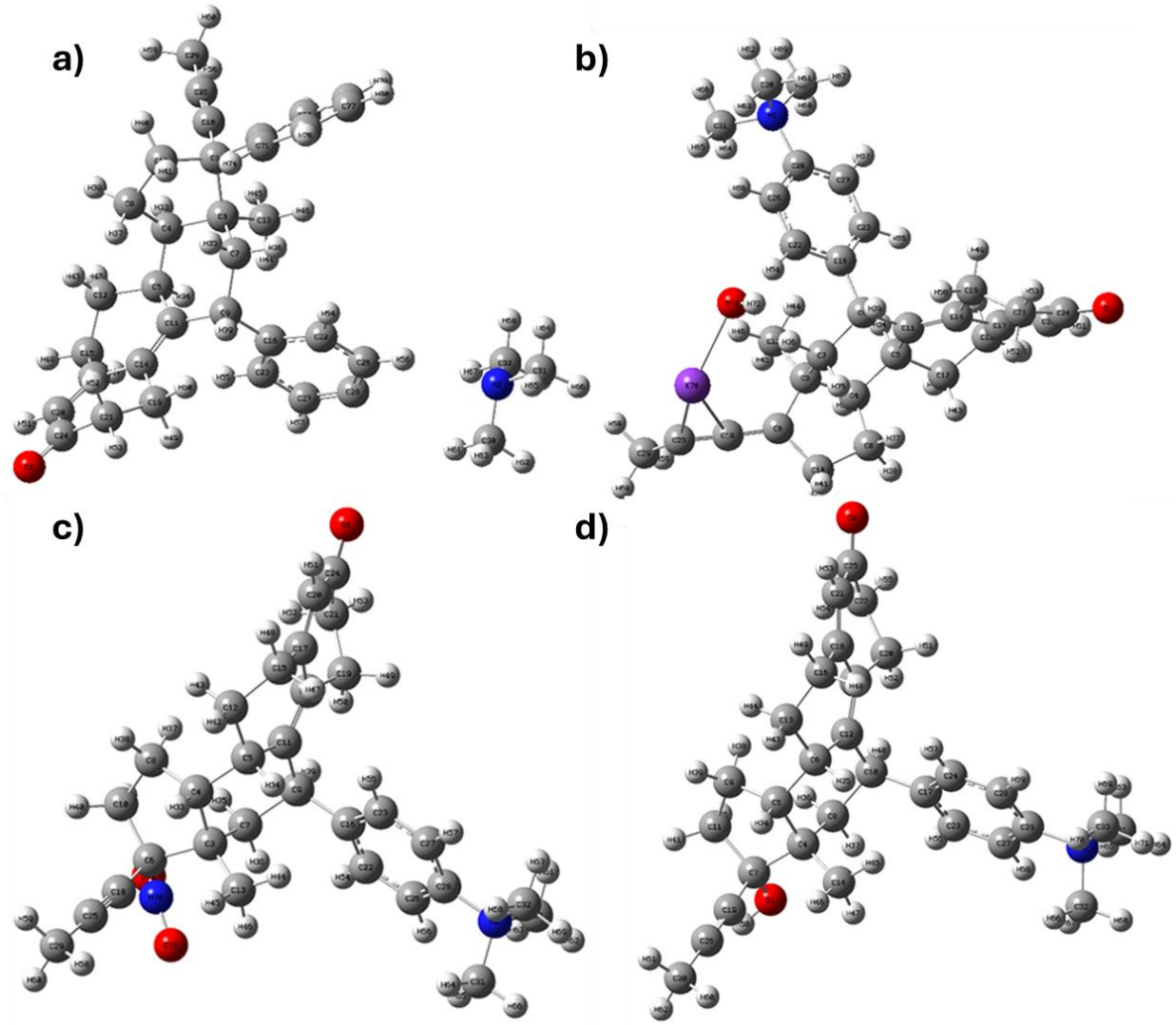


Figure 1. Optimized structure of RU-486 molecule a) Ph b) KOH c) NO_2 d) OH doped.

Table 2. Molecular electrostatic potential (MEP) maps and electron density distributions of RU-486 doped with various functional groups (Ph, KOH, NO_2, OH)

Molecule	**MEP Map Description**	**Electron Density Distribution**	**Chemical Implications**
RU-486-Ph	RU-486 doped with a phenyl group (Ph).	Red regions around the aromatic ring indicate high electron density (electron-rich areas).	Likely sites for electrophilic attacks due to the electron-rich nature of the aromatic ring.
RU-486-KOH	RU-486 doped with a potassium hydroxide (KOH) group.	Potassium is shown in blue (electron-poor), oxygen in red (electron-rich), with green/yellow indicating moderate density.	KOH group creates distinct areas for potential chemical interactions, influencing overall electron distribution.
RU-486-NO_2	RU-486 doped with a nitro group (NO_2).	Red regions around oxygen atoms of the nitro group indicate high electron density.	Potential sites for nucleophilic attacks; nitro group significantly alters overall reactivity and interactions.
RU-486-OH	RU-486 doped with a hydroxyl group (OH).	Red region around the oxygen atom shows high electron density; blue areas suggest lower density regions.	Hydroxyl group affects electrophilic and nucleophilic regions, altering the molecule's chemical reactivity.

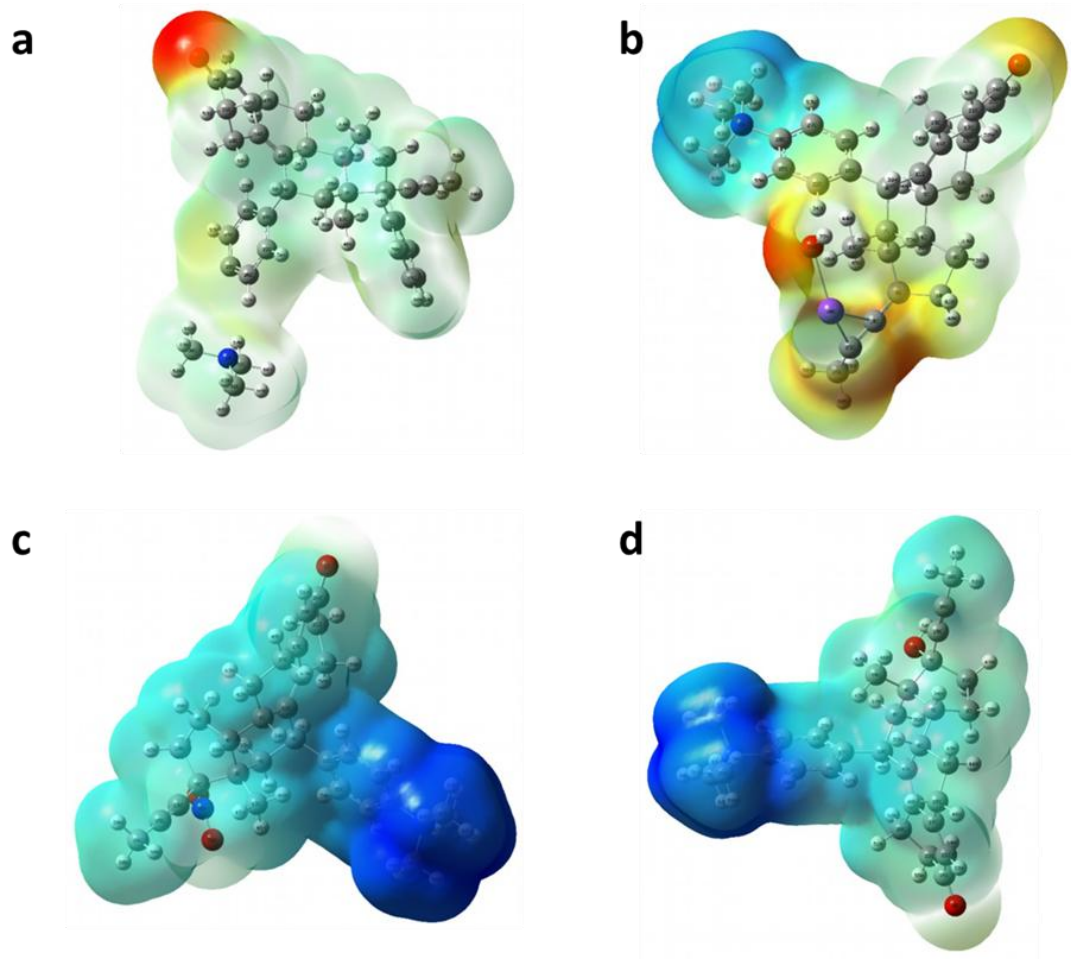


Figure 2. MEP maps of a) RU-486-Ph b) RU-486-KOH, c) RU-486-NO_2, d) RU-486-OH molecules.

3.3. Vibrational spectroscopic analysis spectrum

If the dipole moment of a molecule changes during vibration, the vibrational mode becomes infrared-active, meaning it can absorb infrared light (Mello et al., 2024). Symmetric vibrations, however, are rarely observed in the infrared spectrum, particularly in molecules with a center of symmetry where these vibrations are inactive (Esselman et al., 2024). Asymmetric vibrations are detectable for all molecules, allowing the investigation of various chemical groups, including amino acids and water molecules, which are challenging to detect with conventional spectroscopy (Araújo et al., 2024). In this study, the vibrational spectra of RU-486 and its derivatives were analyzed using the DFT/B3LYP method and the 6-31G basis set. The resulting IR spectra, covering the 3500-0 cm^{-1} range, display absorption peaks that reflect the vibrational frequencies, which are influenced by bond strength and the mass of the bonded atoms. The similarity in spectra and vibrational frequencies across complexes indicates similar structural properties.

Table 3. Summary of peak ıntensities and frequencies in Figure 3a to Figure 3d with associated low-level transmittance changes

Figure	Peak Number with Highest Intensity	Wavenumber (cm^{-1})	Other Transmittance Numbers with Low-Level Changes
Figure 3a	8	3108	67, 26, 36, 15, 14, 27, 54, 64, 80, 82, 88
Figure 3b	0.1	3073	8, 26, 25, 23, 20, 10, 30, 50, 51, 15, 16
Figure 3c	9	3100	69, 25, 20, 16, 26, 20, 47, 64, 79, 81
Figure 3d	6	3091	81, 30, 42, 19, 34, 17, 57, 70, 38

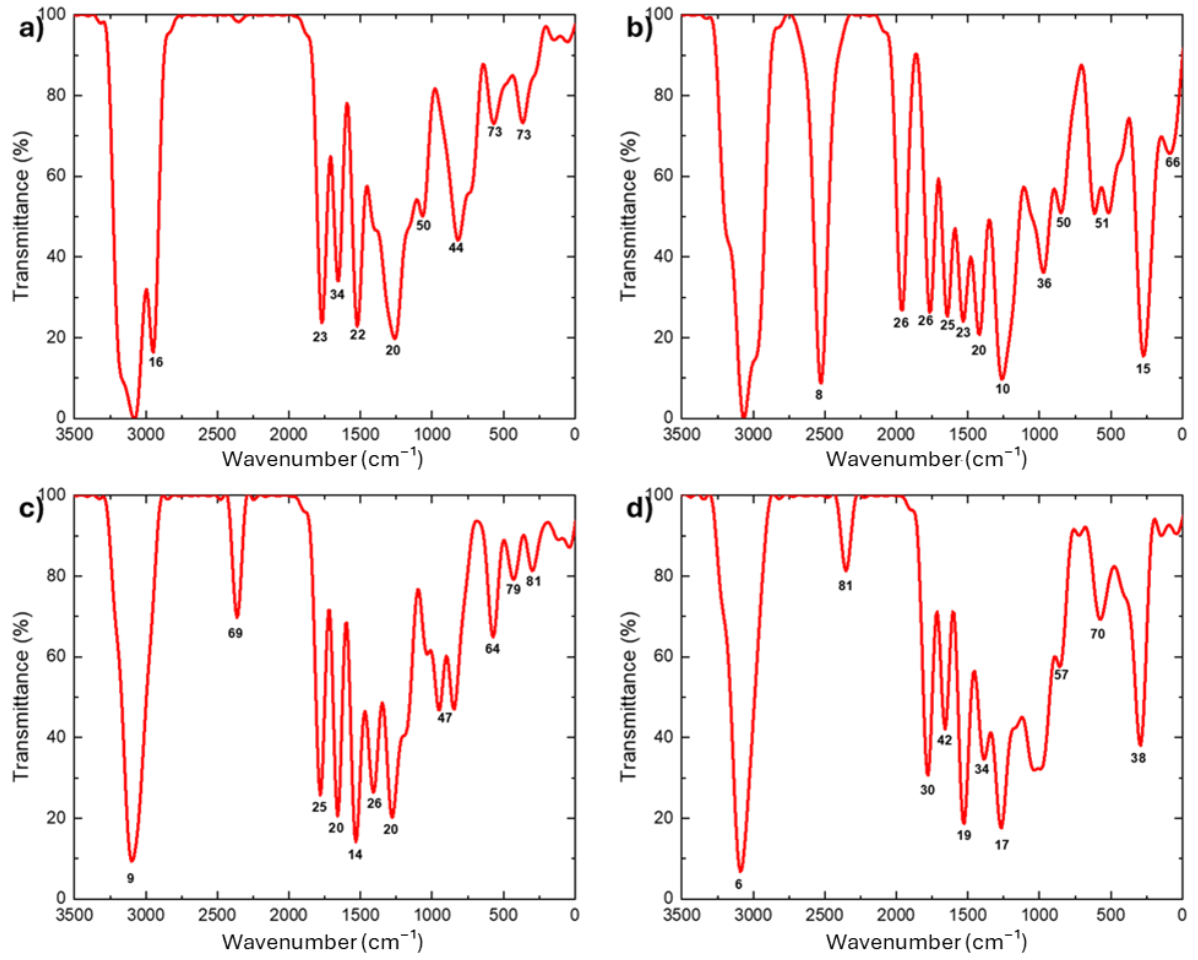


Figure 3. FT-IR spectrum of a) Ru-486-Ph b) Ru-486-KOH, c) Ru-486-NO_2, d) Ru-486-OH molecules.

3.4. Nuclear magnetic resonance spectroscopy

3.4.1. ^{13}C NMR spectrum

The ^{13}C NMR (Nuclear Magnetic Resonance) spectrum is a form of nuclear magnetic resonance spectroscopy used to identify different carbon environments within a molecule, helping to determine the structure of organic compounds (Günther, 2013). In the ^{13}C NMR spectrum of RU-486 in Figure 4, Mifepristone exhibits a complex structure, with details of RU-486 and its derivatives in Table 4.

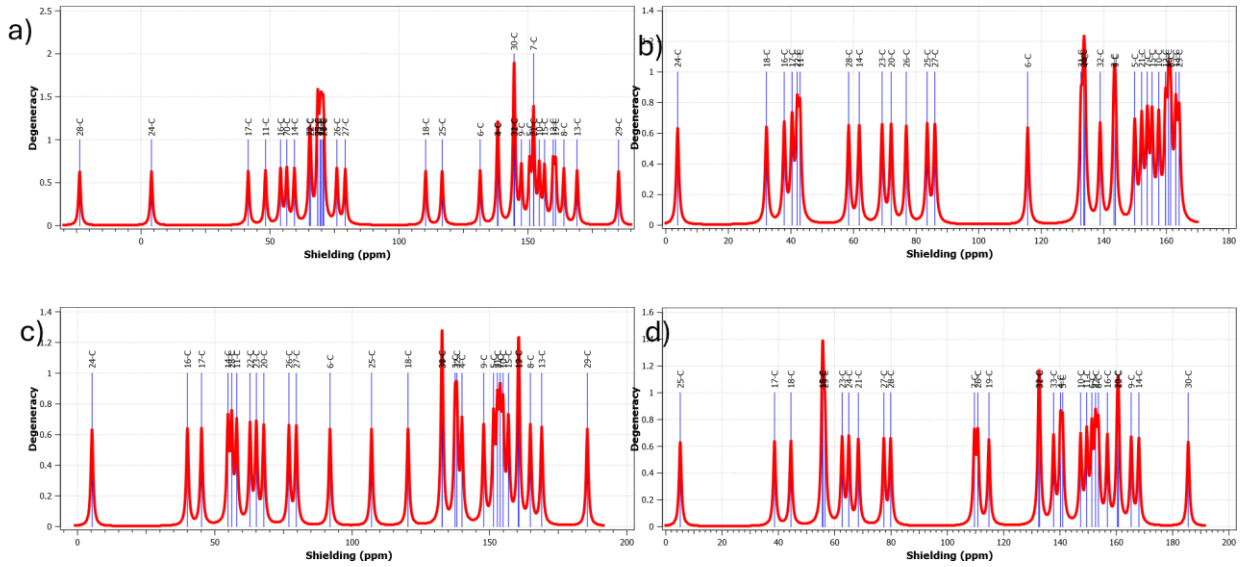


Figure 4. ^{13}C NMR spectrum of a) Ru-486-Ph b) Ru-486-KOH, c) Ru-486-NO_2, d) Ru-486-OH molecules.

Table 4. ^{13}C NMR spectra for Ru-486 and its derivatives

Compound	Region (ppm)	Peak Assignment
Ru-486-Ph	0-50	Peaks in this region likely correspond to alkyl carbons in the structure, such as methylene (CH_2) and methyl (CH_3) groups.
	50-100	Peaks in this region could correspond to carbons attached to electronegative atoms, possibly indicating carbons connected to oxygen or nitrogen atoms.
	100-150	This region includes aromatic and olefinic carbons. Given that Ru-486-Ph includes a phenyl (Ph) group, multiple peaks should appear in this region representing the aromatic carbons.
	150-220	This region typically corresponds to carbonyl carbons (C=O). Ketone or other carbonyl groups in Ru-486 and its derivatives would be indicated by peaks in this region.
Ru-486-KOH	0-50	Alkyl carbons
	50-100	Carbons attached to oxygen or other electronegative atoms
	100-150	Aromatic carbons
	150-220	Carbonyl carbons (C=O)
Ru-486-NO_2	0-50	Alkyl carbons
	50-100	Carbons attached to nitro group (NO_2, de-shielding, downfield shift)
	100-150	Aromatic carbons
	150-220	Carbonyl carbons (C=O)
Ru-486-OH	0-50	Alkyl carbons
	50-100	Carbons attached to oxygen atoms (hydroxyl groups, de-shielding)
	100-150	Aromatic carbons
	150-220	Carbonyl carbons (C=O)

3.4.2. ^{1}H NMR spectrum

The ^{1}H NMR (Nuclear Magnetic Resonance) spectrum is a powerful technique for determining the structure of organic compounds by identifying the different proton environments within a molecule (Chalbot & Kavouras, 2014). Figure 5 presents the ^{1}H NMR spectra for a) Ru-486-Ph, b) Ru-486-KOH, c) Ru-486-NO_2, and d) Ru-486-OH molecules. Table 5 provides the detailed ^{1}H NMR spectra for Ru-486 and its derivatives.

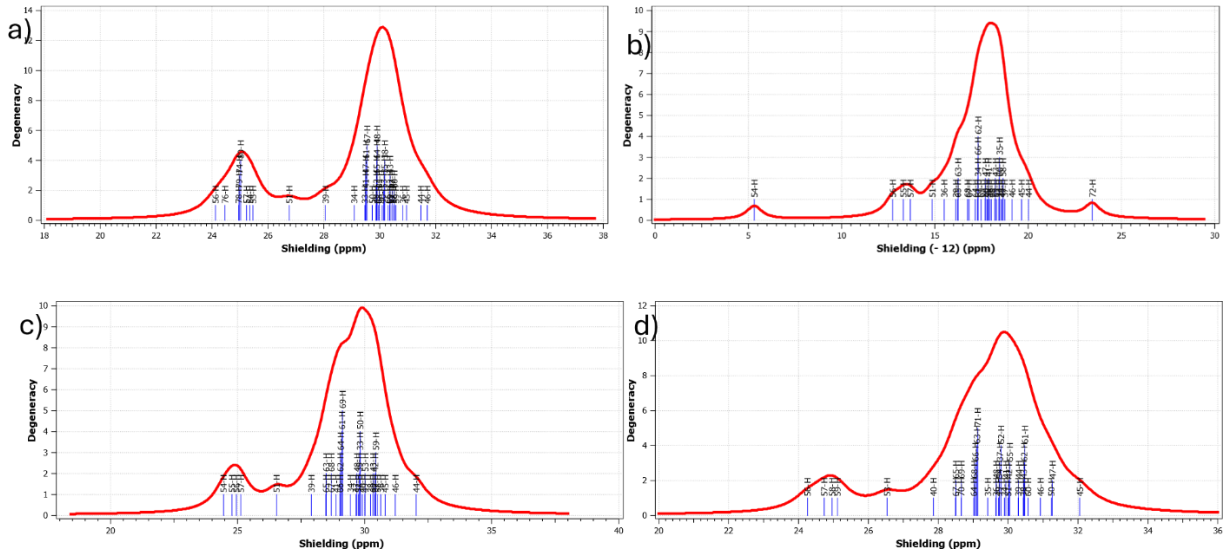


Figure 5. ^{1}H NMR spectrum of a) Ru-486-Ph b) Ru-486-KOH, c) Ru-486-NO_2, d) Ru-486-OH molecules.

Table 5. ^{1}H NMR spectra for Ru-486 and its derivatives

Compound	Region (ppm)	Peak Assignment
Ru-486-Ph	0-3	Likely corresponds to alkyl protons, including methylene (CH_2) and methyl (CH_3) groups. Peaks around 1.0-2.5 ppm likely represent the protons of the methyl groups.
	3-5	Protons attached to sp3 hybridized carbons adjacent to electronegative atoms such as oxygen or nitrogen.
	5-7	This region usually corresponds to olefinic protons (protons on sp2 carbons in alkenes). Significant activity around this region indicates olefinic protons.
	6-9	Aromatic protons typically appear in this region. Multiple peaks indicate the aromatic protons in the structure of Ru-486-Ph.
	9-12	Protons attached to carbonyl groups (aldehydes) or carboxylic acids. No significant peaks suggest a lack of aldehyde or carboxylic acid protons.
Ru-486-KOH	0-3	Alkyl protons (CH_2 and CH_3 groups), peaks around 1.0-2.5 ppm
	3-5	Protons attached to sp3 carbons adjacent to electronegative atoms (O)
	5-7	Olefinic protons (sp2 carbons in alkenes)
	6-9	Aromatic protons
	9-12	No significant peaks (absence of aldehyde or carboxylic acid protons)
Ru-486-NO_2	0-3	Alkyl protons (CH_2 and CH_3 groups), peaks around 1.0-2.5 ppm
	3-5	Protons attached to sp3 carbons adjacent to electronegative atoms (NO_2)
	5-7	Olefinic protons (sp2 carbons in alkenes)
	6-9	Aromatic protons
	9-12	No significant peaks (absence of aldehyde or carboxylic acid protons)
Ru-486-OH	0-3	Alkyl protons (CH_2 and CH_3 groups), peaks around 1.0-2.5 ppm
	3-5	Protons attached to sp3 carbons adjacent to electronegative atoms (OH)
	5-7	Olefinic protons (sp2 carbons in alkenes)
	6-9	Aromatic protons
	9-12	No significant peaks (absence of aldehyde or carboxylic acid protons)

3.4.3. UV–Visible analysis

UV and UV-visible spectroscopy have played a crucial role in the discovery of atomic and molecular structures by chemists (Rahuman et al., 2020). These optical-based methods have further advanced the study of optical and electronic properties of nanoscale particles. The principle of UV-Visible analysis is based on the absorption of photons by molecules, where interaction with photons in the UV or visible spectrum causes electrons to transition from lower to higher energy levels (Kebiroglu

& Yılmaz, 2023). Figure 6 presents the UV-visible absorption spectra for a) RU-486-Ph, b) RU-486-KOH, c) RU-486-NO_2, and d) RU-486-OH molecules, while Table 6 details the absorbance spectra and peaks for RU-486 and its derivatives.

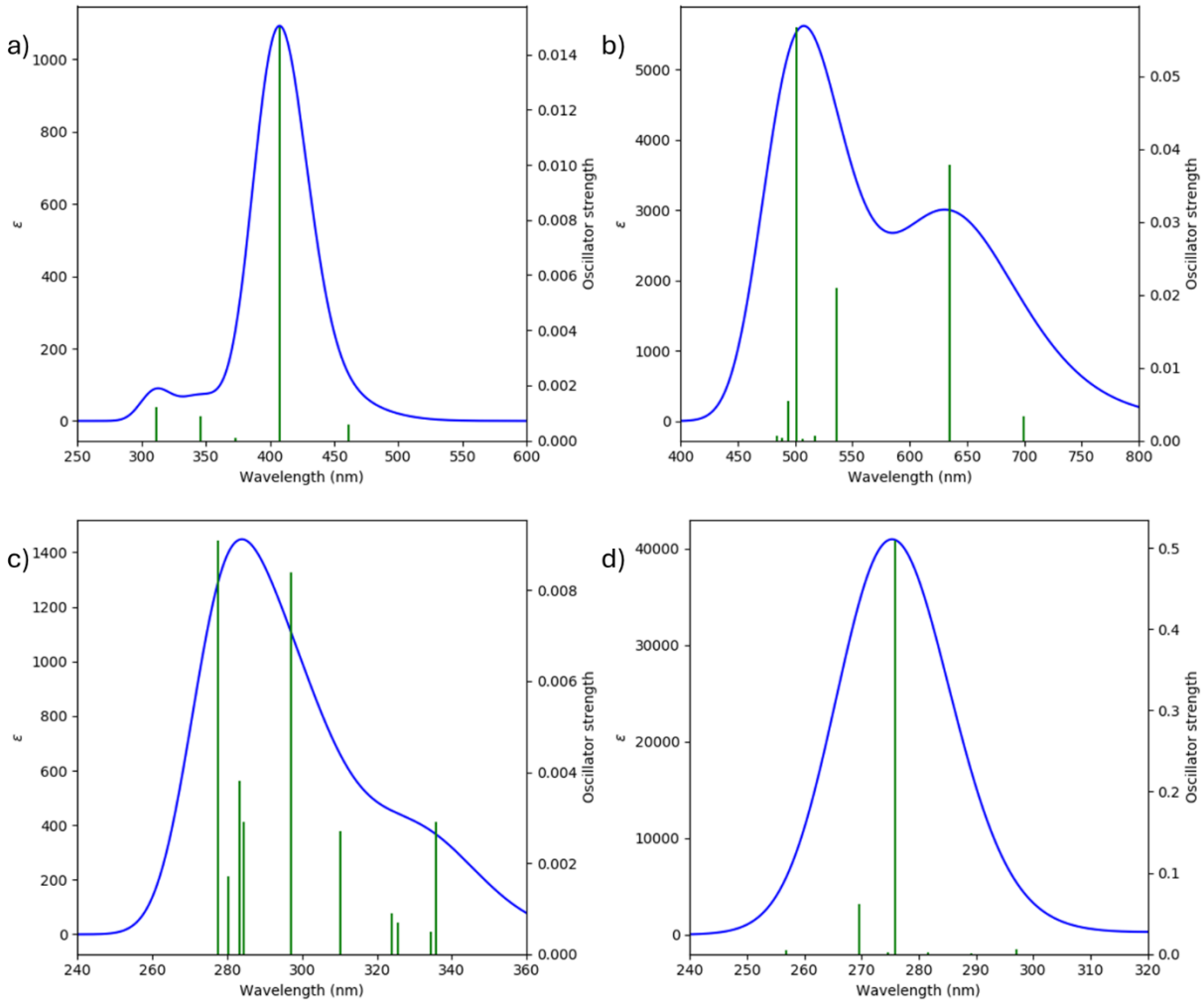


Figure 6. UV-visible absorption of a) Ru-486-Ph, b) Ru-486-KOH, c) Ru-486-NO_2, d) Ru-486-OH molecules.

Table 6. Absorbance spectra and peaks for Ru-486 and its derivatives

Figure	Compound	Peak Wavelength (nm)	Energy (eV)	Description
6a	RU-486-Ph	408	4.276	The peak indicates the color of the Ph-doped RU-486 molecule.
6b	RU-486-KOH	524	1.137	The peak indicates the color of the KOH-doped RU-486 molecule.
6c	RU-486-NO_2	287	4.086	The peak indicates the color of the NO2-doped RU-486 molecule.
6d	RU-486-OH	287	4.094	The peak indicates the color of the OH-doped RU-486 molecule.

3.4.4. Density of states (DOS)

The density of states (DOS) is a crucial physical quantity that represents the number of electronic states available at specific energy levels within a material (Kebiroglu & Ak, 2023). DOS plays a vital role in fields like solid-state physics and materials science, providing insights into the electronic properties of materials (Aghdasi et al., 2024). The Energy (eV) Axis (X-axis) represents these energy

levels in electron volts, typically ranging from approximately -20 eV to +10 eV. In Figure 7 and Table 7, the DOS for a) RU-486-Ph, b) RU-486-KOH, c) RU-486-NO_2, and d) RU-486-OH molecules is illustrated.

Table 7. Overview of density of states (DOS) parameters and energy levels for Ru-486 and its derivatives

Feature	**Description**
DOS Axis (Y-axis)	Represents the density of states, indicating the number of electronic states available at each energy level.
Color-Coded Spectra	- Alpha DOS spectrum (blue): Density of states for alpha spin electrons. - Beta DOS spectrum (green): Density of states for beta spin electrons. - Total DOS spectrum (red): Combined density of states for both alpha and beta spin electrons, scaled by 0.5 for better visualization.
Occupied and Virtual Orbitals	- Alpha Occupied Orbitals (cyan): Energy levels where alpha spin electrons are likely to be found in occupied states. - Alpha Virtual Orbitals (magenta): Energy levels where alpha spin electrons are likely to be found in virtual (unoccupied) states. - Beta Occupied Orbitals (yellow): Energy levels where beta spin electrons are likely to be found in occupied states. - Beta Virtual Orbitals (black): Energy levels where beta spin electrons are likely to be found in virtual (unoccupied) states.

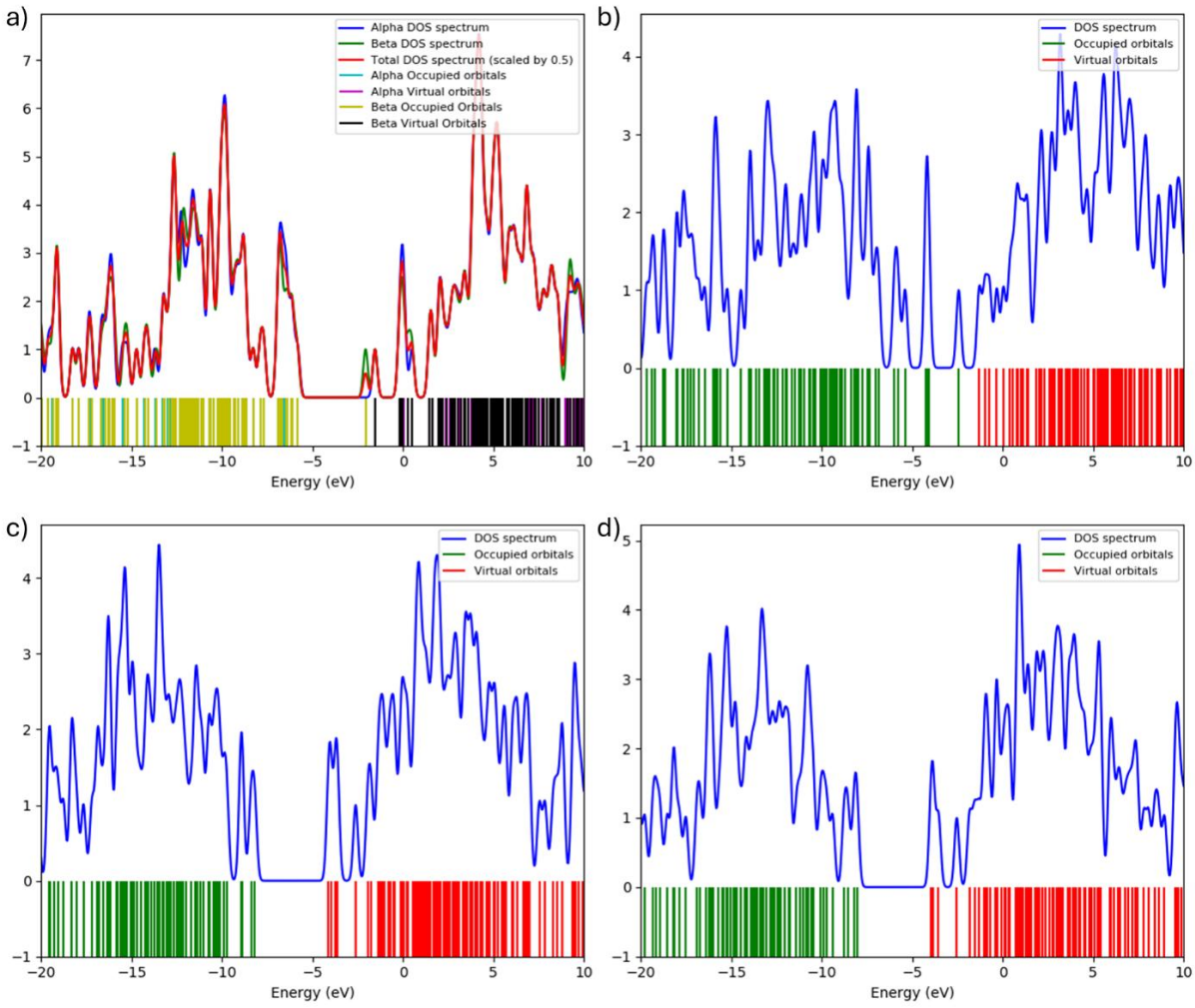


Figure 7. Density of states (DOS) of a) Ru-486-Ph, b) Ru-486-KOH, c) Ru-486-NO_2, d) Ru-486-OH molecules.

4. Discussion and Conclusion

This comprehensive study underscores the critical role of Mifepristone (RU-486) and its derivatives in breast cancer prevention and treatment. By employing advanced computational methods, including Density Functional Theory (DFT) and various spectroscopic techniques, we have successfully elucidated the structural and electronic properties of RU-486 and its derivatives (Ph, KOH, NO_2, OH). The findings reveal these modifications significantly influence molecular geometry, electronic distribution, and chemical reactivity, which are crucial for enhancing the therapeutic potential of these compounds. The study highlights the nucleophilic tendency of RU-486 derivatives, which plays a pivotal role in their interactions with biological targets. The promising antitumor activity of Mifepristone, especially when incorporated into nanosized drug delivery systems like liposomes and micelles, was confirmed. These systems demonstrated enhanced efficacy by effectively penetrating tumor tissues, inhibiting cancer-associated fibroblast (CAF) activation, reducing extracellular matrix (ECM) deposition, and decreasing tumor angiogenesis, leading to significant inhibition of breast cancer metastasis. Using computational tools such as DOS analysis, UV-Visible spectroscopy, NMR, and MEP mapping provided deep insights into the molecular dynamics and potential reactivity of RU-486 and its derivatives. These insights are invaluable for understanding the mechanisms of action and optimizing the design of new pharmaceutical compounds. This study reinforces the importance of combining computational chemistry with experimental validation to develop more effective chemo preventive and therapeutic strategies against breast cancer. The findings pave the way for future research and development of targeted therapies, contributing to better outcomes in breast cancer treatment.

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Research Article

Investigation of the Cytotoxic Effect of 2-Amino-4-phenylthiazole Derivative Against MCF-7 and AGS Cancer Cells

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Abstract: This study aimed to investigate the cytotoxic effects of 2-amino thiazole compound (**3**) on MCF-7 breast and AGS gastric cancer cells. We examined the cytotoxic effects of various concentrations (10-25-50-100 µg/mL) of 2-aminothiazol compound (**3**) on MCF-7 breast cancer and AGS gastric cells at 24, 48 and 72 hours using MTT assay. MTT assays demonstrate that the 2-amino thiazole (**3**) compound has a time- and dose-dependent inhibitory effect on the proliferation of MCF-7 and AGS cancer cells. Analysis of the data obtained from MTT assay showed that IC_{50} values for thiazole were 80.13, 71.03 and 59.24 µg/ml and 75.03, 38.12 and 28.01 µg/ml for 24, 48 and 72 hours on MCF-7 and AGS cells, respectively. The 100 µg/mL dose was demonstrated to be most effective on both cancer cells. Our results suggest that the 2-amino-4-phenylthiazole (**3**) compound has a dose-dependent effect on cytotoxicity in MCF7 breast and AGS gastric cancer cells.

Keywords: AGS cells, Cytotoxic, MCF-7 cell, MTT assay, Thizole

2-Amino-4-feniltiyazol Türevinin MCF-7 ve AGS Kanser Hücrelerine Karşı Sitotoksik Etkisinin Araştırılması

Öz: Bu çalışmada 2-amino-4-feniltiyazol bileşiğinin (**3**) MCF-7 meme ve AGS mide kanseri hücreleri üzerindeki sitotoksik etkilerinin incelenmesi amaçlanmıştır. 2-aminotiyazol bileşiğinin (**3**) çeşitli konsantrasyonlarının (10-25-50-100 µg/mL) MCF-7 meme kanseri ve AGS mide hücreleri üzerindeki sitotoksik etkilerini 24., 48. ve 72. saatlerde MTT testi kullanarak incelenmiştir. MTT deneyleri, 2-amino tiyazol (**3**) bileşiğinin MCF-7 ve AGS kanser hücrelerinin çoğalması üzerinde zamana ve doza bağlı bir inhibitör etkiye sahip olduğunu göstermektedir. MTT deneyinden elde edilen verilerin analizi, tiyazol için IC_{50} değerlerinin MCF-7 ve AGS hücreleri üzerinde 24, 48 ve 72 saat boyunca sırasıyla 80.13, 71.03 ve 59.24 µg/ml ve 75.03, 38.12 ve 28.01 µg/ml olduğunu göstermiştir.100 µg/mL dozunun her iki kanser hücresi üzerinde de en etkili olduğu gösterilmiştir. Sonuçlarımız 2-amino-4-feniltiyazol (**3**) bileşiğinin MCF-7 meme ve AGS mide kanseri hücrelerinde sitotoksisite üzerinde doza bağlı bir etkiye sahip olduğunu göstermektedir.

Anahtar Kelimeler: AGS hücreleri, MCF-7 hücresi, MTT deneyi, Sitotoksik, Tiyazol

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1. Introduction

The existence of 1,3-thiazole rings in the structures of many drug molecules and bioactive molecules has led to the increased studies on this ring system (Ghorab & Al-Said, 2012; Mirza et al., 2017). Numerous clinically used drugs containing 1,3-thiazole nuclei such as abafungin, dasatinib, dabrafenib, epothilone, fentiazac, ixabepilone, itazoxanide, meloxicam, nitazoxanide, nizatidine, niridazole, patellamide A, ritonavir, sulfathiazole and thiazofurine are used to treat cancer, inflammation, parasitic diseases, etc. (Figure 1) (Mirza et al., 2017; Ammar et al., 2018; Sharma et al., 2020; Moghaddam-manesh et al., 2021; Tavallaei et al., 2021; Othman et al., 2022). Bioactivity studies of thiazole derivative molecules demonstrate that they have a broad spectrum of bioactivity (Mirza et al., 2017). Some thiazole ring containing molecules have been developed as polymerase and microtubular inhibitors. These compounds have been reported to exhibit potent anti-cancer activity and less toxicity (Sharma et al., 2020). Thiazole compounds have a large number of studies on anti-cancer activity (Mirza et al., 2017). Ammar et al. (2018) investigated the cytotoxic activity of novel thiazole-oxoindole compounds against cancer cell lines (MCF-7(breast), HepG-2 (liver), HCT-116 (colon)). It was found that the synthesized compounds showed good cytotoxic activity against HepG-2, HCT-116 cell lines. Mohamed et al. (2017) investigated the cytotoxic effect of benzothiazole derivatives against MCF-7 cell lines. It was revealed that many of the derivatives they synthesized showed good cytotoxic effect compared to cis-platinum reference (Mohamed et al., 2017). Mirza et al. (2017) synthesized substituted aryl-thiazole and investigated their cytotoxicity against various cancer cell lines (MCF-7, HCT116, MDA-MB-231, and HeLa). Patil et al. (2010) investigated the anti-cancer properties of 5-benzylidene-2,4-thiazolidinediones derivatives on 7 different cell lines. They obtained the best results against MCF-7, K562 (leukemia) and GURAV (nasopharyngeal cancer) cell lines (Patil et al., 2010; Fayed et al., 2020).

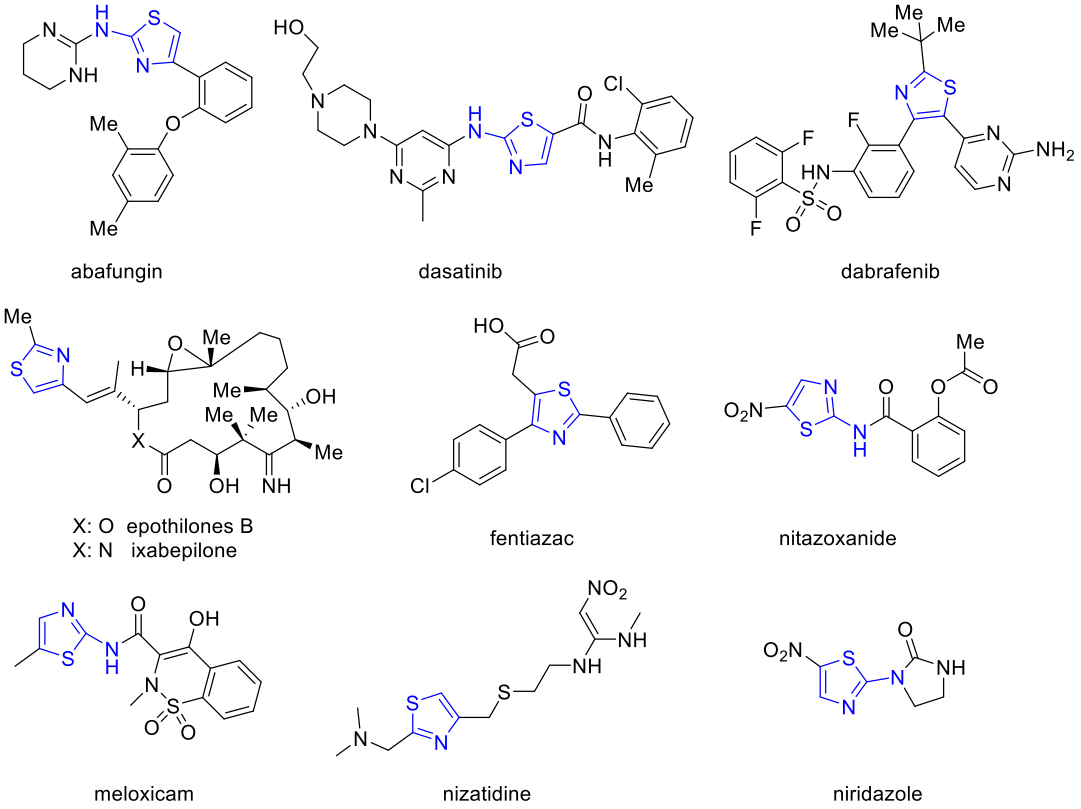


Figure 1. Some drug molecules containing thiazole groups.

Fayed et al. (2020) investigated the synthesis of thiazole-indenoquinoxaline derivative compounds and reported that they showed anti-proliferative activity against cancer cell (HCT-116, HepG-2, MCF-7). Ansari et al. (2020) investigated the anti-cancer activity of 4-(3,4,5-

trimethoxyphenyl) moiety thiazole-2(3H)-thiones anologues against cancer cell lines (A549(lung), MCF-7 and SKOV3(ovarian)). The best inhibitory effect was obtained against the MCF-7 cell lines (Ansari et al., 2020). Salehi et al. (2013) investigated the antiproliferative activity of 2-alkylthio-4-(2,3,4-trimethoxyphenyl)-5-aryl-thiazole analogues against human cancer cell lines (HT-29(colon), MCF-7, AGS(stomach)). These compounds were reported to show good activity against the MCF-7 and AGS cell lines (Salehi et al., 2013). Zou et al. (2021) synthesized ligands containing pyridine thiazole groups and their Cd and Zn complexes and tested the antimicrobial and antitumor activities of the ligands and metal complexes on four human cancer cell lines (SK-NSH, HCT-116, AGS and MCF-7). In their study, they reported that metal complexes showed better activity than ligands (Zou et al., 2021). Habibzadeh et al. (2020) synthesized (3-Chloropropyl) trimethoxysilane (CPTMOS)-coated Fe_3O_4 nanoparticles and attached to its surface the compound 1-((3-(4-chlorophenyl)-1-phenyl-1H-pyrazol-4-yl)methylene)-2-(4-phenylthiazol-2-yl) hydrazine containing thiazole ring. They examined the anti-cancer properties of the nanoparticle they obtained against gastric AGS cancer cells (Habibzadeh et al., 2020). Amooie et al. (2023) synthesized $ZnFe_2O_4$-Ag nanocomposite using Chlorella vulgaris and investigated its cytotoxic activity against some cell lines.

In this study, we investigated the cytotoxic effect of 2-amino-4-phenylthiazole derivatives (**3**) containing *N*,*N*-dimethylformamide and aldehyde functional groups against AGS and MCF-7 human cancer cell lines. The cytotoxicity of thiazole compounds containing these two groups against AGS and MCF-7 human cancer cell lines has not been previously evaluated.

2. Material and Methods

2.1. Chemistry

All chemicals were purchased from commercial suppliers and were used without further purification. FTIR spectra were recorded on Perkin Elmer FTIR spectrometer using the KBr disk in the range of 4000–400 cm^{-1}. ^{1}H-NMR and ^{13}C-NMR spectra were recorded on a Varian Inova 500 MHz spectrometer using $CDCl_3$ as a solvent and tetramethylsilane (TMS) as an internal standard. Splitting patterns are designated as follows; s, singlet; d, doublet; m, multiplet. Chemical shift (d) values are given in ppm.

2.1.1. Synthesis of Thiazole compounds

2-Amino-4-phenylthiazole derivative were synthesized by following the reaction pathway shown in Figure 2. Preparation of the thiazole compound (**2**) was synthesized by Hantzsch reaction starting from acetophenone (**1**). The amino group of compound (**2**) was protected with benzoyl chloride. Then compound (**3**) was synthesized from compound (**2**) by Vilsmayer-Haack reaction (Biçer & Altundaş, 2023).

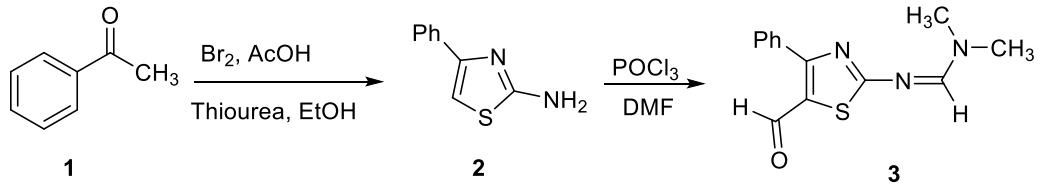


Figure 2. Synthesis scheme of thiazole derivative (**3**).

Synthesis of thiazole compound (**2**): Acetophenone (**1**) (1 equivalent, 10 g) was dissolved in 40 mL ethanol. Bromine (1,2 equivalent, 4 mL) dissolved in 10 mL AcOH was added. The mixture was placed in an oil bath at 60 ^{o}C and refluxed for 3 hours. Thiourea (1 equivalent, 6.50 g) was then added. As a result of TLC analyses, the reaction was terminated after 24 hours. As the reaction proceeds, when acetophenone reacts with bromine to form the intermediate product, the colour of bromine disappears and white solid product is obtained after thiourea. After the reaction solvent was evaporated, the crude product was washed with plenty of water and dried. Compound (**2**) was obtained in 87% yield. For Compound (**2**): M.P. 114-115 ^{o}C (Lit. 114-118 ^{o}C (Kidwai et al., 2011)), IR (cm^{-1}): 3380-3266 (NH_2

strech.), 3125 (Ar-CH strech.), 1597-1625 (C=C and C=N strech.), 722 (C-S-C strech.). ^{1}H-NMR (500 MHz, $CDCl_3$): δ 7.78 (d, *J*=4.0 Hz, 2H), 7.37 (t, *J*=6.0 Hz, 2H), 7.28 (t, *J*= 6.0 Hz, 1H), 5.02 (s, 2H).

2.1.2. Synthesis of formylation products (3)

The synthesis of compound (**3**) was carried out as in the literature (Biçer & Altundaş, 2023). In the literature, when these reactions carried out in nitrogen atmosphere are carried out without using nitrogen atmosphere, the same products are formed, but the yield decreases since the starting compounds are not finished.

2.2. Cytotoxicity evaluation

The cytotoxicity of 2-Amino-4-phenylthiazole derivatives (**3**) against two human cancer cell lines MCF-7, AGS was determined using MTT (3-(4,5-dimethylthiazole-2-yl]-2,5-diphenyl-tet razolium bromide) colorimetric assay.

2.2.1. Cell culture and cell cytotoxicity evaluation

Dulbecco's modified eagle medium (DMEM) and cell culture medium and reagents such as fetal bovine serum, penicillin/streptomycin, and trypsin-EDTA were purchased from GIBCO (Invitrogen Inc., NY, USA). MCF-7 and AGS cell lines were obtained from the American cell bank (ATCC, USA). The cell lines in the liquid nitrogen tank were removed from the tank and kept in a water bath at 37° C for a short time to thaw. The lysed cells were seeded in T75 cm^2 flasks. After 48 hours, MCF-7 and AGS cells were seeded at $5x10^3$ cells/well in DMEM containing 10% FBS, planted in 96-well plates and incubated at 37°C in an oven containing 5% CO_2. After 24 h, cells were exposed to Thiazole at different concentrations (100–10 µg/ml (dissolved with 1% DMSO) (Dang et al., 2021) that have been previously studied in the literature. Afterwards, at 24, 48 and 72 hours, MTT 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) (Cat no: 11465007001, Roche, Germany) method was applied to the cells and absorbance values were measured at 570 nm with a microplate reader spectrophotometer (Epoch, BioTek, USA). was done repeatedly.

Viability rates were analyzed by comparison with control wells (source). All cell culture applications were carried out in accordance with the previously mentioned standards and literature (Cinar et al., 2020). (All medium and other solutions used in cell culture were obtained from Thermo Fisher).

2.2.2. Statistical analysis

For statistical analysis, all data were calculated using Graphpad 8.0.1 software program and the results are presented as mean±standard deviation. Data analysis was performed by one-way analysis of variance (ANOVA), followed by Duncan's test. $P<0.05$ was considered statistically significant**.**

3. Results

3.1. In vitro cell toxicity

Different doses of thiazole (**3**) were tested for cytotoxicity on MCF-7 and AGS cell lines three time-dependent assays using MTT assay for 24 hours, 48 hours and 72 hours. After the examination, the data obtained from the MTT assay were calculated as a percentage to test the growth of the cells. Cell viability was calculated as a percentage using absorbance values at 570 nm for 4 different concentrations (100-10 µg/ml) of media. Based on the data shown in Scheme 2-3, cell viability in the normal control (NC) group was taken as reference and the percentage was determined as 100%.

The results demonstrated that in vitro growth of MCF-7 and AGS cells was suppressed by thiazole in a time- and dose-dependent manner (Fig.3-4). Cell viability increased at all doses after the addition of thiazole (**3**) at concentrations of 100-10 µg/ml for 24, 48 and 72 hours. Looking at the experimental groups, it was found that the proportion of viable cells decreased significantly as the

concentration of thiazole used increased. Moreover, by analyzing the data provided by the MTT assay, it was determined that the IC_{50} values for thiazole on MCF-7 and AGS cells for 24, 48 and 72 hours were 80.13, 71.03 and 59.24 µg/ml and 75.03, 38.12 and 28.01 µg/ml, respectively.

At the 24th hour, no statistically significant difference was detected in viability between MCF-7 and AGS cells applied at doses of 100 µg/ml and 10 µg/ml and the control group ($p>0.05$). No statistically significant difference was detected in terms of viability between MCF-7 and AGS cells applied at 10 µg/ml doses at the 48th hour and the control group ($p>0.05$). However, at the 72nd hour, a statistically significant difference was detected in viability between MCF-7 and AGS cells of all administered doses and the control group ($p>0.05$). A significant decrease in viability was observed with increasing doses. The lowest viability was detected in the cell group to which the highest dose was applied. Best doses of 100 µg/ml and 50 µg/ml of thiazole (**3**) inhibited growth and proliferation in MCF-7 and AGS cells. It has been observed that thiazole (**3**) concentrations have a cytotoxic effect on MCF-7 and AGS cancer cells. Based on these findings, it has been determined that MCF-7 and AGS cancer cells provide a positive response to reduce their viability.

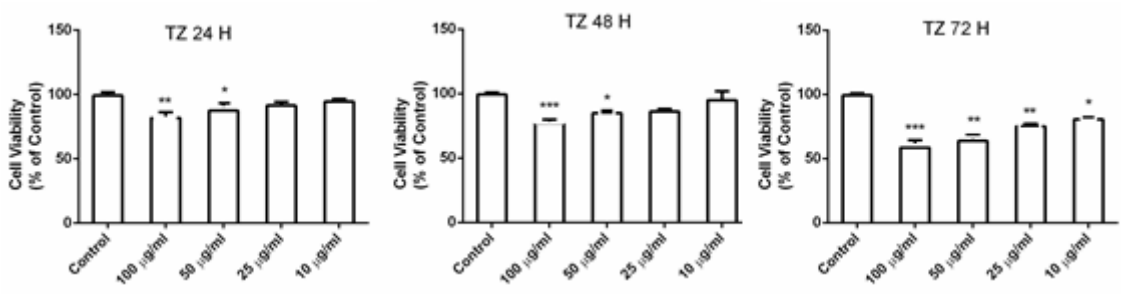


Figure 3. MTT of MCF-7 cells applied with various amounts of thiazole (**3**) results.

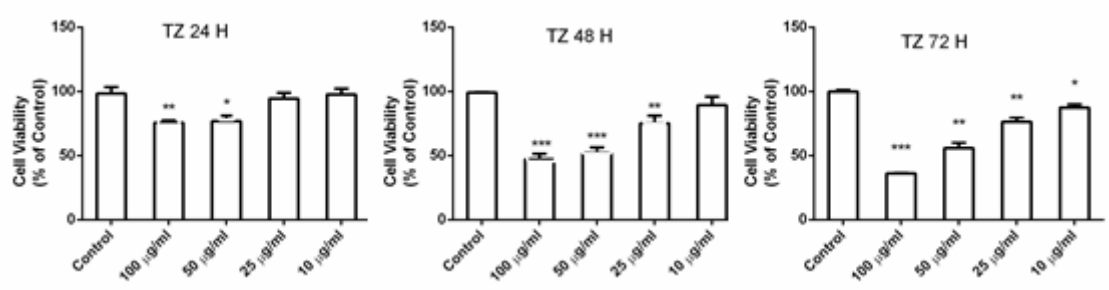


Figure 4. MTT of AGS cells applied with various amounts of thiazole (**3**) results.

The IC_{50} values obtained against MCF-7 and AGS cells were compared with some literature data (Table 1). Habibzadeh et al. (2020) found the IC_{50} value of 1-((3-(4-chlorophenyl)-1-phenyl-1H-pyrazol-4-yl)methylene)-2-(4-phenylthiazol-2-yl) hydrazine derivatives containing pyrazole and thiazole rights as 95.65 µg/ml against AGS cells. This value is higher than the IC_{50} value of our thiazole (**3**) compound. When Salehi et al. (2013) investigated the cytotoxic activity of 2-alkylthio-4-(2,3,4-trimethoxyphenyl)-5-aryl-thiazoles molecules, IC_{50} values against AGS cell lines were found to be 18.1-100<µM, some derivatives did not show activity against MCF-7 cell lines and IC_{50} values of the compounds showing activity were found in the range of 11-27.3 µM. Here, it is seen that our results show better cytotoxic activity than some of the synthesized thiazole derivatives (Salehi et al. 2013).

Mohamed et al. (2017) found the cytotoxicity of benzothazole derivatives against MCF-7 cells and IC_{50} values between 5.15- 553.1 µM. Tavangar et al. (2020) investigated the cytotoxic activity of *N*-heteroaryl enamino amides and dihydropyrimidinethione compounds against both cell cultures AGS; IC_{50} 453.14 µM and MCF-7; IC_{50} 761.90 µM (RPS-15-154). The cytotoxic activity of thiazole (**3**) compound against MCF-7 and AGS cell lines seems to be better than these results (Tavangar et al., 2020).

Mahmoudi et al. (2009) investigated the cytotoxic activity of extracts of Artemisia khorasanica collected from different regions using methanol, EtOAc, dichloromethane and hexane solvents.

Methanol extracts showed IC_{50} values in the range of 89-152 µg/ml against AGS cells, EtOAc extracts 96-338 µg/ml against AGS cells, dicholoromethane extracts 67-197 µg/ml against AGS cells, hexane extracts 263- 1575 µg/ml against AGS cells. When we compare these results with the cytotoxic activity of the thiazole compound, it is seen that it gives better cytotoxic activity than the results obtained from the hexane extract (Mahmoudi et al., 2009).

Table 1. Cytotoxic activities of some thiazole compounds against AGS and MCF-7 cell lines

AGS (IC_{50})	MCF-7 (IC_{50})	Literature
95.65 µg/ml	-	Habibzadeh et al., 2020
18.1- 100 < µM	11-27.3 µM	Salehi et al., 2013
-	5.15- 553.1 µM	Mohamed et al., 2017
453.14 µM	761.90 µM	Tavangar et al., 2020
89-152 µg/ml (Methanol extracts)	-	Mahmoudi et al., 2009
96-338 µg/ml (EtOAc extracts)	-	
67-197 µg/ml (DCM extracts)	-	
263-1575 µg/ml ((Hekzane extracts)	-	

4. Conclusion

A significant decrease in viability was found with increasing application dose. The best doses of 100 µg/ml and 50 µg/ml of Thiazole (**3**) inhibited the growth and replication of MCF-7 and AGS cells. MCF-7 and AGS cancer cells were found to respond affirmatively to reduce their viability. 4-phenyl 2-Amino-4-phenylthiazole derivative (**3**) showed cytotoxic activity against MCF-7 and AGS cells. The thiazole compound (**3**) containing *N*,*N*-dimethylformamide and aldehyde functional groups was compared with the literature data in Table 1 and it was revealed that it showed better cytotoxic activity than these molecules in the literature. We think that our findings from this study will shed a guiding light for scientists who plan to conduct new studies on thiazole derivaitves containing *N*,*N*-dimethylformamide and aldehyde functional groups.

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Research Article

Synthesis, Structural Elucidation and α-Glucosidase Inhibitory Activity of New Hydrazide Derivatives

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Abstract: Diabetes mellitus (DM) is a chronic and progressive metabolic disorder affecting over 422 million people globally. It arises from insufficient insulin production or the inability of cells to respond to insulin, leading to disruptions in carbohydrate, fat, and protein metabolism. Over time, DM can result in severe complications such as cardiovascular diseases, kidney failure, and vision loss. Effective management of DM includes therapeutic strategies aimed at stabilizing blood glucose levels. Among these, α-glucosidase enzyme inhibitors play a crucial role by slowing carbohydrate digestion and reducing postprandial blood glucose spikes. In this study, new hydrazide derivatives linked to non-steroidal anti-inflammatory drugs (NSAIDs) were synthesized and evaluated as potential α-glucosidase enzyme inhibitors. Structural characterization of these derivatives was performed using techniques such as ^{1}H-NMR, FTIR, and mass spectrometry (MS). All of these compounds were tested *in vitro* for their α-glucosidase enzyme inhibition activity. Among the synthesized derivatives, ethyl 2-{3-[3-(trifluoromethyl)anilino]benzoyl}hydrazine-1-carboxylate (compound **3d**), an etofenamate derivative, revealed the highest inhibitory potential with IC_{50} values of 188.30±0.1 μg mL^{-1} when compared with standard acarbose having IC_{50} value 190.70±2.05 μg mL^{-1}. These findings highlight the potential of NSAID-linked hydrazide derivatives as promising candidates for the development of novel DM therapies.

Keywords: Carboxylate, Diabetes Mellitus, Glucosidase, Hydrazide, NSAID

Yeni Hidrazid Türevlerinin Sentezi, Yapı Aydınlatma ve α-Glukozidaz İnhibitör Etki Çalışmaları

Öz: Diabetes mellitus (DM), dünya çapında 422 milyondan fazla insanı etkileyen kronik ve ilerleyici bir metabolik hastalıktır. Yetersiz insülin üretimi veya hücrelerin insüline yanıt verememesi sonucu ortaya çıkar ve karbonhidrat, yağ ve protein metabolizmasında bozulmalara yol açar. Zamanla DM, kardiyovasküler hastalıklar, böbrek yetmezliği ve görme kaybı gibi ciddi komplikasyonlara neden olabilir. DM'nin etkili yönetimi, kan şekeri seviyelerini stabilize etmeyi amaçlayan terapötik stratejileri içerir. Bunlar arasında, α-glukozidaz enzim inhibitörleri, karbonhidrat sindirimini yavaşlatarak ve yemek sonrası kan şekeri yükselmelerinin azaltılmasında önemli bir rol oynar. Bu çalışmada, steroid olmayan anti-inflamatuar ilaçlarla (NSAİİ) bağlantılı yeni hidrazid türevleri sentezlenmiş ve potansiyel α-glukozidaz enzim inhibitörleri olarak değerlendirilmiştir. Bu türevlerin yapısal karakterizasyonu, ^{1}H-NMR, FTIR ve kütle spektrometrisi (MS) gibi teknikler kullanılarak gerçekleştirilmiştir. Bu bileşiklerin tümü, α-glukozidaz enzim inhibisyon aktiviteleri açısından *in vitro* yöntemle test edilmiştir. Sentezlenen türevler arasında etofenamat türevi olan etil 2-{3-[3-(triflorometil)anilino]benzoil}hidrazin-1-karboksilat (bileşik **3d**), 190.70±2.05 μg mL^{-1} IC_{50} değerine sahip standart akarbozla karşılaştırıldığında 188.30±0.1 μg mL^{-1} IC_{50} değeriyle en yüksek inhibisyon gösteren bileşik olduğu sonucuna varılmıştır. Bu bulgular, NSAİİ bağlantılı hidrazid türevlerinin yeni DM tedavilerinin geliştirilmesi için umut verici adaylar olabileceğini göstermektedir.

Anahtar Kelimeler: Diabetes Mellitus, Glukosidaz, Hidrazid, Karboksilat, NSAİİ

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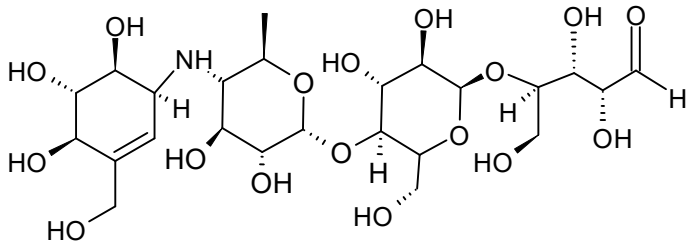
How to cite: Şenkardeş, S., & Baş, Z. H. (2025). Synthesis, structural elucidation and α-Glucosidase inhibitory activity of new hydrazide derivatives. *Yuzuncu Yil University Journal of the Institute of Natural and Applied Sciences*, *30*(1), 69-77. https://doi.org/10.53433/yyufbed.1613136

1. Introduction

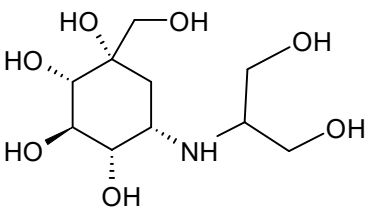
Diabetes mellitus (DM) is a chronic metabolic disorder marked by elevated blood glucose levels, leading to various complications such as cardiovascular diseases, chronic inflammation, and increased risk of infections (Tripathi & Srivastava, 2006; Fowler, 2008; Antar et al., 2023). The World Health Organization reports that approximately 422 million people are affected by diabetes globally, with Type 2 Diabetes Mellitus (T2DM) accounting for over 90% of cases. The incidence of T2DM is expected to rise, with more than 590 million individuals projected to be affected by 2035 (Zheng et al., 2018).

T2DM is characterized by insulin resistance and inadequate insulin secretion by pancreatic β-cells. Effective management focuses on controlling hyperglycemia to prevent chronic complications. Current treatments include oral hypoglycemic agents, such as sulfonylureas, thiazolidinediones, metformin, and α-glucosidase inhibitors. The α-glucosidase enzyme plays a crucial role in carbohydrate digestion by breaking down disaccharides and oligosaccharides into glucose (Dirir et al., 2022). Inhibitors of α-glucosidase delay carbohydrate digestion and absorption, helping to stabilize blood glucose levels and prevent postprandial hyperglycemia.

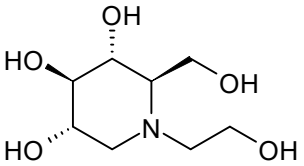
Three α-glucosidase inhibitors -acarbose, voglibose, and miglitol- manage T2DM by reducing glucose formation in the intestine (Figure 1). However, these drugs are often associated with side effects such as flatulence, diarrhea, and abdominal discomfort (Scott & Spencer, 2000; Dabhi et al., 2013; Gao et al., 2018). As a result, there is a continuing need to develop new and more effective α-glucosidase inhibitors to improve treatment outcomes and reduce adverse effects.



Acarbose



Voglibose



Miglitol

Figure 1. α-glucosidase inhibitors.

Non-steroidal anti-inflammatory drugs (NSAIDs) are a class of medications commonly used to alleviate pain and reduce inflammation. Unlike steroids, NSAIDs work by inhibiting the activity of enzymes known as cyclooxygenases (COX), particularly COX-1 and COX-2, which play a significant role in prostaglandin synthesis (Rao et al., 2010). Researchers are focusing on maintaining the core skeletal structures of NSAIDs while synthesizing various derivatives through modifications, and they are working to demonstrate that these resultant molecules are biologically active (Aydın et al., 2014; Şenkardeş et al., 2016; Koç et al., 2022).

Numerous studies have explored the α-glucosidase inhibitory activities of compounds derived from NSAIDs (Kausar et al., 2021; Daud et al., 2024). In 2022, (S)-flurbiprofen hydrazide-hydrazone derivatives were synthesized and their α-glucosidase inhibitory activities were evaluated. The most potent inhibitor in this series was (E)-2-(2-fluoro-[1,1′-biphenyl]-4-yl)-*N*′-(1-

phenylbutylidene)propanehydrazide, which exhibited an impressive IC_{50} value of 0.93 μM (Alam et al., 2022). A study by Sardar et al. examined the glucosidase activities of hydrazide derivatives synthesized from diclofenac. The results concluded that most of the synthesized compounds exhibited stronger α-glucosidase inhibitory effects than standard acarbose (Sardar et al., 2024a). Another investigations identified oxadiazole derivatives starting from ibuprofen and naproxen as potent α-glucosidase inhibitors (Daud et al., 2022; Sardar et al., 2024b). These findings indicate that NSAID-derived compounds have the potential for modulating metabolic processes such as α-glucosidase inhibition.

Herein, a series of NSAID-linked hydrazide derivatives were synthesized, and the structures of all derivatives were confirmed using different techniques, including elemental analysis, ^{1}H-NMR, FTIR and MS techniques. Furthermore, all derivatives were screened for their in vitro α-glucosidase inhibitory activities.

2. Material and Methods

2.1. Chemicals and methods

All the chemicals, such as solvents and reagents were purchased from Sigma/Aldrich and Merck, and were used as such without any purification and distillation. The IR spectra were recorded on a Schimadzu FTIR 8400S spectrometer and the wave numbers were given in cm^{-1}. ^{1}H-NMR spectra were recorded on BRUKER NMR spectrometer and are reported relative to deuterated solvent signals. Elemental analyses were determined by CHNS-932 (LECO) analyzer. Low-resolution mass spectra (LR-MS), which can only separate and detect ions with integer masses and have a resolution of less than 2000, were obtained using the Shimadzu LC-MS/MS-8030 system Shimadzu Corporation, Kyoto, Japan). Thin-layer chromatography (TLC) was performed on pre-coated silica gel aluminum plates (Kieselgel 60, 254, E. Merck, Germany).

2.2. Synthetic procedure

2.2.1. Preparation of compounds 2a-d:

In this study, flurbiprofen, diflunisal, etofenamate and naproxen hydrazides **(2a-d)** were prepared using literature methods (Küçükgüzel et al., 2003; Aboul-Fadl et al., 2011; Aydın et al., 2013; Han et al., 2018). 0.01 mol of diflunisal, naproxen or flurbiprofen dissolved in methanol (20 mL) is treated with concentrated sulfuric acid (1 mL) and heated under reflux for 3 hours. After esterification is complete, the reaction mixture is treated with a 5% $NaHCO_3$ solution and washed with water.

The resulting ester compounds **(1a-c)** (0.01 mol) and etofenamate **(1d)** are dissolved in methanol (20 mL). Hydrazine hydrate (4.5 mL) is added, and the mixture is heated under reflux for 2-4 hours, then cooled, and the precipitated solid is washed with water. The product is crystallized from methanol/ethanol.

*2-(6-methoxynaphthalen-2-yl)propanehydrazide **(2a)***

Yield 78%. mp 136-137 °C (lit. 137 °C, Han et al., 2018*)*

*2',4'-difluoro-4-hydroxy[1,1'-biphenyl]-3-carbohydrazide **(2b)***

Yield 90%. mp 199-201°C (lit 200-202 °C, Küçükgüzel et al., 2003*)*

*2-(2-fluoro[1,1'-biphenyl]-4-yl)propanehydrazide **(2c)***

Yield 86%. mp 96-98 °C (lit. 96 °C, Aydın et al., 2013*)*

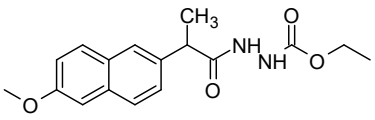
*2-[3-(trifluoromethyl)anilino]benzohydrazide **(2d)***

Yield 76%. mp 134-135 °C (lit. 136-138 °C, Aboul-Fadl et al., 2011*)*

2.2.2. General procedure for synthesis of compounds 3a-d:

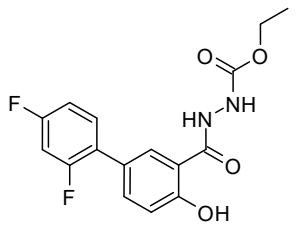
A mixture of acid hydrazide **(2a-d)** (0.002 mol) and ethyl chloroformate (0.002 mol) in toluene in the presence of triethylamine (TEA) was stirred and heated under refluxed for 7-10 h. After cooling and partial evaporation of the solvent, the precipitate obtained was filtered, dried and crystallized from ethanol (Madhavilatha et al., 2018).

Ethyl 2-[2-(6-methoxynaphthalen-2-yl)propanoyl]hydrazine-1-carboxylate (3a)



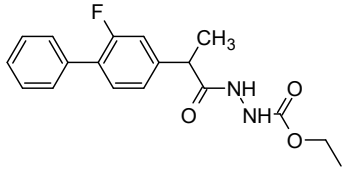
Yield 63 %; m.p. 158-160°C; FT-IR υ_{max} (cm^{-1}): 3285, 3223 (N-H); 1718 (C=O ester); 1676 (C=O amide). ^{1}H-NMR (300 MHz), (DMSO-d_6/TMS) δ ppm: 1.17 (t, 3H, CH_2-C**H**$_3$); 1.44 (d, 3H, CH-C**H**$_3$); 3.76 (q, 1H, C**H**-CH_3); 3.86 (s, 3H, OC**H**$_3$); 4.00 (q, 2H, C**H**$_2$-CH_3); 7.13-7.82 (m, 6H, Ar-**H**); 9.01 (s, 1H, N**H**); 9.89 (s, 1H, N**H**). Anal. Calcd for $C_{17}H_{20}N_2O_4$.1/4 C_2H_5OH: C, 64.11; H, 6.61; N, 8.54; Found: C, 64.26; H, 6.28; N, 8.50. LR-MS (ESI) (m/z): calc. for $(M+H)^+$: 317.150, found: 317.30. Calc. for $(M-H)^-$: 315.135, found: 315.25.

Ethyl 2-(2',4'-difluoro-4-hydroxy[1,1'-biphenyl]-3-carbonyl)hydrazine-1-carboxylate (3b)



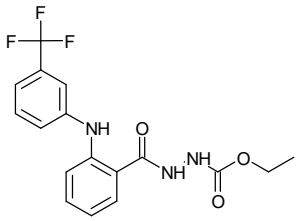
Yield 76 %; m.p. 160-162°C; FT-IR υ_{max} (cm^{-1}): 3333 (O-H); 3173 (N-H); 1697 (C=O ester); 1645 (C=O amide). ^{1}H-NMR (300 MHz), (DMSO-d_6/TMS) δ ppm: 1.23 (t, 3H, CH_2-C**H**$_3$); 3.86 (s, 3H, OC**H**$_3$); 4.09 (q, 2H, C**H**$_2$-CH_3); 7.06-8.02 (m, 6H, Ar-**H**); 9.36 (s, 1H, N**H**); 10.49 (s, 1H, N**H**); 12.02 (s, 1H, O**H**). Anal. Calcd for $C_{16}H_{14}F_2N_2O_4$: C, 57.14; H, 4.20; N, 8.33; Found: C, 57.35; H, 4.26; N, 8.03. LR-MS (ESI) (m/z): calc. for $(M+H)^+$: 337.099, found: 337.30. Calc. for $(M-H)^-$: 335.084, found: 335.20.

Ethyl 2-[2-(2-fluoro[1,1'-biphenyl]-4-yl)propanoyl]hydrazine-1-carboxylate (3c)



Yield 69 %; m.p. 196-197°C; FT-IR υ_{max} (cm^{-1}): 3288 (N-H); 1716 (C=O ester); 1676 (C=O amide). ^{1}H-NMR (300 MHz), (DMSO-d_6/TMS) δ ppm: 1.17 (t, 3H, CH_2-C**H**$_3$); 1.38 (d, 3H, CH-C**H**$_3$); 3.70 (q, 1H, C**H**-CH_3); 4.04 (q, 2H, C**H**$_2$-CH_3); 7.24-7.55 (m, 8H, Ar-**H**); 9.05 (s, 1H, N**H**); 9.93 (s, 1H, N**H**). Anal. Calcd for $C_{18}H_{22}FN_2O_3$.1/2 H_2O: C, 63.71; H, 5.94; N, 8.25; Found: C, 63.52; H, 6.00; N, 8.20. LR-MS (ESI) (m/z): calc. for $(M+H)^+$: 331.145, found: 331.30. Calc. for $(M-H)^-$: 329.130, found: 329.30.

Ethyl 2-{3-[3-(trifluoromethyl)anilino]benzoyl}hydrazine-1-carboxylate (3d)



Yield 77 %; m.p. 172-173°C; FT-IR υ_{max} (cm^{-1}): 3338, 3230 (N-H); 1728 (C=O ester); 1645 (C=O amide). ^{1}H-NMR (300 MHz), (DMSO-d_6/TMS) δ ppm: 1.22 (t, 3H, CH_2-C**H$_3$**); 4.08 (q, 2H, C**H$_2$**-CH_3); 7.00-7.69 (m, 8H, Ar-**H**); 9.25 (s, 1H, N**H**); 9.39 (s, 1H, N**H**); 10.37 (s, 1H, N**H**). Anal. Calcd for $C_{17}H_{16}F_3N_3O_3$: C, 55.59; H, 4.39; N, 11.44; Found: C, 55.32; H, 4.39; N, 11.42. LR-MS (ESI) (m/z): calc. for $(M+H)^+$: 368.121, found: 368.30. Calc. for $(M-H)^-$: 366.106, found: 366.25.

2.3. Biological evaluation

2.3.1. α-Glucosidase inhibition assay

The method for assessing antidiabetic activity described by Ramakrishna et al. was modified and implemented with slight alterations (Ramakrishna et al., 2017; Şen et al., 2019). A 10 µl sample (ranging from 250 to 0.49 µg mL^{-1}) was mixed with 40 µL of 0.1 M sodium phosphate buffer (pH 6.9) and 100 µl of α-glucosidase enzyme (obtained from Saccharomyces cerevisiae, 1 U/mL) prepared in the same buffer. The mixtures were incubated at 25°C for 10 minutes. Subsequently, 50 µl of 5 mM p-nitrophenyl-α-D-glucopyranoside (pNPG) prepared in the buffer. The mixtures were then incubated at 25°C for an additional 5 minutes, and absorbance changes at 405 nm were measured before and after incubation using a microplate reader. Acarbose (135-16.88 µg mL^{-1}) was used as the standard. The percentage inhibition of enzyme activity by the samples was calculated using the following formula:
Percentage inhibition of α-glucosidase enzyme (%): $(A_{control}-A_{sample})/A_{control}\times100$

- $A_{control}$, represents the absorbance of the control containing all components except the sample (replaced with DMSO).
- A_{sample}, represents the absorbance of the sample containing all components.

The inhibition concentration of the samples that reduced 50% of the α-glucosidase enzyme activity (IC_{50}) was determined by plotting the inhibition graph against the concentrations of the samples using GraphPad Prism 5 software. Measurements were repeated four times.

2.4. Statistical analysis

Statistical analysis was conducted using GraphPad Prism 5.0 software. Data are presented as mean ± standard deviation. Statistical comparisons were determined using one-way ANOVA followed by Tukey's multiple comparison test. A p-value of <0.05 was considered statistically significant.

3. Results and Discussion

3.1. Chemistry

In this present work, new NSAID hydrazide derivatives **(3a-d)** were synthesized. The synthetic route for the preparation of compounds **3a-d** is outlined in Figure 2. First, compounds **2a-c** were obtained from naproxen, diflunisal, and flurbiprofen upon treatment with methanol in the presence of sulfuric acid. The NSAID hydrazides were obtained from the condensation of **2a-c** and etofenamate **(1d)** with hydrazine hydrate. In order to prepare the target compounds, ethyl chloroformate and NSAID hydrazides were heated with toluene in the presence of TEA. Among the newly synthesized compounds **(3a-d)**, compound **3a** has got only a CAS number (CAS No: 1389160-65-9) with no spectroscopic and synthesis data in Scifinder database. So, all of the synthesized compounds were checked for purity using

elemental microanalysis and melting points and fully characterized by their spectral data for the first time.

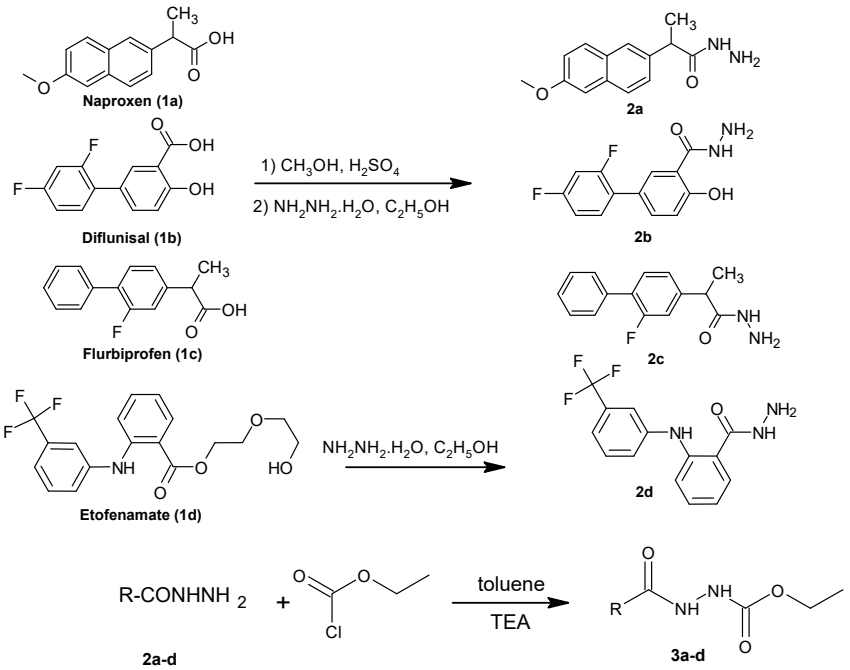


Figure 2. Synthesis of compounds **3a-d.**

The structures of the synthesized compounds were elucidated by spectral methods (IR, ^{1}H-NMR and mass spectra) and confirmed by elemental analysis. In the IR spectra, characteristic C=O ester stretching bonds (1697-1728 cm^{-1}) were observed, which are supported by the literature (Roller et al., 2005). In the ^{1}H-NMR spectra, the signal of the -O-C**H$_2$**-CH$_3$ protons of the carboxylate moiety observed 1.17-1.23 ppm as quartets, while the signals of the -O-CH$_2$-C**H$_3$** protons were at 4.00-4.09 ppm as triplets (Thakkalapally & Benin, 2005; Das et al., 2024). The mass spectra of the compounds were recorded via the electrospray ionisation technique and $(M+H)^+$ and $(M-H)^-$ seen in the spectra of all compounds. Elemental analysis results were within ±0.4 of the theoretical values for all compounds.

3.2. Biological Activity

3.2.1. α-Glucosidase enzyme inhibition results

In one of our recent studies, the alpha glucosidase inhibitory effect of hydrazide derivatives was investigated and effective compounds were found (Şenkardeş et al., 2022). In this study, compounds **3a-d** were synthesized to evaluate their potency as α-glucosidase inhibitors. The results are detailed in Table 1, highlighting IC$_{50}$ values in comparison with acarbose, which was used as the positive control.

Table 1. α-Glucosidase inhibition potential of **3a-d** (IC$_{50}$, µg mL^{-1})

Compound	IC$_{50}$ *
3a	648.10±3.47^{d}
3b	218.50±1.84^{b}
3c	237.40±3.32^{c}
3d	188.30±0.14^{a}
Acarbose	190.70±2.05^{a}

*Values in the table are expressed as mean ± SD (n = 4). Different letters (superscript) in the same row indicate significant differences between values ($p < 0.05$).

Because of the lower IC_{50} (the concentration of the sample required to inhibit 50% of enzyme activity) indicates higher activity, Table 1 shows that among the samples, compound **3d**, the derivative of etofenamate, exhibited the highest α-glucosidase inhibitory activity, followed sequentially by **3b**, **3c**, and **3d** ($p<0.05$).

The weak inhibitory effect of compound **3a** may be due to the absence of electron-withdrawing groups (F and –NH) found in compounds **3b-d**. The -F and -NH atoms found in compounds **3b-d** provide electron flow, making them more effective and polarizable. As seen in the literature (Sardar et al., 2024b), the reason for the compound **3d** exhibiting the strongest activity may be due to the strong hydrogen bonding interaction between the NH atom and the active residues of the enzyme.

Nawaz et al. (2022) found that several analogues with fluorine atoms attached to the benzene rings exhibited significant α-glucosidase inhibition. They also highlighted that the presence of the fluorine group plays a key role in enhancing the activity of these compounds. This may be the reason why the naproxen derived compound **(3a)** showed the lowest inhibition.

When comparing these results with similar studies examining the glucosidase activities of derivatives synthesized from flurbiprofen and naproxen (Alam et al., 2022; Rane et al., 2025), it is found that our compounds **(3a-c)** exhibit lower inhibitory activity. Furthermore, no literature reports have been found regarding the glucosidase activity of diflunisal and etofenamate derivatives.

4. Conclusion

Novel hydrazide derivatives linked to different NSAIDs were synthesized, and characterized via spectroscopic techniques. All compounds were evaluated for their α-glucosidase inhibitory potential. The synthesized derivatives exhibited a range of inhibitory activities when tested for glucosidase inhibition, using acarbose as the standard (IC_{50}=190.70±2.05 μg mL^{-1}). Biological activity results revealed that ethyl 2-{3-[3-(trifluoromethyl)anilino]benzoyl}hydrazine-1-carboxylate **(3d)** as the most potent derivative exhibited better potency (IC_{50}=188.30±0.14 μg mL^{-1}) than the clinically used drug, acarbose. This research could provide insights into the development of new therapeutic agents for conditions such as diabetes, where regulating glucosidase activity is essential for controlling blood sugar levels. Furthermore, our future goal is to perform molecular docking studies and make the necessary modifications to these compounds for improved efficacy, as well as to gather information on their stability.

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Research Article

Bibliometric Analysis on Methods and Tools Developed for DGE Analysis: Current Trends and Future Perspectives

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Abstract: Differential gene expression (DGE) analysis has gained significant attention with the advent of next-generation sequencing technologies, leading to the development of a wide range of methods and tools for DGE analysis. We performed bibliometric analysis using Biblioshiny and VOSviewer software to investigate the trends over the investigated period. Relevant papers with differential gene expression related terms as the subjects from 2005 to 2023 were retrieved from the Web of Science database. Network maps were generated using Biblioshiny and VOSviewer software to illustrate the published trends over the investigated period. A total of 729 studies were examined to reveal trends in the DGE analysis methodologies, tools, and packages. In the analysis, co-authorship, bibliographic coupling, and co-occurrence analyses were conducted for country, institution, source, author, and keyword productivity. It was found that the output and citation numbers increased after 2005. During the study period, the USA and China emerged as the leading contributors to the field. The temporal study revealed a significant increase in publications at certain times, followed by period of slight decrease. The greatest fall was observed between 2008 and 2010. Despite these decreases, DGE analysis remains a critical topic in genomics due to its essential role in understanding the mechanisms of any disease, gene function, and therapeutic targets. This trend suggests that current methods and tools are considered sufficiently powerful for identifying key informative genes associated with diverse diseases.

Keywords: Bibliometric analysis, Differential expression analysis, Differential gene expression, Gene expression, RNA-seq

DGE Analizi için Geliştirilen Yöntemler ve Araçlar Üzerine Bibliyometrik Analiz: Güncel Eğilimler ve Gelecek Perspektifleri

Öz: Diferansiyel gen ekspresyonu (DGE) analizi, yeni nesil dizileme teknolojilerinin ortaya çıkışıyla önemli bir ilgi kazanmıştır. Bu durum, DGE analizi için çeşitli yöntemlerin ve araçların geliştirilmesine yol açmıştır. Bu çalışmada, Biblioshiny ve VOSviewer yazılımları kullanılarak, incelenen dönem boyunca eğilimleri araştırmak amacıyla bibliyometrik analiz yapılmıştır. 2005-2023 yılları arasında Web of Science veri tabanından, diferansiyel gen ekspresyonu ile ilgili terimleri konu alan ilgili makaleler taranmıştır. İncelenen dönem boyunca yayımlanan eğilimleri göstermek için Biblioshiny ve VOSviewer yazılımları kullanılarak ağ haritaları oluşturulmuştur. Toplamda 729 çalışma, DGE analizi metodolojilerindeki, araçlarındaki ve paketlerindeki eğilimleri ortaya koymak amacıyla incelenmiştir. Bu amaçla, ülke, kurum, kaynak, yazar ve anahtar kelime üretkenliği açısından eş-yazarlık, bibliyografik eşleşme ve eş-oluşum analizleri yapılmıştır. 2005 yılından sonra çıktı ve atıf sayılarında artış gözlenmiştir. Çalışma süresince ABD ve Çin, DGE analizine en çok katkı sağlayan ülkeler olarak öne çıkmıştır. Zamansal çalışmalar, belirli aralıklarla bir miktar azalma olmakla birlikte, zaman içinde yayınlarda önemli bir artış olduğunu ortaya koymuştur. En büyük düşüş, 2008 ile 2010 yılları arasında gözlenmiştir. Bu düşüşlere rağmen, DGE analizi, herhangi bir hastalığın mekanizmalarını, gen işlevlerini ve terapötik hedefleri anlamadaki temel rolü nedeniyle genomikte kritik bir konu olmaya devam etmektedir. Bu eğilim, mevcut yöntemlerin ve araçların, çeşitli hastalıklarla ilişkili anahtar bilgilendirici genleri tanımlamak için yeterince güçlü kabul edildiğini göstermektedir.

Anahtar Kelimeler: Bibliyometrik analiz, Diferansiyel dizileme analizi, Diferansiyel gen ekspresyonu, Gen ifadesi, RNA-dizileme

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1. Introduction

Differential gene expression (DGE) analysis has become increasingly popular in recent decades due to the development of high-throughput sequencing technologies such as next-generation sequencing, microarrays, proteomics, and metabolomics. DGE analysis is a common method frequently used to compare gene expression profiles among various samples/groups, such as healthy vs disease or control vs treatment or cells subjected to different treatments (Kebschull et al., 2017). The primary goal is to identify the informative genes whose patterns vary across samples. These genes, differentially expressed, are called biomarkers. These offer insights into the underlying mechanism of disease and gene regulation, and can be used to develop further treatments and targeted therapies. Additionally, DGE analysis plays a crucial role in drug discovery by providing insights into how drugs influence gene activity and cellular pathways. By monitoring gene expression changes in response to drug treatments, researchers can identify specific genes and pathways affected by a drug, helping to uncover potential therapeutic targets and biomarkers (Bai et al., 2013; Melouane et al., 2018).

Despite its importance, differentially expressed gene discovery can be challenging since gene expression data consists of thousands of genes and a relatively small number of samples. Numerous techniques have been developed to identify the genes that differ statistically between comparable groups or samples. To this end, a number of software applications and/or R packages have been introduced. One of the most powerful and efficient tools for RNA-seq analysis is edgeR (Empirical Analysis of Digital Gene Expression data in R) (Robinson et al., 2009; 2010), which is widely used due to its low false discovery rate (Robinson et al., 2009; 2010). Another common tool is DESeq2 (Differential Expression analysis for Sequence Count data) (Love et al., 2014), which is frequently used for datasets produced from a large number of samples with low variability. Cephe et al. (2023) and Rosati et al. (2024) provide a list of tools and approaches offered thus far, as well as elaborating on the advantages and disadvantages of DEG analysis methods. Rosati et al. (2024) provided an in-depth analysis of the bioinformatic pipelines and computational methods developed for DGE analysis, highlighting their strengths and limitations in biomarker discovery. They emphasizethe importance of selecting appropriate analytical strategies to enhance DGE studies' accuracy and reliability, which are crucial in advancing personalized medicine and understanding complex biological processes. The review serves as a valuable resource for researchers aiming to navigate the complexities of DGE analysis and its applications in biomarker identification. Similarly, Clark & Lillard (2024) explored the significance of these tools in analyzing complex genomic data to identify biomarkers that can guide personalized treatment strategies in precision oncology.

Recent studies have demonstrated that machine learning and deep learning approaches have begun to play an important role in DGE analysis, enabling the investigation of complex diseases, as well as the identification of genes or biomarkers for prognosis and/or diagnosis (Liñares Blanco et al., 2019; Mahendran et al., 2020; Dhillon et al., 2023). These approaches have great potential in the processing of high-dimensional gene expression data and in improving prediction accuracy.

As highlighted by the studies above, the rapid advancement of high-throughput sequencing technologies has significantly expanded research on DGE analysis tools and methodologies. Despite this extensive research, there is a lack of bibliometric studies assessing trends, collaborations, and research focus in this field. To address this gap, we conducted a bibliometric analysis of DGE research from 2005 to 2023, examining publication trends, international collaborations, keyword patterns, and emerging research directions. This study's comprehensive overview of the field's evolution offers insights into future developments, which is crucial for identifying research priorities, guiding funding decisions, future studies, and fostering interdisciplinary collaboration in gene expression analysis. Given the pivotal role of DGE in biomarker discovery, disease classification, and personalized medicine, understanding research trends can help accelerate the development of targeted therapies and improve clinical outcomes.

2. Material and Methods

2.1. Search strategy, data collection and data analysis

Data were obtained from the Web of Science (WoS) database and the search period included the scientific outputs from January 1, 2005 to December 31, 2023. A comprehensive online search was

carried out using the following search strategy: (AB=(("differential-expression" OR "differential expression" OR "differentially expressed" OR "differential analysis" OR "differential analyses" OR "differentially gene expression" OR "differential gene expression analyses" OR "differential gene expression")) AND AB=(("gene-expression" OR "RNA-Sequencing" OR "RNA-Seq" OR "microarray" OR "RNA-seq" OR "gene expression" OR "RNA-sequencing" OR "RNA sequencing")) AND AB=(("method" OR "approach" OR "software" OR "algorithm" OR "statistical" OR "estimation" OR "modeling" OR "technique")) NOT TI=(("normalization" OR "transformation" OR "alignment" OR "outlier")) AND TI=(("differential-expression" OR "differential expression" OR "differentially expressed" OR "RNA-Seq" OR "differential analysis" OR "differential analyses" OR "differentially gene expression" OR "differential gene expression analyses" OR "differential gene expression"))) AND (DT==("ARTICLE" OR "REVIEW") AND LA==("ENGLISH")). All records obtained from the literature using this strategy were exported to a Plain Text File (.txt). This query resulted in a total of 1881 outputs, however, after titles and abstracts were screened for relevancy, only 729 of these were considered for biometric analysis. This filtering step was necessary prior to the bibliometric analysis given the large number of studies that employed only current approaches for DGE analysis.

2.2. Bibliometric analysis

The R-based **Bibliometrix** package (Biblioshiny v.4.1.4, www.bibliometrix.org) (Aria & Cuccurullo, 2017), the VOSviewer software (v.1.6.20) (van Eck & Waltman, 2010) and the R programming language (v.4.2.2) were used to conduct bibliometric analysis. The final dataset of 729 papers was analyzed after filtering by year and language using the **Bibliometrix** package. In line with the study's primary focus, the analyses focused on the annual scientific production of countries and institutions, most cited articles, most influential authors, trending topics, and common word analysis.

3. Results

3.1. General information about data

After year, language and document type filters were applied to the bibliometric analysis, a total of 729 differential expression analysis studies, consisting of 723 articles and 6 reviews, were included (Table 1). Figure 1 reports annual numbers of publications from 2005 to 2023, revealing fluctuations in the numbers. Peaks with noticeable increases are seen around 2014, and again in 2021, followed by a decline after 2022.

Table 1. Main data information

Main Information About Data	**Results**
Timespan	2005:2023
Sources (Journals, Books, etc)	184
Documents	729
Annual Growth Rate %	2.28
Document Average Age	8.83
Average citations per doc	205.6
References	14937
Document Contents	
Keywords Plus (ID)	1152
Author's Keywords (DE)	1187
Authors	
Authors	2781
Authors of single-authored docs	23

Table 1. Main data information (continued)

Main Information About Data	Results
Authors Collaboration	
Single-authored docs	26
Co-Authors per Doc	4.67
International co-authorships %	21.54
Document Types	
article	656
article; book chapter	17
article; data paper	1
article; early access	2
article; proceedings paper	47
review	5
review; book chapter	1

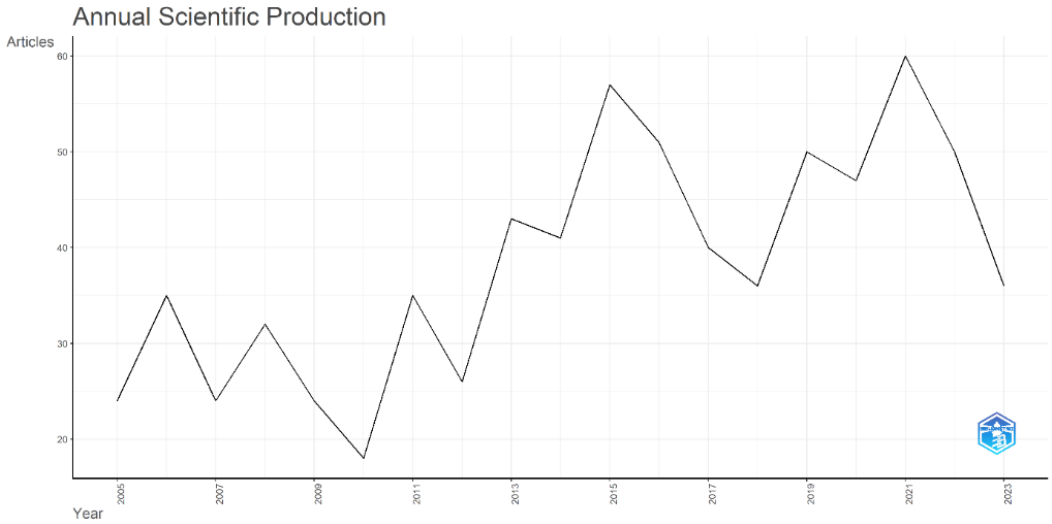


Figure 1. Annual number of publications on developing methods, tools or packages for differential expression analysis.

3.2. Countries and institutions analysis

In total, 51 countries and 810 institutions were encompassed in differential-expression studies research. The 10 countries display a global distribution, including the USA, China, Austria, England, and Germany (Table 2). The USA recorded the highest number of publications (n=358), followed by China (n=133), and Australia (n=46). Co-authorship country analysis was carried out to shed light on international collaborations. Table 2 shows each country's co-authorship relationships with other countries, as well as its overall strength. Notably, the USA leads with 358 publications and a total link strength of 113. In the network representation, each circle represents an author's country, and font size denotes the frequency of collaboration (Figure 2). The size of the nodes in Figure 2 reflects the number of collaborations from each country, while the connecting lines indicate the strength of collaboration. Similar research fields for countries are represented by the same colors. For instance, the USA has many strong collaborations with China (Figure 2).

Table 2. The topmost 10 strong co-authorship linked document-productive countries

Rank	Countries	Clusters	Links	Total link strength	Documents	Citations
1	USA	4	21	113	358	104591
2	China	2	8	56	133	2322
3	Australia	2	12	35	46	62694
4	England	1	14	35	40	7830
5	Germany	5	15	33	38	51625
6	South Korea	4	2	10	28	329
7	Japan	2	3	6	24	399
8	India	4	3	10	22	771
9	Canada	1	7	12	20	271
10	France	1	5	9	20	1141

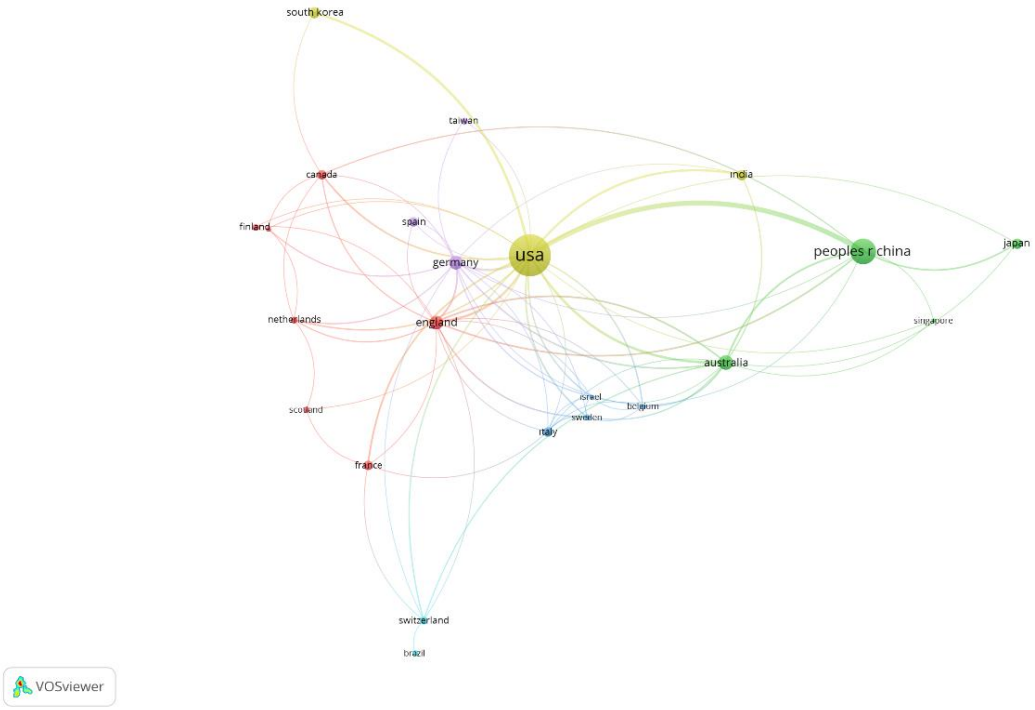


Figure 2. Map of visualization of countries on research of differential expression analysis methods.

The analysis identified 6 clusters, with a total of 76 links and 202 total link strength. Cluster 1 (red) shows significant co-authorship for, England (n=40), Canada (n=20), France (n=20), Finland (n=11), Netherlands (n=10), Russia (n=6), and Scotland (n=8). Cluster 2 (green) is characterized by a high level of cooperation among Australia (n=46), Japan (n=24), China (n=133), and Singapore. Differential expression analysis research reveals a close relationship among Belgium (n=6), Israel (n=5), Italy (n=18), and Sweden (n=9) in cluster 3 (Blue). Cluster 4 (yellow) is characterized by strong ties among the United States (n=358), South Korea (n=28), and India (n=22). In cluster 5 (purple), Germany (n=38), Spain (n=18), and Taiwan (10) have significant co-authorship. In addition, Brazil (n=9) and Switzerland (13) collaborate closely in cluster 6 (light blue).

According to the most frequent affiliations stated by the corresponding authors, as shown in Figure 3**,** University of California System has the highest number of papers (n=63), closely followed by University of Texas System (55 papers), Harvard University (54 papers), and John Hopkins University (47 papers).

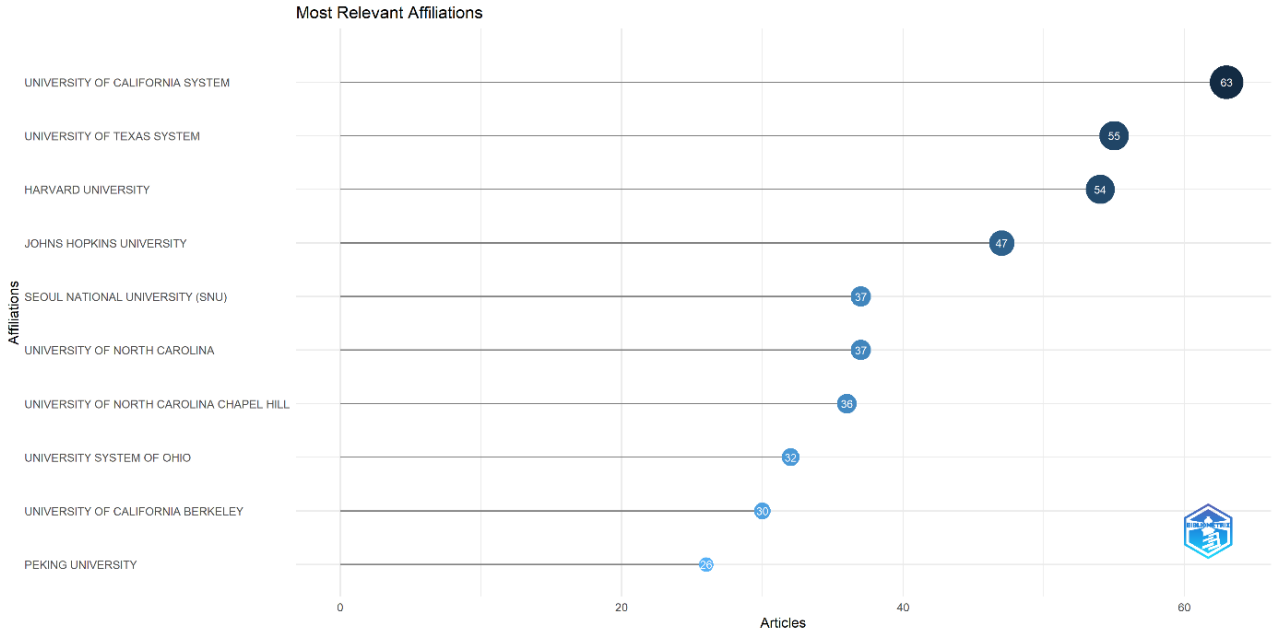


Figure 3. Most relevant institutions.

Figure 4 depicts the connection between different institutions, countries, and publications. The height of the rectangular boxes indicates the frequency of the appearance of a particular institution, country, or journal within the collaborative network. The findings demonstrated that the United States is the leading country, with all ten of the highest ranking institutions. Harvard University, John Hopkins University, and the University of California System are among the most notable instances. China and Australia, respectively, are the next most prominent countries.

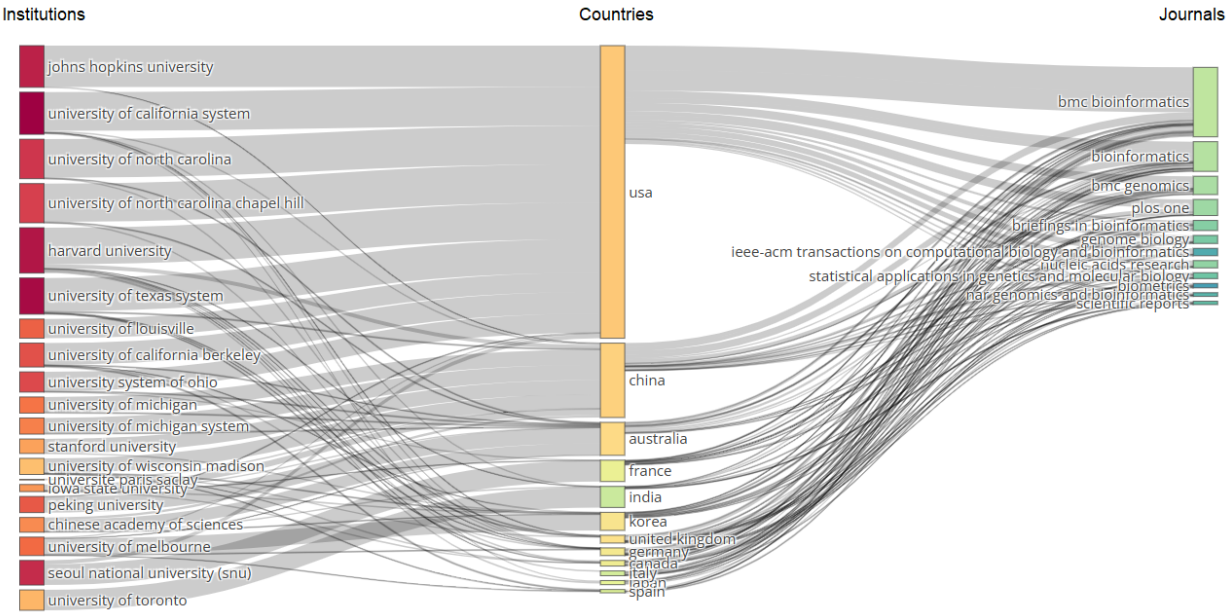


Figure 4. Three-field plot displaying the network between institutions (left), countries (middle), and journals (right).

3.3. Bibliographic coupling with sources

In total, 184 sources were created from scientific outputs and the complete counting method was applied with a minimum threshold of 5. Only 27 outputs were able to meet these criteria, and for each

of these, the overall strength of bibliographic linkages to other sources was calculated (see Table 3, Figure 5). The analysis showed 351 links and a total connection strength of 130101, forming 4 clusters of 27 items. The clusters consisted of 14, 9, 3, and 1 elements, respectively.

Sources in the first cluster include Annals of Applied Statistics (n=5), Bioinformatics (n=84), Biometrics (n=9), Biostatistics (n=8), BMC Bioinformatics (n=102), Cancer Informatics (n=6), Computational Biology and Chemistry (n=6), Computational Statistics & Data Analysis (n=9), Genomics (7), IEEE-ACM Transactions on Computational Biology and Bioinformatics (n=10), Journal of Computational Biology (n=9), Plos One (n=39), Statistical Applications in Genetics and Molecular Biology (n=14), and Statistics in Biosciences (n=7). Sources in the second cluster include Briefings in Bioinformatics (n=19), Frontiers in Genetics (n=9), Genome Biology (n=14), Methods (n=8), Nar Genomics and Bioinformatics (n=11), Nature Communications (n=8), Peerj (n=9), Plos Computational Biology (n=8), and Scientific Reports (n=13). In the third cluster, sources include BMC Genomics (n=46), Journal of Bioinformatics and Computational Biology (n=6), and Nucleic Acids Research (n=28), while in the fourth cluster, Current Bioinformatics (n=5) has the highest overall link strength.

Table 3. The topmost 10 strong bibliographic coupling with sources

Rank	Sources	Clusters	Links	Total link strength	Documents	Citations
1	BMC Bioinformatics	1	26	43745	102	3686
2	Bioinformatics	1	26	36866	84	33561
3	BMC Genomics	3	26	24039	46	1028
4	Plos One	1	26	22249	39	1791
5	Nucleic Acids Research	3	26	19500	28	28342
6	Briefings in Bioinformatics	2	26	9732	19	543
7	Genome Biology	2	26	10233	14	44638
8	Statistical Applications in Genetics and Molecular Biology	1	26	7769	14	460
9	Scientific Reports	2	26	7300	13	383
10	Nar Genomics and Bioinformatics	2	26	6361	11	629

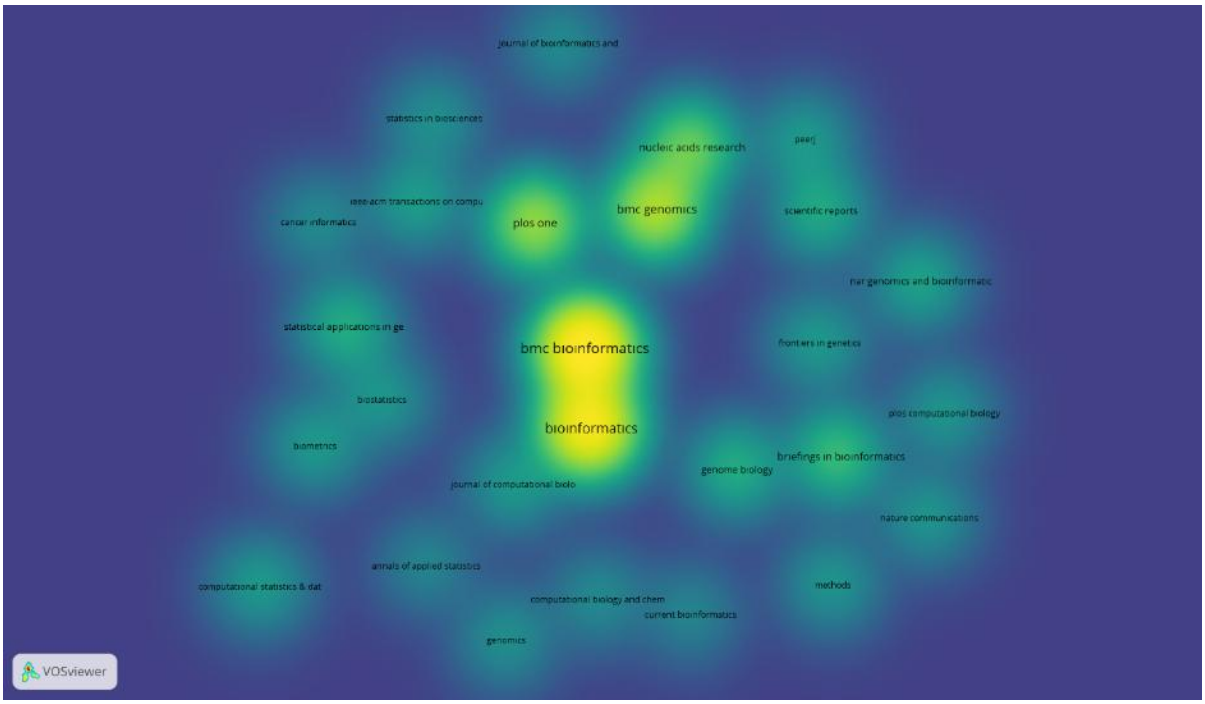


Figure 5. Bibliographic coupling with sources.

Among the 10 leading journals, as indicated in Table 4, “BMC Bioinformatics” is notable for its significant contribution to the categories of Biochemical Research Methods, Biotechnology and Applied Microbiology, Mathematical and Computational Biology. It is ranked first in the number of published documents (102) in these fields, and its Journal Impact Factor (JIF) percentile is 76.5, placing it in Q1. However, this journal's most recent impact factor is 2.9, considerably lower than journals such as "Nucleic Acids Research" and "Briefings in Bioinformatics", which have JIF percentiles of 98.2 and 95.9, respectively, positioning them as more authoritative.

Table 4. Top 10 journals with the highest number of published papers

Rank	Journals	Documents	JIF Percentile	JIF Quartile
1	BMC Bioinformatics	102	76.5	Q1
2	Bioinformatics	84	90.2	Q1
3	BMC Genomics	46	67.8	Q2
4	Plos One	39	76.5	Q1
5	Nucleic Acids Research	28	98.2	Q1
6	Briefings in Bioinformatics	19	95.9	Q1
7	Genome Biology	14	95.1	Q1
8	Statistical Applications in Genetics and Molecular Biology	14	34.8	Q3
9	Scientific Reports	13	81.7	Q1
10	Nar Genomics and Bioinformatics	11	88.6	Q1

JIF: Journal Impact Factor

The 10 journals with the most publications in the field of differential expression analysis are reported in Figure 6a. It was found that "BMC Bioinformatics" journal was the leader, 102 articles, followed by "Bioinformatics" with 84 articles. Figure 6b depicts the earliest scientific research on differential expression analysis conducted in the Bradford area. Journals in this core region are regarded as top-tier publications in the field of differential expression analysis, serving as the foundation for the development of most later articles in the field. This chart serves to identify the most productive journals in the field of differential expression analysis studies.

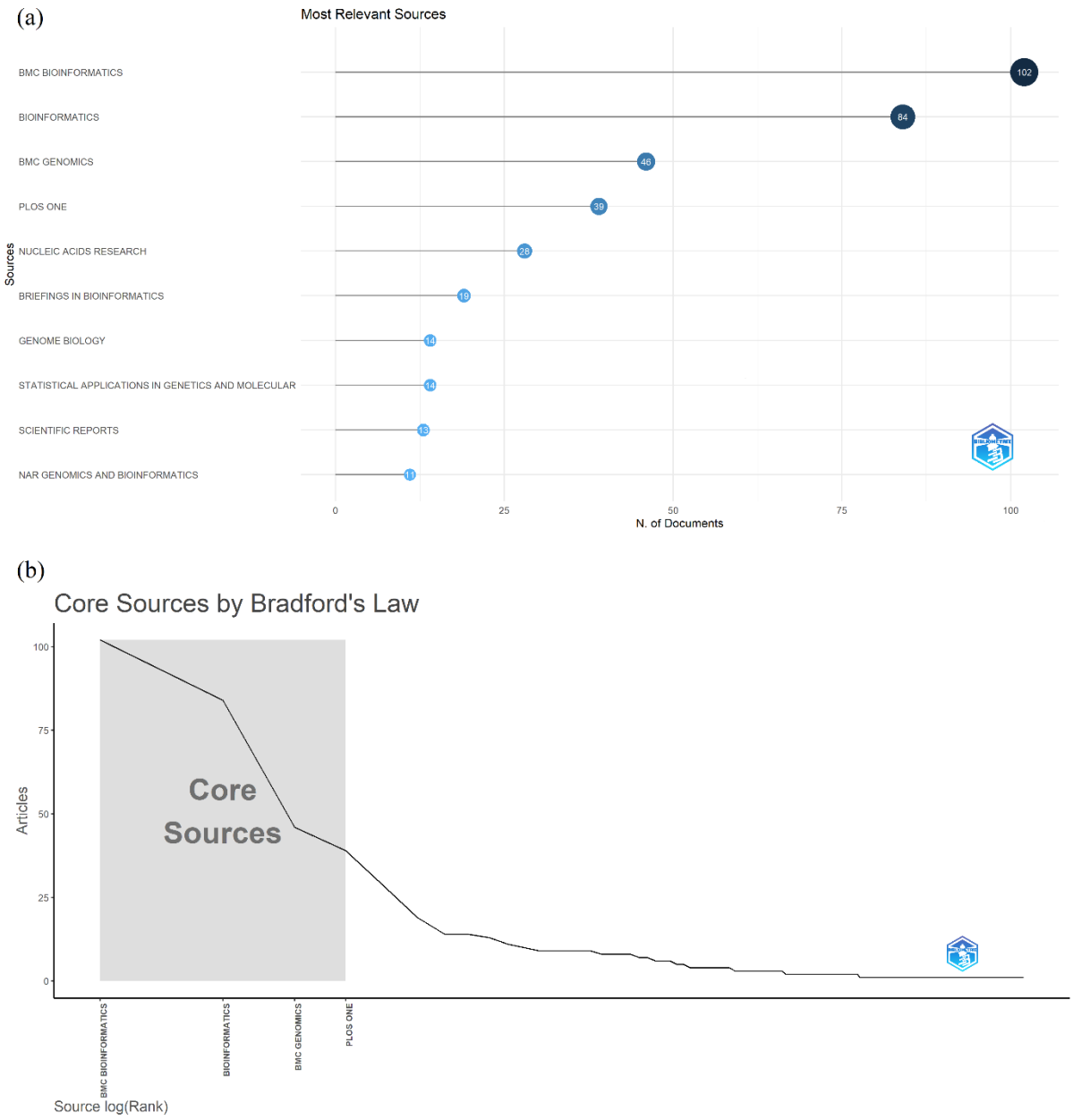


Figure 6. (a) Most relevant sources, (b) Core Sources by Bradford's Law.

3.4. Highly cited articles and most prolific authors

Figure 7a shows the most highly cited research articles. The paper receiving the most citations in the field was "Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2" by Love et al. (2014), with a total of 43481 during the investigation period. This is followed by Robinson et al. (2010) 's publication "edgeR: a Bioconductor package for differential expression analysis of digital gene expression data", which has 26930 citations.

Figure 7b displays the most prolific authors in the field of differential-expression analysis. The density of circle in the visualization represents the author' number of citations for the year, while the size of the circle represents the number of published papers. As the number of citations and publications increases, the darkness and size of the circles increase in direct proportion. It is seen that GK Smyth constantly published articles from 2005 until 2017. The most trending year for GK Smyth is 2015. In 2015, there is a substantially larger and darker dot, indicating that GK Smyth authored many publications with a high citation impact (1000 or more). The second most prolific author is Nettleton D,

who consistently published articles from 2005 to 2020, followed by Zhang Y (2008-2022) and Elo LL (2009-2022).

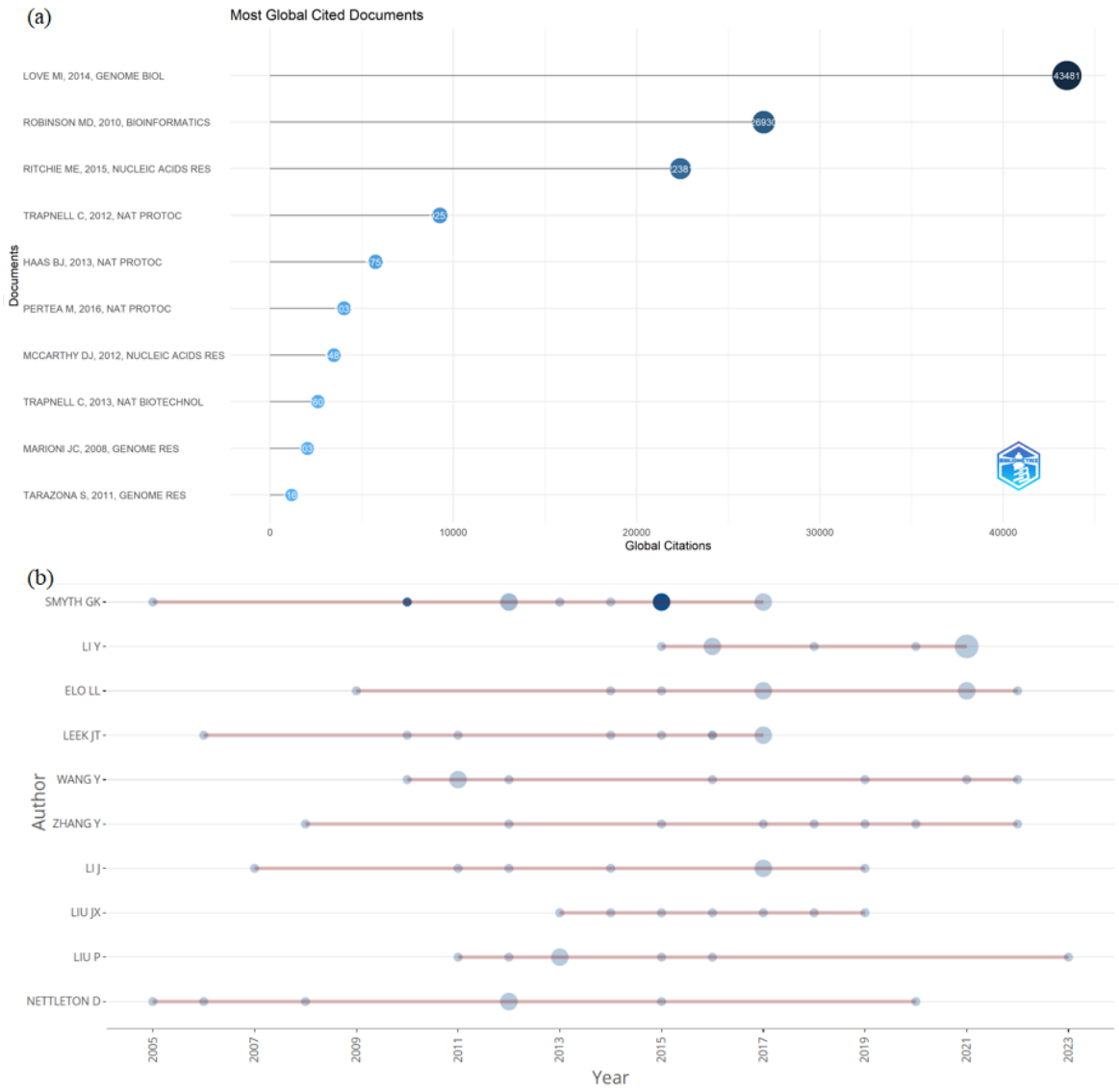


Figure 7. (a) Most global cited documents and (b) production of the most productive authors over time.

3.5. Keyword and trend topics analysis

Keyword analysis is critical for gaining insight into the key topics and trends suitable for further exploration in a research field. This type of analysis enables an understanding of the most discussed subjects and significant topics. Figure 8a shows a word cloud with the commonly used keywords in the relevant subject, including terms like "gene-expression," "microarray," "differential expression," and "rna-seq." This indicates the key areas of application/use of microarray and RNA-seq data in DGE analysis.

Figure 8b depicts the findings of the keyword co-occurrence network analysis, demonstrating that frequently used keywords are divided into six clusters. The results suggest that DGE analysis incorporates concepts from the fields of statistics, biology, computational biology, and genetics, demonstrating its intrinsic multidisciplinary nature**.** Figure 8c displays trend topics across years (2004–2022) with topics on the y-axis and years on the x-axis. Each topic is shown by a horizontal line that

depicts the period of its relevance, with larger bubble sizes representing higher term frequency. The three most trending topics in the field are differentially expressed genes from 2011 to 2020, gene expression from 2009 to 2018 and differential gene expression from 2014 to 2021. Figure 8c indicates that the focus of research is shifting away from statistical approaches such as multiple tests towards more sophisticated computational tools such as machine learning approaches.

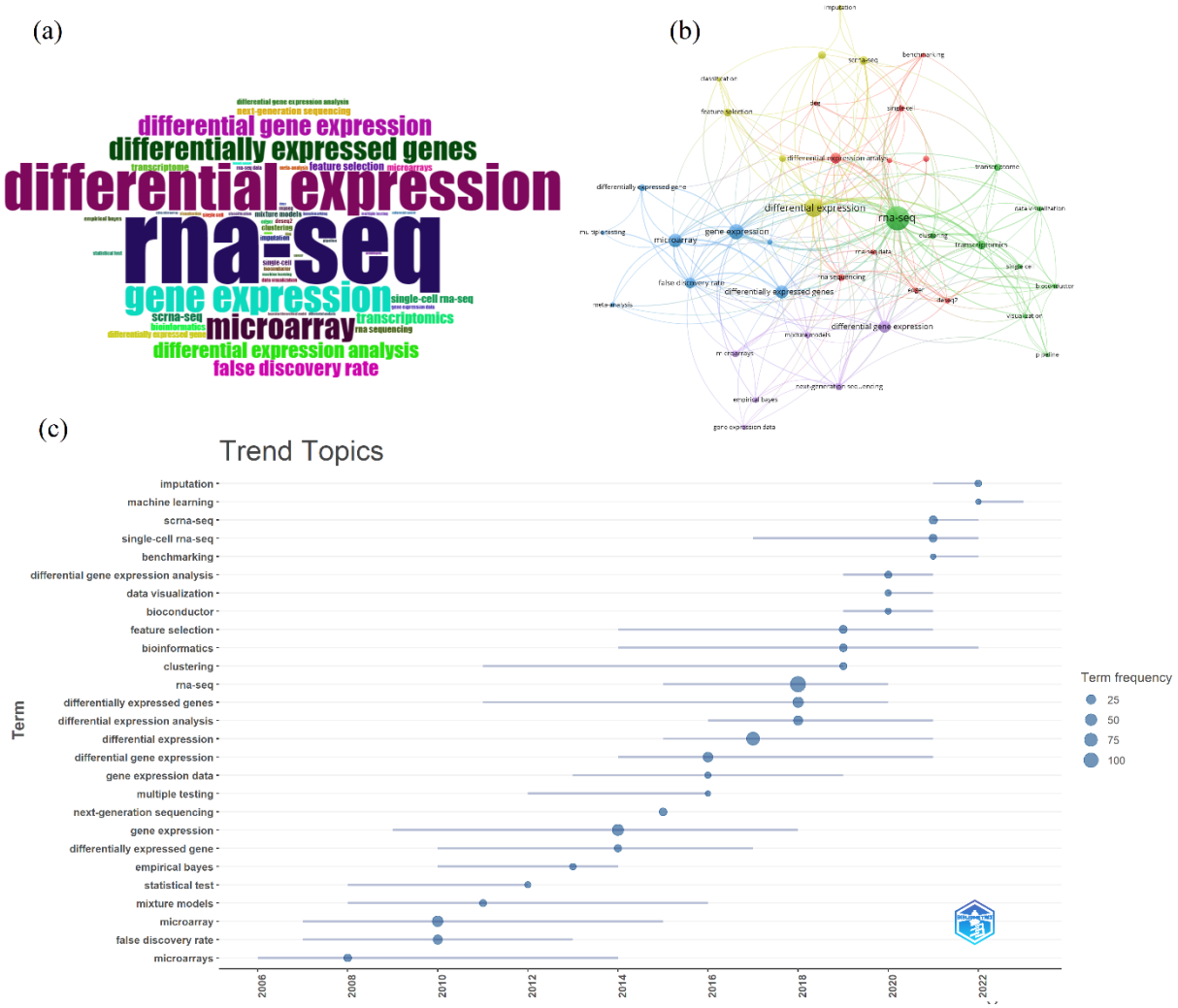


Figure 8. (a) Word cloud of the most frequent terms in the author's keywords of selected articles, (b) keyword co-occurrence network in differential-expression analysis research, and (c) trend topics across years.

4. Discussion and Conclusion

Differential gene expression analysis is a technique used in bioinformatics to better understand the complex mechanisms underlying various biological processes. Researchers can identify differentially expressed genes by comparing gene expression levels across various groups, such as healthy versus diseased tissues subjected to different treatments. This offers insight into fundamental biological processes and facilitates the identification of genes associated with specific biological processes, particularly in the context of identifying biomarkers for diagnosis or prognosis. As a result, many methods/tools have been developed for DGE analysis (Hardcastle & Kelly, 2010; Di et al., 2011; Kvam et al., 2012; Rapaport et al., 2013; Law et al., 2014; Seyednasrollah et al., 2015; Chowdhury et al., 2020; Costa-Silva et al., 2022). Understanding how these methodologies have evolved over time is crucial for identifying key contributors, emerging trends, and potential research gaps. This study presents a detailed analysis of articles proposing methodologies and tools for DGE analysis between 2005 and 2023, in terms of sources, authors, institutions, countries, keywords, and clusters. Furthermore,

we present an overview of the shifting trends in the literature on these topics. The data reveal that, despite fluctuations in interest in the development of methods and tools, DGE analysis remains critical in genomics due to its importance in disease processes, gene function, and therapeutic targets. This fact is not disproven by the relative fall in interest in developing tools and methods for DGE analysis, but rather, it implies that the current methods and tools are considered sufficiently powerful to identify important informative genes associated with specific disorders.

There was an increase in the number of studies between 2010 and 2015 (Figure 1), due to an increasing interest and demand for more advanced computational methods and tools for analyzing gene expression data. During this period, there was greater interest in high-throughput sequencing technologies like RNA-seq. This resulted in an exponential growth in the volume and complexity of transcriptomic data, prompting the development of novel algorithms, statistical approaches, and software tools for efficient analysis. There was a slight temporary decline in the number of studies after 2015, which was an unexpected trend. We hypothesize that this may be dure to the maturation of existing methods/tools, where current tools are deemed sufficiently robust for most applications. However, DGE analysis regained its importance after a few years. This increase peaked in 2021. The studies at this time were mostly published in top-tier journals, including BMC Bioinformatics, Bioinformatics, BMC Genomics, Nucleic Acids Research, Briefings in Bioinformatics, etc. Publication in these widely recognized journals in genetics and bioinformatics confirms the high scientific impact and credibility of the DGE analysis.

The University of California System is the leading associated institution, and the United States, China, and Australia are the main contributors. With the most publications and citations, the USA is clearly leading in the field in developing methods/tools, driven by the country's robust research infrastructure, prestigious universities/institutions such as the University of California System, along with substantial funding for genomics and bioinformatics. The USA's number of publications and citations reflects its major contributions to developing and applying computational tools to innovative research.

The paper "Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2" by Love et al. (2014) received the most citations in the field of differential-expression analysis, with 43481 citations), followed by Robinson et al. (2010)'s publication "edgeR: a Bioconductor package for differential expression analysis of digital gene expression data", with 26930 citations. GK Smyth, among the authors of the second and third most cited papers, was the most prolific contributor in the field, highlighting his role in promoting and increasing the efficiency of the methods and tools for DGE analysis. This demonstrates Smyth contributions' substantial impact on advancing the field, which is in line with our expectations.

The simplest DE detection techniques employ a test statistic to determine whether genes exhibit a statistically significant change in gene expression under various conditions. While it is possible to use non-parametric methods (Li & Tibshirani, 2013) for this purpose, due to the small number of replicates, non-parametric methods may not be sufficiently efficient to detect those genes that are differentially expressed. To overcome this, parametric methods are utilized (Robles et al., 2012; Seyednasrollah et al., 2015). The most frequently used parametric methods in analysis tools are based on the Poisson and Negative Binomial (NB) distributions. For instance, edgeR uses NB distribution for DGE analysis, since NB distribution accounts for the overdispersion commonly observed in RNA-Seq data. However, trend topic analysis shows a shift towards machine learning and/or deep learning techniques in recent years (Figure 8c). These more flexible and powerful approaches have the advantage of being able to learn complex patterns in the data without any assumptions about the underlying distribution. Machine learning models can more effectively process high-dimensional, noisy data, offering more accurate and robust predictions for DE detection, especially with a small number of replicates, or highly complex data.

Despite its enormous potential use, differential gene expression analysis poses several challenges, including data normalization, batch effects, and the need for robust/strong statistical approaches (Chowdhury et al., 2020; Costa-Silva et al., 2022). Development including integrating multi-omics data and developing sophisticated computational tools will further enhance the accuracy, reliability and biological interpretation of differential gene expression analysis.

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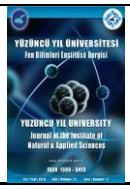
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Research Article

Tessarine Number Sequences and Quantum Calculus Approach

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Abstract: This paper presents a detailed study of a new generation of tessarine number sequences with components including quantum integers Also, several fundamental identities are defined such as Binet formulas, Catalan, Cassini, D'ocagnes. After that, the q-Fibonacci tessarine and q-Lucas tessarine polynomials and function sequences are definedand obtained several properties for these sequences.

Keywords: q-Fibonacci tessarine number sequences, q-Lucas tessarine number sequences, Tessarine numbers

Tessarine Sayı Dizileri ve Kuantum Kalkulus Yaklaşımı

Öz: Bu makalede, kuantum tam sayıları içeren bileşenlere sahip yeni nesil tessarin sayı dizilerinin ayrıntılı bir çalışması sunulmaktadır. Ayrıca, Binet formülleri, Catalan, Cassini, D'ocagnes gibi çeşitli temel özdeşlikler tanımlanmıştır. Daha sonra, q-Fibonacci tessarine ve q-Lucas tessarine polinomları ve fonksiyon dizileri tanımlanmış ve bu diziler için çeşitli özellikler elde edilmiştir.

Anahtar Kelimeler: q- Fibanacci sayı dizileri, q- Lucas sayı dizileri, Tessarine sayıları

1. Introduction

Complex numbers were discovered by the Italian mathematician G. Cardano while he tries to solve a simpler state of the cubic equation and using the notation $i = \sqrt{-1}$. The complex numbers as points with rectangular coordinates were represented by Euler. After that, Cockle, (1849) proposed the tessarine numbers, an algebraic successor to complex numbers and quaternionic algebra, employing more modern notation. In the exponential series, he employed tessarine numbers to separate the hyperbolic sine and cosine series (Cockle, 1849; Cockle, 1850).

A tessarine number is a hypercomplex number of the form

$$\gamma = \gamma_0 + \gamma_1 i_1 + \gamma_2 i_2 + \gamma_3 i_3$$

where γ_0, γ_1, γ_2 and γ_3 are real numbers and i_1, i_2 and i_3 are the imaginary units which satisfy the following rules:

$$i_1^2 = -i_2^2 = i_3^2 = -1 \ ; i_1 i_2 = i_2 i_1 = i_3. \quad (1)$$

The addition and multiplication of tessarine numbers $\gamma = \gamma_0 + \gamma_1 i_1 + \gamma_2 i_2 + \gamma_3 i_3$ and $\delta = \delta_0 + \delta_1 i_1 + \delta_2 i_2 + \delta_3 i_3$ are defined, respectively, as:

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$$\gamma + \delta = (\gamma_0 + \delta_0) + (\gamma_1 + \delta_1)i_1 + (\gamma_2 + \delta_2)i_2 + (\gamma_3 + \delta_3)i_3$$

and

$$\gamma\delta = \gamma_0\delta_0 - \gamma_1\delta_1 + \gamma_2\delta_2 - \gamma_3\delta_3 + (\gamma_0\delta_1 + \gamma_1\delta_0 - \gamma_2\delta_3 - \gamma_3\delta_2)i_1$$

$$+(\gamma_0\delta_2 + \gamma_2\delta_0 - \gamma_3\delta_1 - \gamma_1\delta_3)i_2 + (\gamma_0\delta_3 + \gamma_3\delta_0 + \gamma_1\delta_2 + \gamma_2\delta_1)i_3.$$

It is easy to see that the multiplication of tessarine numbers is commutative In mathematics, the Fibonacci numbers and Lucas numbers are an infinite sequences of integers in which each number is the sum of the two preceding ones. These numbers have been researched extensively because of their complex characteristics and deep connections to several fields of mathematics and their related numbers are of essential importance due to their various applications in biology, physics, statistics, and computer science (Horadam, 1961; 1963; Nalli & Haukkanen, 2009; Koshy, 2018; 2019; Oduol & Okoth, 2020).

For n ≥ 2, the second order linear sequences F_n and L_n are defined by:

$$\begin{cases} F_n = F_{n-1} + F_{n-2} \\ L_n = L_{n-1} + L_{n-2.} \end{cases}$$

Here, the initial conditions are $F_0 = 0, F_1 = 1, L_0 = 2$ and $L_1 = 1$, respectively. The Binet formulas of these numbers are

$$\begin{cases} F_n = \dfrac{\alpha^n - \beta^n}{\alpha - \beta} \\ L_n = \alpha^n + \beta^n \end{cases}$$

where α and β are roots of characteristic equation $\varphi^2 - \varphi - 1 = 0$.

Now, we give definitions and facts from the quantum calculus necessary for understanding of this paper (Kac & Cheung, 2002; Kome et. al., 2022; Babadağ, 2023).
For any integers n and m, we define the function

$$[n]_q = \frac{1 - q^n}{1 - q} = 1 + q + \cdots + q^{n-1} \tag{2}$$

and

$$\begin{cases} [m + n]_q = [m]_q + q^m[n]_q \\ [mn]_q = [m]_q + [n]_{q^m} . \end{cases} \tag{3}$$

During the last few years, few researchers have studied the tessarine numbers with Fibonacci numbers, Lucas numbers , Homothetic Motions, Surfaces and Neural Networks (Babadağ, 2017; Babadağ & Uslu, 2021; Senna & Valle, 2021). For example, Babadağ & Uslu, (2021) defined the Fibonacci tessarines with Fibonacci and Lucas numbers, and they examined the identities related to the tessarines, Fibonacci numbers and Lucas numbers. Babadağ, (2017) defined the homothetic motions and homothetic exponential motions. Senna & Valle, (2021) give tessarine and quaternion-valued deep neural networks for image classification.

In this paper, using different perspective, we define the tessarine number sequences with components including quantum integers and get several new results for these number sequences. Section 2. we give the q-Fibonacci tessarine number sequences and q-Lucas tessarine number sequences. Section 3. we explore some identities used in various areas of mathematics, including

Binet's formula, the exponential generating function, and Catalan, Cassini, and D'Ocagne's identities and we define quantum tessarine polynomial sequences or, briefly q-Fibonacci tessarine polynomial sequences $\gamma_{q,n}(t)$ and q-Lucas tessarine polynomial sequences $\delta_{q,n}(t)$ and then derive the Binet formula for these type of polynomial sequence. In addition some results of q-tessarine polynomial sequences are given. Then, we define quantum tessarine function sequences or briefly q-Fibonacci and q-Lucas tessarine function sequences $\Gamma_{q,n}(t)$ and $\Delta_{q,n}(t)$.

2. Material and Methods

To reach our goal, we obtain relation between the q-Fibonacci tessarine numbers and q-Lucas tessarine numbers. After that using these numbers, we introduce some identities used in various areas of mathematics, including Binet's formula, the exponential generating function, and Catalan, Cassini, and D'Ocagne's identities and we give quantum tessarine polynomial sequences and then derive the Binet formula for these type of polynomial sequence.

3. Resultants

Resultants are plays an important role in physics, combinatorics, number theory and other fields of the mathematics. Since quantum calculus may be viewed as generalization of ordinary calculus, there is a relationship between quantum calculus and number sequences

Definition 3.1. Tessarine number sequences of the form

$$\gamma_n = \alpha^{n-1}[n]_q + \alpha^n[n+1]_q i_1 + \alpha^{n+1}[n+2]_q i_2 + \alpha^{n+2}[n+3]_q i_3 \tag{4}$$

are called the n^{th} q-Fibonacci tessarine number sequences and

$$\delta_n = \alpha^n \frac{[2n]_q}{[n]_q} + \alpha^{n+1}\frac{[2n+2]_q}{[n+1]_q} i_1 + \alpha^{n+2}\frac{[2n+4]_q}{[n+2]_q} i_2 + \alpha^{n+3}\frac{[2n+6]_q}{[n+3]_q} i_3$$

are called as the n^{th} q-Lucas tessarine number sequences. Furthermore, we can rewrite these number sequences in the following forms:

$$\gamma_n = \frac{\alpha^n(1-q^n)}{\alpha-\alpha q} + \frac{\alpha^{n+1}(1-q^{n+1})}{\alpha-\alpha q} i_1 + \frac{\alpha^{n+2}(1-q^{n+2})}{\alpha-\alpha q} i_2 + \frac{\alpha^{n+3}(1-q^{n+3})}{\alpha-\alpha q} i_3$$

and

$$\delta_n = \alpha^n \frac{1-q^{2n}}{1-q^n} + \alpha^{n+1}\frac{1-q^{2n+2}}{1-q^{n+1}} i_1 + \alpha^{n+2}\frac{1-q^{2n+4}}{1-q^{n+2}} i_2 + \alpha^{n+3}\frac{1-q^{2n+6}}{1-q^{n+3}} i_3 \tag{5}$$

where i_1, i_2 and i_3 are the imaginary units which satisfy the rules in (1).

Theorem 3.1. (Binet formulas) For any integer n,

$$\begin{cases} \gamma_n = \alpha^{n-1}[n]_q \underline{\alpha} + (\alpha q)^n \underline{\beta} \\ \delta_n = \alpha^n \dfrac{[2n]_q}{[n]_q} \underline{\gamma} + \alpha^{n+1}(1-q)\underline{\beta}. \end{cases} \tag{6}$$

Furthermore, these formulas have another expression of the form

$$\begin{cases} \gamma_n = \dfrac{\alpha^n \underline{\alpha} - (\alpha q)^n \underline{\varphi}}{\alpha - \alpha q} \\ \delta_n = \alpha^n \underline{\alpha} + (\alpha q)^n \underline{\varphi} \end{cases} \tag{7}$$

where

$$\begin{cases} \underline{\alpha} = 1 + \alpha i_1 + \alpha^2 i_2 + \alpha^3 i_3 \\ \underline{\beta} = i_1 + \alpha [2]_q i_2 + \alpha^2 [3]_q i_3 \\ \underline{\varphi} = 1 + (\alpha q) i_1 + (\alpha q)^2 i_2 + (\alpha q)^3 i_3 \end{cases} \tag{8}$$

Proof. By using (2), (3), (4) and (8), we can write

$$\begin{aligned} \gamma_n &= \alpha^{n-1}[n]_q + \alpha^n [n+1]_q i_1 + \alpha^{n+1}[n+2]_q i_2 + \alpha^{n+2}[n+3]_q i_3 \\ &= \alpha^{n-1}[n]_q + \alpha^n \big([n]_q + q_n\big) i_1 + \alpha^{n+1}([n]_q + q^n [2]_q) i_2 + \alpha^{n+2}([n]_q + q^n [3]_q) i_3 \\ &= \alpha^{n-1}[n]_q (1 + \alpha i_1 + \alpha^2 i_2 + \alpha^3 i_3) + \alpha^n q^n \big(i_1 + \alpha [2]_q i_2 + \alpha^2 [3]_q i_3\big) \\ &= \alpha^{n-1}[n]_q \underline{\alpha} + (\alpha q)^n \underline{\beta}. \end{aligned}$$

For q-Lucas tessarine number sequences by using (2), (5) and (8):

$$\begin{aligned} \delta_n &= \alpha^n \frac{1-q^{2n}}{1-q^n} + \alpha^{n+1} \frac{1-q^{2n+2}}{1-q^{n+1}} i_1 + \alpha^{n+2} \frac{1-q^{2n+4}}{1-q^{n+2}} i_2 + \alpha^{n+3} \frac{1-q^{2n+6}}{1-q^{n+3}} i_3 \\ &= \alpha^n (1 + \alpha i_1 + \alpha^2 i_2 + \alpha^3 i_3) + (\alpha q)^n (1 + (\alpha q) i_1 + (\alpha q)^2 i_2 + (\alpha q)^3 i_3) \\ &= \alpha^n \underline{\alpha} + (\alpha q)^n \underline{\varphi}. \end{aligned}$$

Theorem 3.2. (Exponential generating functions) The exponential generating functions for q-Fibonacci and q-Lucas tessarine number sequences are:

$$f(x) = \frac{e^{\alpha x} \underline{\alpha} - e^{(\alpha q)x} \underline{\varphi}}{\alpha - \alpha q}$$
$$g(x) = e^{\alpha x} \underline{\alpha} + e^{(\alpha q)x} \underline{\varphi}$$

respectively.

Proof. Using Binet-like formula for q-Fibonacci tessarine numbers and $e^{\alpha x} = \sum_{n=0}^{\infty} \alpha^n \frac{x^n}{n!}$ we get:

$$\begin{aligned} f(x) &= \sum_{n=0}^{\infty} \gamma_n \frac{x^n}{n!} \\ &= \frac{1}{\alpha - \alpha q} \sum_{n=0}^{\infty} \left(e^{\alpha x} \underline{\alpha} - e^{(\alpha q)x} \underline{\varphi}\right) \frac{x^n}{n!} \\ &= \frac{e^{\alpha x} \underline{\alpha} - e^{(\alpha q)x} \underline{\varphi}}{\alpha - \alpha q}. \end{aligned}$$

The proof for q-Lucas number sequences can be done similarly.

Theorem 3.3. (Catalan identities) For positive integers n, r such that $n > r$, then we have

$$\gamma_{n+r}\gamma_{n-r} - \gamma_n^2 = \alpha^{2n-1}q^n([-r]_q + [r]_q)\underline{\alpha}\,\underline{\varphi}$$

$$\delta_{n+r}\delta_{n-r} - \delta_n^2 = \alpha^{2n}q^n(q-1)([-r]_q + [r]_q)\underline{\alpha}\,\underline{\varphi}$$

where

$$\underline{\alpha}\,\underline{\varphi} = (1-\alpha^2 q)(1+(\alpha^2 q)^2) + (1+(\alpha^2 q)^2)\alpha(1+q)i_1 + (1-\alpha^2 q)\alpha^2(1+q^2)i_2 + \alpha^3(1+q^2)i_3.$$

Proof. By using (2), (3) and (7), we obtain

$$\gamma_{n+r}\gamma_{n-r} - \gamma_n^2 = \left(\frac{\alpha^{n+r}\underline{\alpha} - (\alpha q)^{n+r}\underline{\varphi}}{\alpha - \alpha q}\right)\left(\frac{\alpha^{n-r}\underline{\alpha} - (\alpha q)^{n-r}\underline{\varphi}}{\alpha - \alpha q}\right) - \left(\frac{\alpha^n\underline{\alpha} - (\alpha q)^n\underline{\varphi}}{\alpha - \alpha q}\right)^2$$

$$= \frac{\alpha^{2n}q^n(2 - q^{-r} - q^r)\underline{\alpha}\underline{\varphi}}{\alpha - \alpha q}$$

$$= \alpha^{2n-1}q^n([-r]_q + [r]_q)\underline{\alpha}\,\underline{\varphi}.$$

Similarly we can get the result for q-Lucas number sequences.

Theorem 3.4. (Cassini identities) For $n \geq 1$, we have

$$\gamma_{n+1}\gamma_{n-1} - \gamma_n^2 = \alpha^{2n-1}q^{n-1}(q-1)\underline{\alpha}\underline{\varphi}$$

$$\delta_{n+1}\delta_{n-1} - \delta_n^2 = \alpha^{2n}q^{n-1}(q-1)^2\underline{\alpha}\,\underline{\varphi}.$$

Proof. By writing $r = 1$ in Theorem (3.4), we can get the results.

Theorem 3.5. (d'Ocagne identities) For positive integer n and m, we have

$$\gamma_m\gamma_{n+1} - \gamma_n\gamma_{m+1} = \alpha^{m+n-1}\left([m]_q - [n]_q\right)\left(\underline{\alpha}^2 + \alpha(q-1)\underline{\alpha}\,\underline{\beta}\right)$$

$$\delta_m\delta_{n+1} - \delta_n\delta_{m+1} = \alpha^{m+n+1}(q-1)^2\left([m]_q - [n]_q\right)\underline{\alpha}\,\underline{\varphi}.$$

Proof. Using (2), (3) and (6), we obtain

$$\gamma_m\gamma_{n+1} - \gamma_n\gamma_{m+1} = \left(\alpha^{m-1}[m]_q\underline{\alpha} + (\alpha q)^m\underline{\beta}\right)\left(\alpha^n[n+1]_q\underline{\alpha} + (\alpha q)^{n+1}\underline{\beta}\right)$$

$$-\left(\alpha^{n-1}[n]_q\underline{\alpha} + (\alpha q)^n\underline{\beta}\right)\left(\alpha^m[m+1]_q\underline{\alpha} + (\alpha q)^{m+1}\underline{\beta}\right)$$

$$= \alpha^{m+n-1}\left([m]_q[n+1]_q - [n]_q[m+1]_q\right)\underline{\alpha}^2$$

$$+\alpha^{m+n}\left(q^n\left(q[m]_q - [m+1]_q\right) + q^m\left([n+1]_q - q[n]_q\right)\right)\underline{\alpha}\,\underline{\beta}$$

$$= \alpha^{m+n-1}\frac{q^n - q^m}{1-q}\underline{\alpha}^2 + \alpha^{m+n}(q^m - q^n)\underline{\alpha}\underline{\beta}$$

$$= \alpha^{m+n-1}\left([m]_q - [n]_q\right)\underline{\alpha}^2 + \alpha^{m+n}\left([m]_q - [n]_q\right)(q-1)\underline{\alpha}\underline{\beta}$$

$$= \alpha^{m+n-1}\left([m]_q - [n]_q\right)\left(\underline{\alpha}^2 + \alpha(q-1)\underline{\alpha}\,\underline{\beta}\right).$$

For the proof of q-Lucas tessarine number sequences, we use (2), (3) and (7) and get the result easily.

Theorem 3.6. For positive integers, n, r and s, the q-Fibonacci and q-Lucas tessarine number sequences satisfy the following identity

$$\delta_{n+r}\gamma_{n+s} - \delta_{n+s}\gamma_{n+r} = 2q^n\alpha^{2n+r+s-1}\left([s]_q - [r]_q\right)\underline{\alpha}\,\underline{\varphi}$$

Proof. By using (2) and (7), we get

$$\delta_{n+r}\gamma_{n+s} - \delta_{n+s}\gamma_{n+r} = \left(\alpha^{n+r}\underline{\alpha} + (\alpha q)^{n+r}\underline{\varphi}\right)\left(\frac{\alpha^{n+s}\underline{\alpha} - (\alpha q)^{n+s}\underline{\varphi}}{\alpha - \alpha q}\right)$$

$$-\left(\alpha^{n+s}\underline{\alpha} + (\alpha q)^{n+s}\underline{\varphi}\right)\left(\frac{\alpha^{n+r}\underline{\alpha} - (\alpha q)^{n+r}\underline{\varphi}}{\alpha - \alpha q}\right)$$

$$= 2q^n\alpha^{2n+r+s-1}\frac{q^r - q^s}{1-q}\underline{\alpha}\,\underline{\varphi}$$

$$= 2q^n\alpha^{2n+r+s-1}\left([s]_q - [r]_q\right)\underline{\alpha}\,\underline{\varphi}.$$

Definition 3.2. For complex polynomials $h(t)$ and $g(t)$, the q-Fibonacci $F_{q,n}(t)$ and q-Lucas $L_{q,n}(t)$ polynomials are defined as follows:

$$\begin{cases} F_{q,n}(t) = h(\mathrm{t})\,F_{q,n-1}(t) - g(t)F_{q,n-2}(t) \\ L_{q,n}(t) = h(\mathrm{t})L_{q,n-1}(t) - g(t)L_{q,n-2}(t). \end{cases} \tag{9}$$

Here, $F_{q,0}(t) = 0, F_{q,1}(t) = 1, L_{q,0}(t) = 2$ and $L_{q,1}(t) = h(t)$, respectively. Classify the q-polynomials $F_{q,n}(t)$ and $L_{q,n}(t)$ according to the $h(t)$ and $g(t)$ values, respectively.

i. Assume that $h(t) = aq + 1$ and $g(t) = a^2q$ are constant polynomials. In this case, we can write as follows:

$$\begin{cases} F_{q,n}(t) = (aq+1)F_{q,n-1}(t) - a^2qF_{q,n-2}(t) \\ L_{q,n}(t) = (aq+1)L_{q,n-1}(t) - a^2qL_{q,n-2}(t). \end{cases}$$

ii. Assume that $h(t) = \lambda(s)$ and $g(t) = -1$ are not constant polynomials. For this case, we obtain the following equality:

$$\begin{cases} F_{q,n}(t) = \lambda(s)F_{q,n-1}(t) + F_{q,n-2}(t) \\ L_{q,n}(t) = \lambda(s)L_{q,n-1}(t) + L_{q,n-2}(t). \end{cases}$$

Roots of $r^2 - h(t)r - 1 = 0$ in (9) are

$$\alpha(r) = \frac{h(t) + \sqrt{h^2(t) + 4}}{2}$$

$$\beta(r) = \frac{h(t) - \sqrt{h^2(t) + 4}}{2}.$$

Then, the Binet formulas for q-polynomials $F_{q,n}(t)$ and $L_{q,n}(t)$ are

$$F_{q,n}(t) = \frac{\alpha(r)^n - \beta(r)^n}{\alpha(r) - \beta(r)}$$

and

$$L_{q,n}(t) = \alpha(r)^n + \beta(r)^n.$$

Definition 3.3. The q-Fibonacci tessarine polynomial sequences $\gamma_{q,n}(t)$ and the q-Lucas tessarine polynomial sequences $\delta_{q,n}(t)$ are defined by the recurrence relation

$$\gamma_{q,n}(t) = F_{q,n}(t) + F_{q,n+1}(t)i_1 + F_{q,n+2}(t)i_2 + F_{q,n+3}(t)i_3$$

$$\delta_{q,n}(t) = L_{q,n}(t) + L_{q,n+1}(t)i_1 + L_{q,n+2}(t)i_2 + L_{q,n+3}(t)i_3.$$

The initial conditions of the $\gamma_{q,n}(t)$ and $\delta_{q,n}(t)$ are

$$\begin{aligned}\gamma_{q,0}(t) &= F_{q,0}(t) + F_{q,1}(t)i_1 + F_{q,2}(t)i_2 + F_{q,3}(t)i_3 \\ &= i_1 + h(t)i_2 + \big(h(t)^2 - g(t)\big)i_3,\end{aligned}$$

$$\begin{aligned}\gamma_{q,1}(t) &= F_{q,1}(t) + F_{q,2}(t)i_1 + F_{q,3}(t)i_2 + F_{q,4}(t)i_3 \\ &= 1 + h(t)i_1 + \big(h(t)^2 - g(t)\big)i_2 + \big(h(t)^3 - 2h(t)g(t)\big),\end{aligned}$$

$$\begin{aligned}\delta_{q,0}(t) &= L_{q,0}(t) + L_{q,1}(t)i_1 + L_{q,2}(t)i_2 + L_{q,3}(t)i_3 \\ &= 2 + h(t)i_1 + \big(h(t)^2 - 2g(t)\big)i_2 + \big(h(t)^3 - 3h(t)g(t)\big)i_3\end{aligned}$$

and

$$\begin{aligned}\delta_{q,1}(t) &= L_{q,1}(t) + L_{q,2}(t)i_1 + L_{q,3}(t)i_2 + L_{q,4}(t)i_3 \\ &= h(t) + \big(h(t)^2 - 2g(t)\big)i_1 + \big(h(t)^3 - 3h(t)g(t)\big)i_2 \\ &\quad + (h(t)^4 - 4h(t)^2g(t) - 2g(t)^2)i_3\end{aligned}$$

where i_1, i_2 and i_3 are the imaginary units satisfies the multiplication rule in (1).

Theorem 3.7. The Binet-like formulas of the q-tessarine polynomials $\gamma_{q,n}(t)$ and $\delta_{q,n}(t)$ are

$$\gamma_{q,n}(t) = \frac{\alpha(t)^n \underline{\alpha}(t) - \beta(t)^n \underline{\beta}(t)}{\alpha(t) - \beta(t)}$$

and

$$\delta_{q,n}(t) = \alpha(t)^n \underline{\alpha}(t) + \beta(t)^n \underline{\beta}(t).$$

Here,

$$\underline{\alpha}(t) = 1 + \alpha(t) i_1 + \alpha(t)^2 i_2 + \alpha(t)^3 i_3$$

$$\underline{\beta}(t) = 1 + \beta(t) i_1 + \beta(t)^2 i_2 + \beta(t)^3 i_3.$$

Proof. The proof can be done easily by using Binet-like formulas of q-Fibonacci and q-Lucas tessarine polynomial sequences.

Definition 3.4. (Kac & Cheung, 2002; Stum & Quiros, 2013) Suppose that $p(t)$ is an arbitrary function. Its q-derivative operator is given by

$$d_q p(t) = p(qt) - p(t).$$

Note that in particular $d_q(t) = (q-1)t$,

$$\lim_{q \to 1} D_q p(t) = \lim_{q \to 1} \frac{p(qt) - p(t)}{(q-1)t} = \frac{dp(t)}{dt} \tag{10}$$

where $q \neq 1$.

Definition 3.5. The n^{th} q-Fibonacci and q-Lucas tessarine function sequences are defined as follows:

$$\Gamma_{q,n}(t) = \mathcal{F}_{q,n}(t) + \mathcal{F}_{q,n+1}(t) i_1 + \mathcal{F}_{q,n+2}(t) i_3 + \mathcal{F}_{q,n+3}(t) i_4$$

and

$$\Delta_{q,n}(t) = \mathcal{L}_{q,n}(t) + \mathcal{L}_{q,n+1}(t) i_1 + \mathcal{L}_{q,n+2}(t) i_2 + \mathcal{L}_{q,n+3}(t) i_3,$$

respectively. Where $\mathcal{F}_{q,n}(t)$ and $\mathcal{L}_{q,n}(t)$ are the n^{th} q-Fibonacci and q-Lucas functions and i_1, i_2 and i_3 are the imaginary units satisfy rules in (1).
The q-derivative of $\Gamma_{q,n}(t)$ and $\Delta_{q,n}(t)$ is defined as:

$$D_q \Gamma_{q,n}(t) = D_q \mathcal{F}_{q,n}(t) + D_q \mathcal{F}_{q,n+1}(t) i_1 + D_q \mathcal{F}_{q,n+2}(t) i_3 + D_q \mathcal{F}_{q,n+3}(t) i_4$$

and

$$D_q \Delta_{q,n}(t) = D_q \mathcal{L}_{q,n}(t) + D_q \mathcal{L}_{q,n+1}(t) i_1 + D_q \mathcal{L}_{q,n+2}(t) i_2 + D_q \mathcal{L}_{q,n+3}(t) i_3$$

where $D_q \mathcal{F}_{q,n}(t)$ means the derivative of $\mathcal{F}_{q,n}(t)$.

Example 3.1. For any integer n, if $\mathcal{F}_{q,n}(t) = (t-a)^n$,then

$$D_q \mathcal{F}_{q,n}(t) = [n]_q \mathcal{F}_{q,n-1}(t)$$

Proof. From (10), compute q-derivative of the function sequences $\mathcal{F}_{q,n}(t)$,

$$\begin{aligned} D_q \mathcal{F}_{q,n}(t) &= \frac{\big(q(t-a)\big)^n - (t-a)^n}{(q-1)(t-a)} \\ &= \frac{q^n - 1}{q-1} (t-a)^{n-1} \end{aligned}$$

$$= [n]_q \mathcal{F}_{q,n-1}(t)$$

and from above example the derivative of the n^{th} q-Fibonacci tessarine function sequences is

$$D_q \Gamma_{q,n}(t) = [n]_q \mathcal{F}_{q,n-1}(t) + [n+1]_q \mathcal{F}_{q,n}(t) i_1 + [n+2]_q \mathcal{F}_{q,n+1}(t) i_2 + [n+3]_q \mathcal{F}_{q,n+2}(t) i_3$$

4. Discussion and Conclusion

In this study, tessarine number sequences are defined using notations from quantum calculus. We derive several fundamental identities, including Binet-like formulas, exponential generating functions, and Catalan-like, Cassini-like, and d'Ocagne-like identities for these numbers. Additionally, we introduce new tessarine polynomial and function sequences, namely the q-Fibonacci tessarine and q-Lucas tessarine polynomials and function sequences. We then present various properties and identities for these polynomials and function sequences. In the future, researchers may explore additional identities of tessarine number sequences within the framework of quantum calculus.

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Research Article

Zero Truncated Models in Regression Analysis: An Examination of Their Advantages on Small Mean Values†

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Abstract: In this study, two of the most commonly used zero-truncated regression models for modeling positive count data, namely Zero Truncated Poisson and Zero Truncated Negative Binomial, are compared with the classical Poisson and Negative Binomial regression models. The role of the mean of the dependent variable in model selection is examined. Simulations were first conducted using different mean values for the dependent variable, followed by a comparison of model performances using two different real data sets. The real data sets were constructed using crime data published by Turkish Statistical Institude (TSI). AIC, BIC, and residual plots were utilized to determine the most suitable model. The study found that zero-truncated models perform better when the mean of the dependent variable is below 5, compared to classical models.

Keywords: Negative binom, Poisson, Zero truncated negative binom, Zero truncated poisson

Sıfır Değer Kesilmiş Modellerin Regresyon Analizindeki Avantajları: Küçük Ortalama Değerler Üzerine Bir İnceleme

Öz: Bu çalışmada, pozitif sayım verilerinin modellenmesinde en sık kullanılan zero-truncated regresyon modellerinden ikisi Sıfır değer kesilmiş Poisson, Sıfır değer kesilmiş Negatif Binom ile klasik Poisson ve Negatif Binom regresyon modelleri karşılaştırılmış ve bağımlı değişkenin ortalamasının model seçimindeki rolü incelenmiştir. Öncelikle bağımlı değişken için farklı ortalama değerleri kullanılarak simülasyonlar gerçekleştirilmiş, ardından iki farklı gerçek veri seti üzerinden model performansları karşılaştırılmıştır. Gerçek veri setleri, Türkiye İstatistik Kurumu (TÜİK) tarafından yayımlanan suç verileri kullanılarak oluşturulmuştur. En uygun modelin belirlenmesinde AIC, BIC ve residual grafikleri kullanılmıştır. Bağımlı değişkenin ortalamasının 5'ten küçük olduğu durumlarda, sıfır değer kesilmiş modellerin daha üstün bir performans sergilediği tespit edilmiştir.

Anahtar Kelimeler: Negatif binom, Poisson, Sıfır değer kesilmiş negatif binom, Sıfır değer kesilmiş poisson

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1. Introduction

Count data often deviate from normal distribution and typically start from zero with positive values (Zeileis et al., 2008; Coxe et al., 2009). Such data generally do not satisfy the assumptions of normality and take on positive, greater-than-zero values. This can lead to biased parameter estimates when applying linear regression to count data. Count data typically follow a Poisson distribution, for which Poisson regression is commonly used (Agresti, 1997). However, issues such as overdispersion or underdispersion arise when the equality between the variance and the mean is violated (Cox, 1983). Overdispersion occurs when the variance exceeds the mean, indicating greater variability in the data than expected under a Poisson model, whereas underdispersion refers to the case where the variance is smaller than the mean, suggesting less variability than anticipated. In such cases, alternative models like negative binomial (NB) and generalized Poisson (GP) regressions can be employed (Lawal, 2012; Sáez-Castillo & Conde-Sánchez, 2013; Hilbe, 2014). Zero-truncated regression models also provide an effective approach for positive count data.

Poisson regression is suitable when the variance equals the mean, but it may yield biased estimates and narrow confidence intervals in the presence of overdispersion (Hilbe, 2011). In such situations, NB and GP regressions are preferred (Long, 1997; Jansakul & Hinde, 2002). For count data that do not include zeros, zero-truncated regression models are appropriate. These models estimate probabilities based on positive count data and are utilized in fields such as modeling gene expression in medicine (Thygesen & Zwinderman, 2006). When overdispersion stems from multiple sources, the zero-truncated generalized negative binomial method is preferred (Hilbe, 2011). The comparison of Poisson, negative binomial, and zero-truncated models is often based on AIC and BIC values; the model with the smallest value is considered the best fit (Rose et al., 2006; Sileshi, 2008). Truncated models are widely applied in various fields. For instance, Thygesen & Zwinderman, (2006) and Lee et al. (2003) employed these models in medical studies; Liu et al. (2013) used zero-truncated negative binomial regression with quantile regression to estimate train derailment probabilities; Puza et al. (2008) applied a Bayesian approach to truncated Poisson regression for analyzing illegal immigrant data in the Netherlands; Creel and Loomis (1990) analyzed deer hunting in California; and Van Der Heijden et al. (2003) used zero-truncated regression models to estimate offender populations based on police records in Germany.

Residual analysis is an effective method for determining the best-fitting model, as it directly impacts the accuracy and validity of the model (Draper & Smith, 1998). Residual plots displaying a wide distribution and systematic patterns indicate poor model fit (Montgomery et al., 2012). Another approach to identifying the best model involves examining the AIC and BIC values, with lower values indicating a better model fit (Burnham & Anderson, 2002).

This study investigates the role of the dependent variable's mean in model selection and discusses potential issues arising from the failure to choose an appropriate regression model. By employing AIC, BIC, and residual plots, the study aims to determine the best model theoretically and practically, providing insights into model performance evaluation.

2. Material and Methods

The real data used in this study consists of crime statistics recorded in 81 provinces of Turkey between 2009 and 2013, obtained from the Turkish Statistical Institute (TÜİK). The crimes analyzed include bad treatment, sexual crimes, crimes related with firearms and knifes, homicide, assault, robbery, production and commerce of drugs, use and purchase of drugs, and kidnapping. These statistics, categorized by province in the TÜİK dataset, were grouped into seven geographical regions and incorporated into the regression model as the "region" variable. Additionally, each year was included in the model as the "year" variable. The study utilized a total of 11 variables (considering "year" and "region" as single variables) and 405 data points.

The study employed the R 3.5.2 statistical software and several R packages. The packages used include "msm" and "sandwich" for Poisson regression, "MASS" and "foreign" for negative binomial regressions, and "VGAM," "ggplot2," and "boot" for zero-truncated regression methods. In the simulation study, 1,000 samples, 1 dependent variable, 10 independent variables, and the **"pscl"** package in R were utilized. A sample size of 1,000 was chosen to ensure the statistical stability of the

estimators, maintain computational efficiency, and adopt an approach consistent with the existing literature.

The regression methods applied in this study were Poisson, negative binomial, zero-truncated Poisson (ZTP), and zero-truncated negative binomial (ZTNB) regressions.

2.1. Poisson regression

Poisson regression is one of the generalized linear models in regression analysis. It is used for analyzing count data and contingency tables. When modeling contingency tables, it is often referred to as log-linear regression. In this model, the dependent variable follows a Poisson distribution, and a log link function is used to relate the dependent variable to the independent variables, resulting in a linear equation (Winkelmann, 2008; Yesilova et al., 2010).
When the independent variables are $X_1, X_2, \ldots . X_m$, the log link function is expressed as follows:

$$\log(\mu) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_m X_m \quad (1)$$

where $X_1, X_2, \ldots, X_m$ is the vector of independent variables and $\beta_0, \beta_1, \beta_2, \ldots, \beta_m$ represents the regression coefficients (Kutner et al., 2004).

Here, μ is an exponential function of the independent variables. The log-likelihood function is defined as (Khoshgoftaar et al., 2005):

$$L(\beta / y_i, x_i) = \sum_{i=1}^{n} [y_i x_i' \beta - \exp(x_i' \beta) - ln y_i!] \quad (2)$$

2.2. Negative binomial regression

Negative binomial (NB) regression is a method used as an alternative to Poisson regression when overdispersion is observed in the dependent variable. It relates the dependent and independent variables through a log link function. The probability function is given as:

$$P_r(Y) = \frac{\Gamma(y_i + \frac{1}{\alpha})(\alpha\mu_i)^{y_i}}{y_i!\,\Gamma(\frac{1}{\alpha})(1+\alpha\mu_i)^{y_i+\frac{1}{\alpha}}} \quad , \quad \alpha > 0 \quad (3)$$

In this equation, μi is the mean of the distribution, α is the NB dispersion parameter, and $\Gamma(.)$ denotes the gamma function (Simo et al., 2007).

The log-likelihood function of the NB regression model can be expressed as (Lawless, 1987):

$$L(\beta, \alpha, y) = \sum_{i=1}^{n} \left[\frac{1}{\alpha}\log(1+\alpha\mu_i) - y_i \log\left(1 + \frac{1}{\alpha\mu_i}\right) + \log\Gamma\left(y_i + \frac{1}{\alpha}\right) - \log\Gamma\left(\frac{1}{\alpha}\right) - \log y_i!\right] \quad (4)$$

2.3. Zero truncated poisson regression

Zero-truncated Poisson (ZTP), also known as positive Poisson, is a distribution where all values are positive and zero (0) is not included, unlike the standard Poisson distribution. The zero-truncated Poisson model is given by (Van Der Heijden et al., 2003):

$$P(y_i | y_i > 0, \lambda) = \frac{P(y_i|\lambda)}{P(y_i > 0, |\lambda)} = \frac{\exp(-\lambda)\lambda^{y_i}}{y_i!\,(1-\exp(-\lambda))} \quad (5)$$

$$P(y_i > 0, |\lambda) = (1 - \exp(-\lambda)), y_i = 1,2, \ldots \quad , \quad i = 1,2, \ldots . N, \quad (6)$$

For the i-th observation, the log-likelihood function is expressed as:

$$I(y_i;\mu_i|y_i>0)=y_i[X^T{}_i\beta]-exp(X^T{}_i\beta)-ln(y_i!)-\ln[1-exp\{-exp(X^T{}_i\beta)\}] \quad (7)$$

Here, y_i represents the observed count outcome, while λ denotes the Poisson rate parameter. The term $X_i^T\beta$ represents the linear predictor in the regression model.

The log-likelihood for the ZTP model is given by (Hilbe, 2014):

$$I(y_i;\mu_i|y_i>0)=\sum y_i[X^T{}_i\beta]-exp(X^T{}_i\beta)-ln(y_i!)-\ln\left[1-\exp\{-\exp(X^T{}_i\beta)\}\right] \quad (8)$$

2.4. Zero truncated negative binomial regression

Zero-truncated negative binomial (ZTNB) regression is a method used for modeling dependent variables with positive values ($y_i>0$) that also exhibit overdispersion. The log-likelihood for the ZTNB model can be written as:

$$L(\mu;y|y>0)=\sum_{i=1}^{n}\{L_{NB2}-ln[1-\{1+\alpha exp(x_i'\beta)\}^{-\frac{1}{\alpha}}]\} \quad (9)$$

where L_{NB2} is given by (Hilbe, 2014):

$$L(\beta;y,\alpha)=\sum_{i=1}^{n}\{y_i\log\left(\frac{\alpha\exp(x_i'\beta)}{1+\alpha\exp(x_i'\beta)}\right)-\left(\frac{1}{\alpha}\right)\log(1+\alpha\exp(x_i'\beta))+log\Gamma\left(y_i+\frac{1}{\alpha}\right)-log\Gamma(y_i+1)-log\Gamma(\frac{1}{\alpha})\} \quad (10)$$

3. Results

3.1. Simulation study

In the simulation study, one dependent variable and 10 independent variables were generated. The sample size was set to 1,000. The dependent variable had a minimum value of 1 and followed a Poisson distribution with a mean of 100. This mean value was subsequently altered to 50, 10, 5, and 3, and model performances were compared accordingly.

In the second simulation study, the dependent variable was again a count variable with a minimum value of 1 but exhibited overdispersion. The mean values were similarly set to 100, 50, 10, 5, and 3, and model performances under conditions of overdispersion were compared.

Residual plots, along with AIC and BIC criteria, were used to determine the best-performing model. Residual plots for the highest mean of 100 and the lowest mean of 3 were presented to visualize changes in model performance across the two extreme mean values. The goal was to observe the variation in model performance across different mean levels.

The results obtained for models using one dependent variable (consisting of positive values following a Poisson distribution) and 10 independent variables across different mean values are summarized below.

Table 1. AIC and BIC values of Poisson and ZTP regressions for different mean values

MODEL	μ=100		μ =50		μ =10		μ =5		μ =3	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
POISSON	7453	7507.77	6785.1	6839.1	5153.547	5207.532	4342.98	4396.96	3702.74	3756.72
ZTP	7453	7507.77	6785.1	6839.1	5153.455	5207.44	4328.02	4382.00	3589.41	3643.40

For μ=100, the Poisson and ZTP models show similar AIC and BIC values, suggesting similar fit performance. As μ decreases, the ZTP model generally provides a slightly better fit (lower AIC and BIC values) compared to the Poisson model. This indicates that the ZTP model may be more appropriate for datasets where zero values are truncated, as it results in lower AIC and BIC values, signaling better model fit.

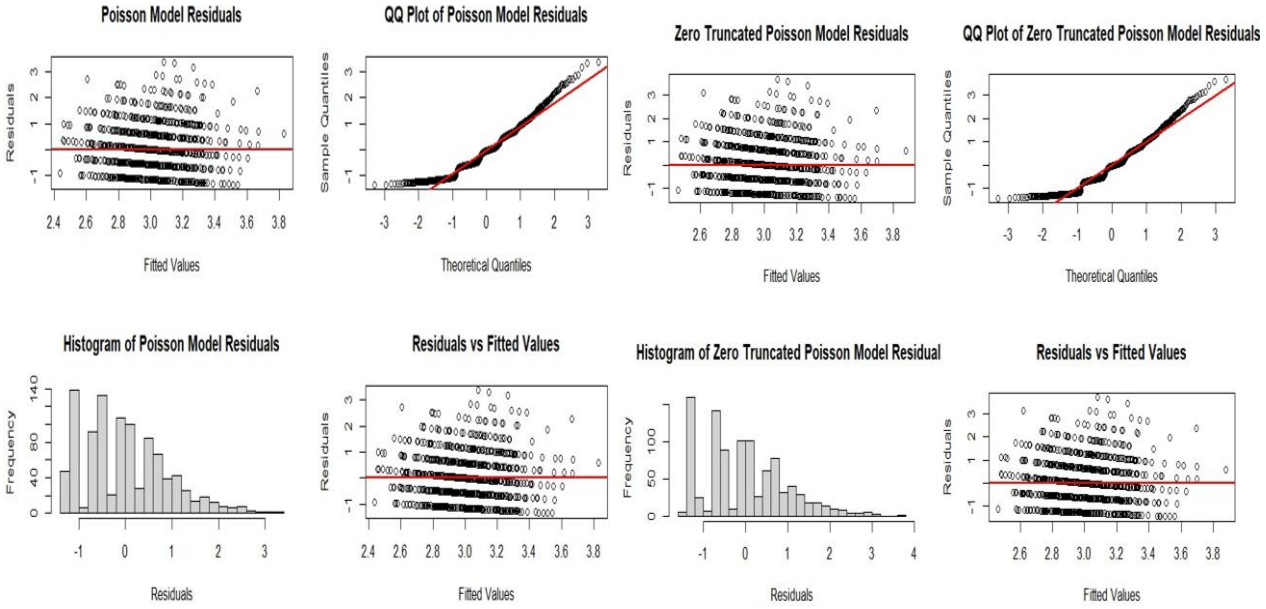


Figure 1. Residual plots for a mean value of 100.

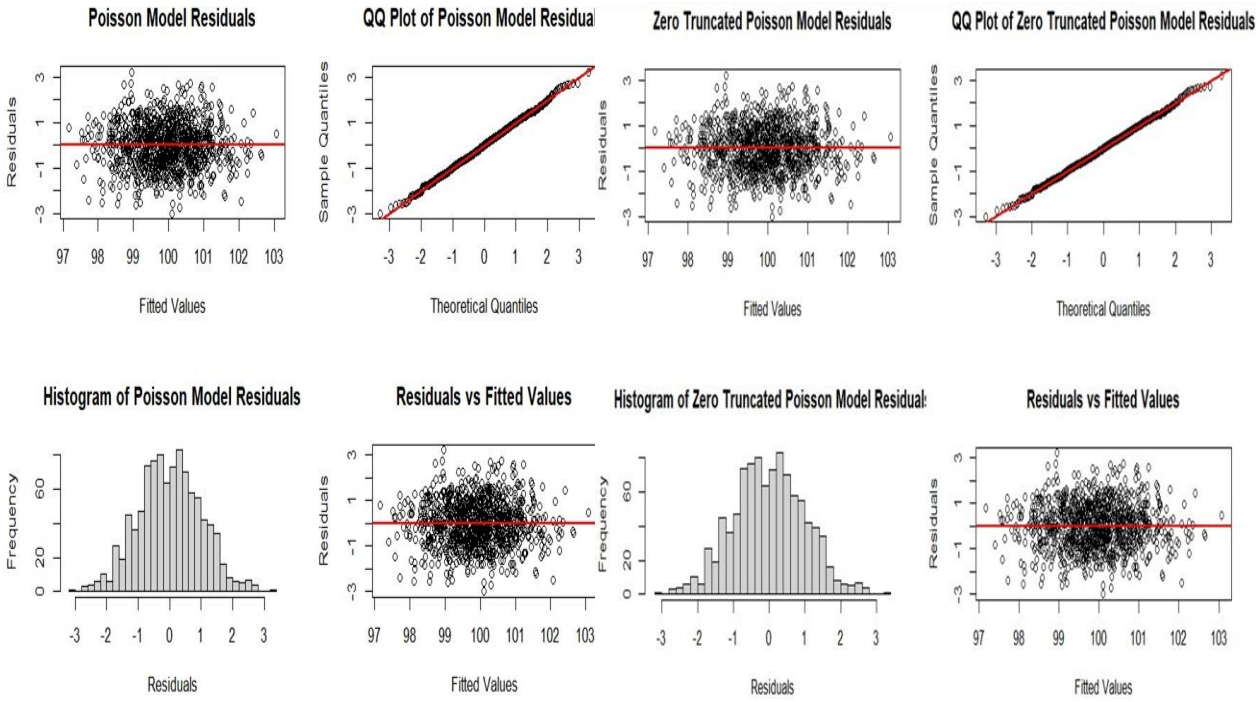


Figure 2. Residual plots for a mean value of 3.

Residual plots exhibit a wide distribution and systematic patterns, which indicate poor model fit. This behavior is observed in the residual plots of the Poisson model. Particularly, when the mean decreases (μ=3), the model demonstrates inadequate fit to the dataset and produces higher prediction errors. In contrast, the Zero-Truncated Poisson (ZTP) model shows better fit to the data, with residuals

distributed more narrowly and homogeneously. The ZTP model is more suitable for count data without zero values, and this suitability becomes more pronounced at lower mean values.

In Table 1, the AIC and BIC values for the models at means of 100, 50, and 10 are identical. As the mean decreases, these values also decrease. However, when the mean is set to 5, the AIC and BIC values begin to diverge, and the differences grow significantly at a mean of 3. For larger mean values, no significant differences are observed in AIC and BIC values across the regression models employed. So, for dependent variables with a mean of 5 or less, the ZTP model is preferable to the Poisson model.

Table 2. AIC and BIC values of NB and ZTNB regressions for different mean values

MODEL	μ=100		μ=50		μ=10		μ=5		μ=3	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
NB	9755.43	9814.32	8446	8505	5785	5844	4781	4840	3995	4054
ZTNB	9755.43	9814.32	8446	8505	5782	5841	4745	4804	3851	3910

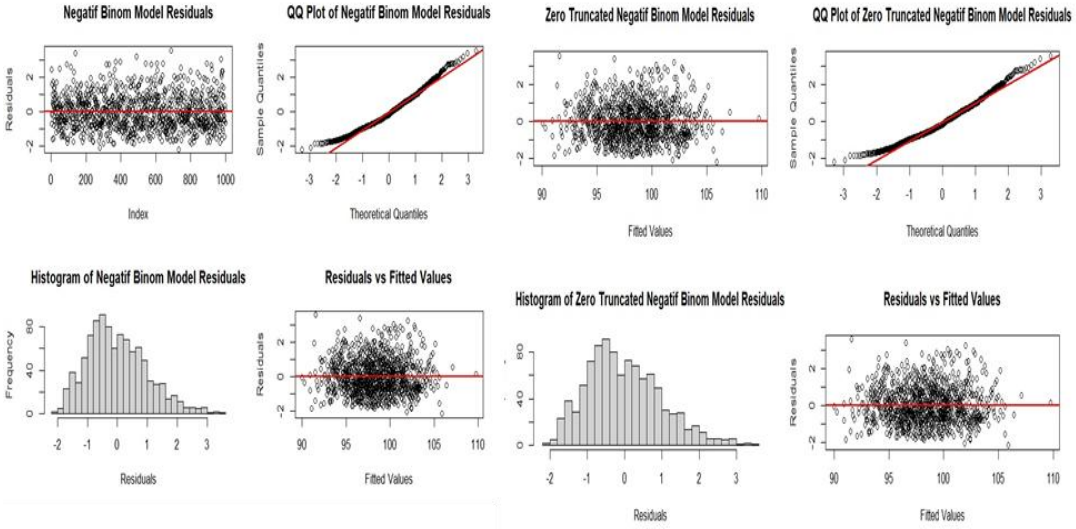


Figure 3. Residual plots for a mean value of 100.

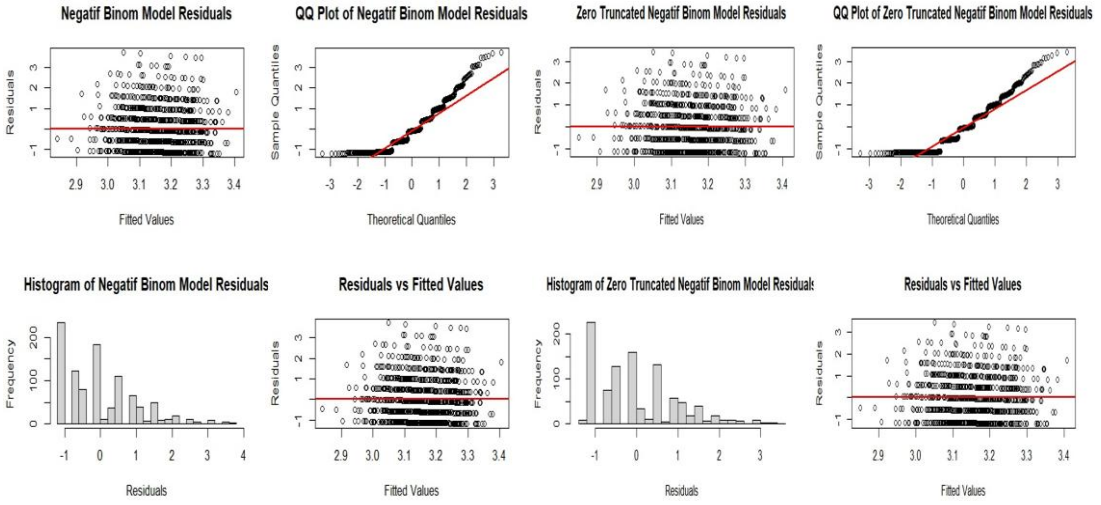


Figure 4. Residual plots for a mean value of 3.

Similar results were obtained in Negative Binomial (NB) and Zero-Truncated Negative Binomial (ZTNB) regressions as in the Poisson application. When the mean is 3, the residual plot of the

ZTNB model shows a narrower and more homogeneous distribution compared to the NB model. This indicates that the ZTNB regression is a more suitable model for the dataset.

Moreover, the AIC and BIC values diverge when the mean is set to 10, and as the mean decreases, it becomes increasingly evident that the ZTNB model is the more appropriate choice.

3.2. Real dataset application

In this study, one of the dependent variables, the crime of bad treatment, was found to consist of positive values, with a minimum value of 1 and a maximum value of 18. Additionally, it exhibited a Poisson distribution with a standard deviation of 1.603 and a mean of 1.54.
Four different regression models were employed in the study, and the results are presented in Table 3.

Table 3. AIC and BIC values of regression models used in the study

Model	AIC value	BIC value
Poisson(PR)	1052.4	1128.43
Negatif binomial(NB)	1054.4	1134.44
Zero truncated Poisson(ZTP)	590.89	666.97
Zero truncated negatif binomial(ZTNB)	1021.81	1101.89

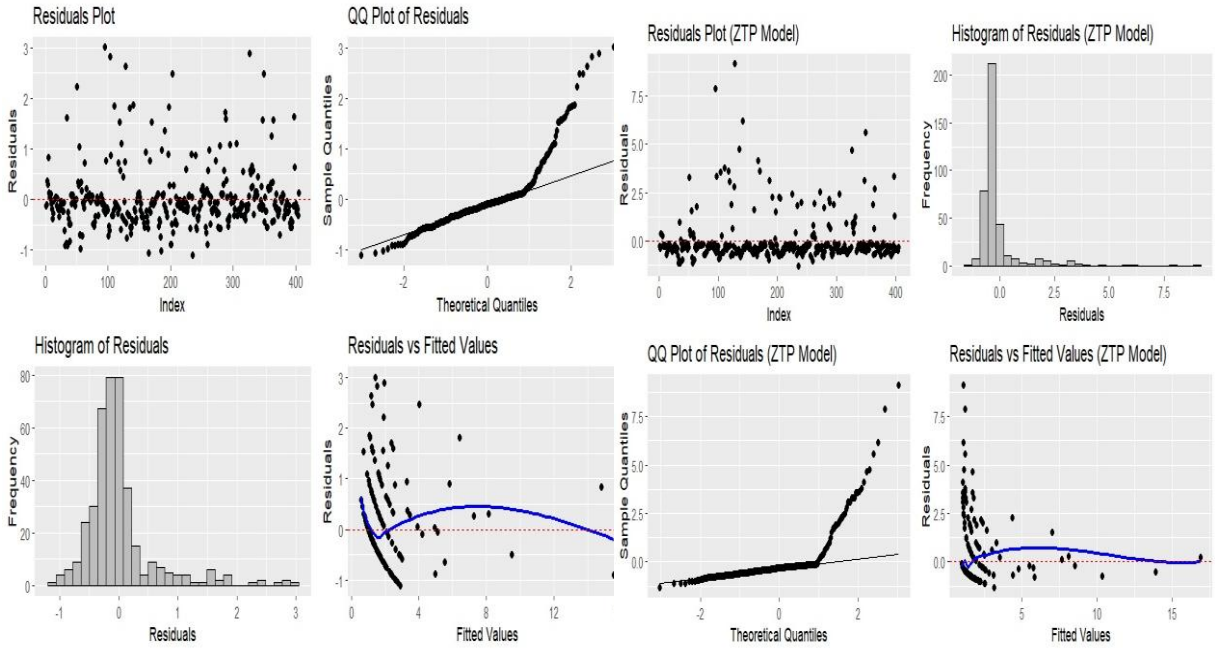


Figure 5. Residual values of Poisson regression and ZTP regression models (Real Data).

The second dependent variable used in the study is "sexual crimes." This variable has a minimum value of 1, a maximum value of 324, a mean of 21.56, and a variance of 1355.98. The variance being significantly larger than the mean indicates overdispersion. The regression models employed and the results obtained are presented in Table 4.

Table 4. Regression methods used and their AIC and BIC values

Model	AIC value	BIC value
Poisson(PR)	3556.7	3632.821
Negatif Binomial(NB)	2622.3	2702.341
Zero Truncated Poisson(ZTP)	3553.009	3629.082
Zero Truncated Negatif Binomial(ZTNB)	2595.403	2675.481

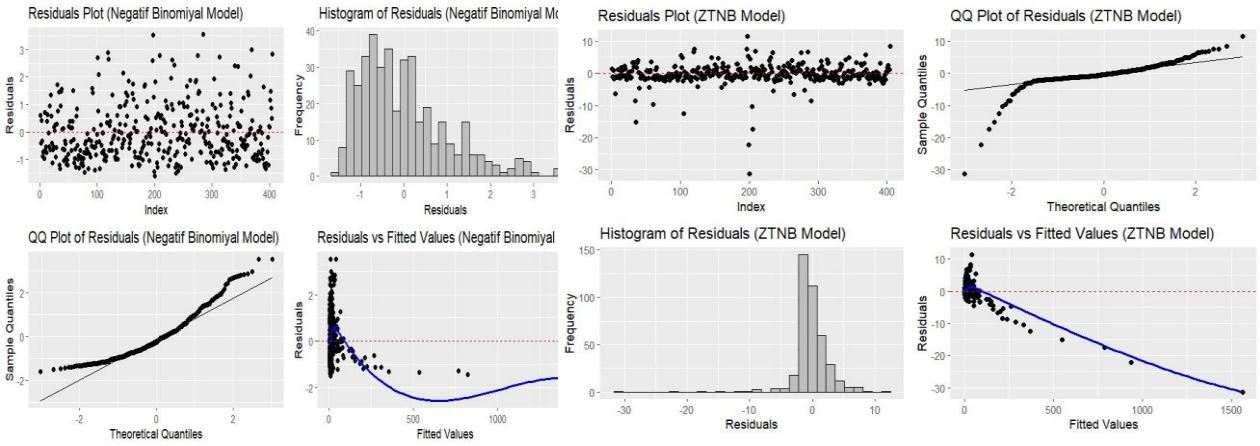


Figure 6. Residual values of negative binomial regression and ZTNB regression models (Real Data).

The residual plot of the negative binomial regression demonstrates a more balanced residual distribution. Systematic errors are less pronounced, and residuals are generally symmetric around zero. In contrast, the residual plots for the ZTNB regression show significant deviations and systematic errors, particularly at the negative extremes.

Table 5 provides the parameter estimates and standard errors for the Poisson and ZTP regression models when the dependent variable is "bad treatment."

Table 5. Comparison of independent variable estimates for PR and ZTP models when the dependent variable is "bad treatment" crime

VARIABLE	Poisson Parameter Estimates exp (β)	Poisson Standard Errors	ZTP Parameter Estimates exp (β)	ZTP Standard Errors
Sexual crimes	**0.98*** **	0.003	**0.96*** **	0.004
2010	**1.04**	0.13	**1.11**	0.22
2011	**1.01**	0.14	**1.02**	0.26
2012	**0.96**	0.14	**0.74**	0.28
2013	**0.89**	0.16	**0.63**	0.33
Aegean	**0.99**	0.17	**0.96**	0.26
Marmara	**1.30**	0.17	**1.56**	0.24
Black Sea	**0.92**	0.17	**0.48***	0.34
Central Anatolia	**0.96**	0.16	**0.69**	0.28
Eastern Anatolia	**0.81**	0.17	**0.23****	0.48
Sotheast Anatolia	**0.72**	0.2	**0.15*** **	0.54
Homicide	**0.97***	0.001	**1.007*** **	0.001
Crimes related with firearms and knifes	**0.99**	0.001	**1.003**	0.001
Production and commerce of drugs	**1.001**	0.0006	**1.001**	0.0007
Use and purchase of drugs	**1.003****	0.2	**0.99**	0.001
Robbery	**0.99*** **	0.001	**0.99*** **	0.0001
Kidnapping	**1.001**	0.004	**1.004**	0.005
Assault	**1.002*** **	0.0005	**1.004*** **	0.0007

*(p<0.1), **(p<0.01), ***(p<0.001)

In Table 5, significant differences were observed between the parameter estimates of the Poisson and ZTP models. For instance, the "Eastern Anatolia" variable was estimated as 0.81 in the Poisson model and 0.23 in the ZTP model. Similar differences were observed for other variables as well.

The AIC and BIC values presented in Table 3 also reflect this difference, with values of 1052.4 and 1128.43 for the Poisson regression, and 590.89 and 666.97 for the ZTP regression, respectively (Table 3).

Similarly, the "Southeast Anatolia" variable was estimated as 0.72 in the Poisson model, whereas this value dropped to 0.15 in the ZTP model. This indicates that the ZTP model is more sensitive to zero-truncated datasets and better captures the structure of the data.

In contrast, variables such as "Robbery" (0.99 in both models) and "Production and Commerce of Drugs" (1.001 in both models) showed consistent parameter estimates across the models. This suggests that the effect of zero truncation on these variables is limited, and their sensitivity to model selection is relatively low.

Table 6. Comparison of Independent Variable Estimates for NB and ZTNB Models When the Dependent Variable is "Sexual Offenses"

VARIABLE	NB Parameter Estimates exp (β)	NB Standard Errors	ZTNB Parameter Estimates exp (β)	NB Standard Errors
Bad treatment	**1.03**	0.02	**1.03**	0.02
2010	**1.41*** **	0.10	**1.47*** **	0.11
2011	**1.16**	0.10	**1.19**	0.11
2012	**2.07*** **	0.10	**2.18*** **	0.11
2013	**3.09*** **	0.11	**3.35** **	0.12
Aegean	**1.15**	0.12	**1.16**	0.13
Marmara	**1.06**	0.12	**1.06**	0.13
Black sea	**0.65*** **	0.12	**0.64*** **	0.13
Central Anatolia	**0.79**	0.12	**0.78**	0.13
Eastern Anatolia	**0.37*** **	0.12	**0.34*** **	0.14
Southeast Anatolia	**0.36*** **	0.14	**0.33*** **	0.15
Homicide	**1.006*** **	0.001	**1.007*** **	0.001
Crimes related with firearms and knifes	**1.004*** **	0.001	**1.004*** **	0.001
Production and commerce of drugs	**0.99***	0.0005	**0.99***	0.0006
Use and purchase of drugs	**0.99** **	0.001	**0.99** **	0.001
Robbery	**0.99***	0.001	**0.99***	0.001
Kidnapping	**0.99**	0.003	**0.99**	0.003
Assault	**1.001** **	0.0004	**1.001** **	0.0004

*($p<0.1$), **($p<0.01$), ***($p<0.001$)

In Table 6, it was observed that the parameter estimates of the NB regression and ZTNB regression models were very close to each other, with some variables even having identical estimates. The AIC and BIC values for the two methods also showed similar results.

The AIC value for the NB regression was found to be 2622.3, while for the ZTNB regression, it was slightly lower at 2595.403. Similarly, the BIC values were also close, with the NB regression having a BIC value of 2702.341 and the ZTNB regression yielding a BIC value of 2675.481.

These results suggest that both models perform similarly for this dataset, with ZTNB showing a slight advantage in terms of model fit as indicated by its lower AIC and BIC values.

4. Conclusion

In this study, the effects of the mean of the dependent variable on the choice of regression models were examined in models where the dependent variable consisted of positive count data. Both simulation studies and real datasets were utilized to evaluate these effects. Zero-truncated models (ZTP and ZTNB) were compared with classical Poisson and Negative Binomial (NB) models, and model fit was assessed using AIC, BIC values, and residual plots.

The findings indicated that when the mean of the dependent variable was 5 or lower, zero-truncated models provided better fit compared to classical models. Using classical models for datasets with low mean values may result in biased parameter estimates, which could have critical implications in certain fields. For example, in areas such as medicine or pharmacology, where minimal differences in values can lead to significant outcomes, this could directly influence theoretical and application strategies.

The AIC and BIC values obtained in the real data application suggested that the ZTP regression model explained the data more effectively. However, residual plots indicated that the ZTP model could produce larger errors for low-fitness observations. A similar result was observed for the ZTNB regression model. When the mean of the dependent variable was less than 5, zero-truncated models generally performed better in terms of overall fit. If producing large errors for specific observations is acceptable and general fit is prioritized, zero-truncated models can be preferred.

When the mean of the dependent variable exceeded 5, no significant differences were observed between zero-truncated models and classical models. However, slight deviations were noted in the NB models when the mean was slightly above 5, indicating the need for more caution in model selection. This consideration is particularly important for datasets where the dependent variable exhibits overdispersion.

In light of the study's general findings, it is recommended that the mean of the dependent variable be taken into account when modeling positive count-dependent variables. Specifically, zero-truncated models should be preferred for dependent variables with a mean of 5 or less. In such cases, the use of classical methods could lead to biased parameter estimates depending on the research topic, scientific discipline, and dataset characteristics.

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Research Article

Using the Sound of Scrambled Images for Innovative IoT Underwater Data Transmission

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Abstract: The development of a hybrid approach for underwater IoT communication involves the integration of chaotic map algorithms with acoustic wave technology to ensure efficient transmission of data through the water. The Arnold Cat Map algorithm is a chaotic image scrambling technique that rearranges the pixels of an image through a mathematical transformation, creating a seemingly random pattern. A particularly intriguing application is the use of complex steganography, which is traditionally employed for image scrambling, to generate sound files for underwater communication. In this novel approach, the algorithm first scrambles an image, converting it into a sophisticated sound file. This sound file, which consists of a series of acoustic waves, is transmitted through the water, where sound waves are the primary communication medium due to their superior ability to travel underwater. Upon receipt, the sound waves are transformed back into their image form using an inverse transformation. By reversing the Arnold's cat map algorithm, the scrambled image is decoded, revealing the original message. This hybrid strategy leverages the power of acoustic waves in underwater communication and the encryption capabilities of image processing algorithms, providing a secure and efficient communication method. It addresses issues such as signal attenuation and noise interference, making it a promising solution for complex underwater IoT systems that require high security and reliability. The combination of image scrambling and acoustic wave transmission creates a sophisticated communication system capable of handling complex maritime IoT applications, thus enhancing the underwater communications.

Keywords: Acoustic wave, Chaotic maps, Data encryption, Image sound steganography, Underwater communication

Karıştırılmış Görüntülerin Sesini Yenilikçi Nesnelerin İnterneti Sualtı Veri İletimi için Kullanma

Öz: Su altı IoT iletişimi için hibrit bir yaklaşımın geliştirilmesi, verilerin su altından verimli bir şekilde iletilmesini sağlamak amacıyla kaotik harita algoritmalarının akustik dalga teknolojisiyle entegrasyonunu içerir. Arnold Cat Map algoritması, bir görüntünün piksellerini matematiksel bir dönüşümle yeniden düzenleyerek, görüntüyü rastgele bir desen haline getiren kaotik bir görüntü karıştırma tekniğidir. Bu yaklaşımın özellikle ilginç bir uygulaması, geleneksel olarak görüntü karıştırma için kullanılan steganografi algoritmasının, su altı iletişimi için ses dosyaları üretmek amacıyla kullanılmasıdır. Bu yenilikçi yaklaşımda, algoritma ilk olarak bir görüntüyü karıştırarak onu karmaşık bir ses dosyasına dönüştürür. Akustik dalgalardan oluşan bu ses dosyası, su altındaki ortamda iletilir; burada ses dalgaları, su altındaki mükemmel iletim özellikleri nedeniyle birincil iletişim ortamıdır. Alındığında, ses dalgaları ters dönüşüm işlemiyle tekrar görüntü formuna dönüştürülür. Arnold'un kedi haritası algoritması tersine çevrilerek karıştırılmış görüntü çözümlenir ve orijinal mesaj ortaya çıkar. Bu hibrit strateji, su altı iletişimindeki akustik dalgaların gücünden ve görüntü işleme algoritmalarının şifreleme yeteneklerinden yararlanarak güvenli ve verimli bir iletişim yöntemi sunar. Ayrıca, sinyal zayıflaması ve gürültü interferansı gibi sorunları ele alarak, yüksek güvenlik ve güvenilirlik gerektiren karmaşık su altı IoT sistemleri için umut verici bir çözüm sunar. Görüntü karıştırma ve akustik dalga iletiminin birleşimi, karmaşık deniz IoT uygulamalarını yönetebilecek sofistike bir iletişim sistemi oluşturur ve böylece su altı iletişimini geliştirir.

Anahtar Kelimeler: Akustik dalga, Görüntü ses steganografisi, Kaotik haritalar, Sualtı iletişimi, Veri şifreleme

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1. Introduction

Over the last decade, underwater data security has evolved significantly, driven by the increasing complexity and demand for underwater technology. As global dependence on underwater communication systems has grown through Internet of Things (IoT) commercial systems, the need to safeguard sensitive information in these environments has become crucial (Strelkoff, 2021). The challenges of underwater data security are unique, given the reliance on acoustic waves for communication and the inherent vulnerabilities such as signal attenuation, noise interference, and potential interception (Pradhan et al., 2016; Wang & Li, 2022).

In underwater IoT communication, acoustic waves are the primary means of data transfer (Mileva, 2018). However, the security protocols and encryption techniques are coupled with these protocols to overcome the specific challenges of the medium (Yin et al., 2015). In order to protect the data from unauthorized access and tampering, symmetric encryption algorithms such as Advanced Encryption Standard (AES) are commonly used due to their efficiency in handling the low bandwidth and high latency typical of underwater environments. Message authentication codes (MACs) and the digital signatures are employed for ensuring data integrity and authenticity (Mandal et al., 2022; Kumar et al., 2023). The error correction codes like Reed-Solomon and Turbo codes are also mitigating the effects of signal distortion and noise prevalent in underwater channels. Additionally, to address the unique constraints of underwater communication, adaptive modulation techniques are used to adjust the transmission parameters dynamically, enhancing both security and performance. These specialized approaches are crucial for safeguarding sensitive information and maintaining reliable communication across challenging underwater conditions (Ray et al., 2021). Advances in cryptographic methods, signal processing, and hybrid communication systems have played a crucial role in enhancing the protection of underwater data. This development has triggered the emergence of innovative approaches, including the use of chaotic algorithms and advanced scrambling techniques, which have redefined how data is secured beneath the surface. As underwater IoT applications expand, the field of underwater data security remains at the forefront of technological advancement, striving to meet the ever-growing demands for secure and reliable communication in challenging underwater conditions.

IoT is a rapidly growing field that connects multiple devices and systems, enabling them to communicate and interact autonomously. This interconnectivity facilitates automation and efficiency across various sectors, including healthcare, smart homes, and industrial control systems (Pradhan et al., 2016; Wang & Li, 2022). However, the proliferation of IoT devices has introduced significant security challenges. The sensitive nature of the data transmitted, and the sheer volume of devices create vulnerabilities that could be exploited by malicious usage. As a result, securing IoT systems is critical to ensure data integrity, confidentiality, and overall system reliability. An innovative approach to enhancing IoT security is the use of steganography (Hussain & Hussain, 2013; Hussain et al., 2018). The steganography offers a novel method for safeguarding data in IoT networks. Traditionally, it is associated with hiding information within digital media such as images or audio files. Unlike cryptography, which secures data by making it unreadable without the proper key, steganography hides the existence of the data itself. The primary goal is to prevent the detection of hidden information, making it a valuable tool for maintaining privacy and security. In the context of IoT, steganography can be employed to protect sensitive data communicated between devices (Goel et al., 2013; Ray et al., 2021). The data packets transmitted over a network can be embedded within benign-looking packets or encrypted payloads. This concealed data can include authentication tokens, control signals, or other critical information necessary for the operation of IoT devices.

Steganography reduces the likelihood of unauthorized access or interception by hiding the sensitive information within benign data (Bachrach & Shih, 2012). This is particularly useful in IoT environments where the data might be transmitted over insecure networks, especially in maritime and underwater environments (Hamid et al., 2012; Ghoul et al., 2023). Traditional encryption methods can sometimes attract attention due to the noticeable nature of encrypted traffic. The steganography obscures the presence of data altogether, making it less conspicuous to potential attackers. Moreover, combining steganography with other security measures, such as encryption and authentication, creates a multi-layered defense system (Mustafa et al., 2018; Kaur et al., 2022). This approach enhances the overall

security posture of IoT devices and networks. Steganographic techniques can be adapted to various types of IoT data and communication protocols. This flexibility allows for the integration of steganography into existing security frameworks without significant modifications (Qin et al., 2019; Koptyra & Ogiela, 2023).

The aim of this study is to develop a novel hybrid approach for underwater IoT communication that integrates chaotic map algorithms with acoustic wave technology to enhance the security, efficiency, and reliability of data transmission in marine environments. The proposed method leverages the Arnold Cat Map algorithm, a chaotic image scrambling technique, to encrypt data by converting it into a scrambled image. This image is then transformed into a sound file, which is transmitted underwater using acoustic waves. Upon reception, the sound file is decoded back into the original image through the inverse transformation of the Arnold Cat Map algorithm. By combining the encryption capabilities of image processing with the robustness of acoustic waves for underwater communication, this method addresses challenges such as signal attenuation, noise interference, and the need for secure data transfer in complex underwater IoT systems. The study aims to demonstrate that this hybrid approach can provide a more secure and efficient solution for underwater communication, making it suitable for a wide range of marine applications.

The study is organized as follows. Section 2 reviews related works in steganography techniques and its recent applications on IoT and underwater environments. Section 3 details the proposed methodology Section 4 shows encoding results and highlights the scope of the study through obtained results. Finally, Section 5 concludes the study with the effects of findings and the future steps.

2. Literature Review

While the steganography offers significant advantages, its implementation in IoT security comes with several challenges. Incorporating steganography into IoT systems requires careful planning and execution. Ensuring that hidden data does not interfere with the normal operation of devices and communications can be complex. The process of embedding and extracting hidden data can introduce additional computational overhead. This is a crucial consideration for the resource-constrained IoT devices where the processing power and the bandwidth are limited. Although the steganography aims to hide data, sophisticated techniques and tools can potentially detect the steganographic methods. It is essential to continuously update and refine steganographic techniques to stay ahead of detection methods. Securing IoT systems is essential as the number and complexity of connected devices continue to expand. The steganography offers a promising approach to enhancing IoT security by concealing sensitive information within seemingly harmless data. Its potential benefits include improved data privacy, reduced attack susceptibility, and flexibility in integration (Ray et al., 2021). However, the challenges such as integration complexity, performance impact, and detection risks must be carefully managed. The integration of steganography with other security measures, such as encryption and robust authentication protocols, can contribute to a more comprehensive and resilient IoT security strategy.

Figure 1 illustrates a general scheme of modern maritime and underwater communication channels. The maritime industry is increasingly leveraging IoT technologies to enhance operational efficiency, safety, and navigation. The integration of IoT into underwater operations also introduces significant security challenges, including potential cyber threats and data breaches. Securing IoT systems in maritime services is therefore essential to ensure the safety and efficiency of maritime operations. In order to reduce security risks and protect IoT systems in underwater services, several strategies can be employed (Fabbri et al., 2018). The implementation of Multi-Factor Authentication for accessing IoT devices and systems ensures that only authorized personnel can access critical data and control functions. Also, assigning access permissions based on user roles helps limit access to sensitive information and system functions. In advanced approaches, the encryption of data transmitted between IoT devices and centralized systems protects it from interception and unauthorized access. Network security is considered a severe problem in maritime IoT systems. Deploying firewalls to protect IoT networks from unauthorized access, cyber threats, the intrusion detection systems become a regular activity for potential security breaches to monitor the network traffic for suspicious activities. As the underwater industry continues to embrace IoT, ongoing vigilance and adaptation to emerging threats will be crucial. By adopting a proactive and layered security approach, the organizations can ensure the

resilience and security of their IoT systems, ultimately contributing to safer and more efficient maritime operations.

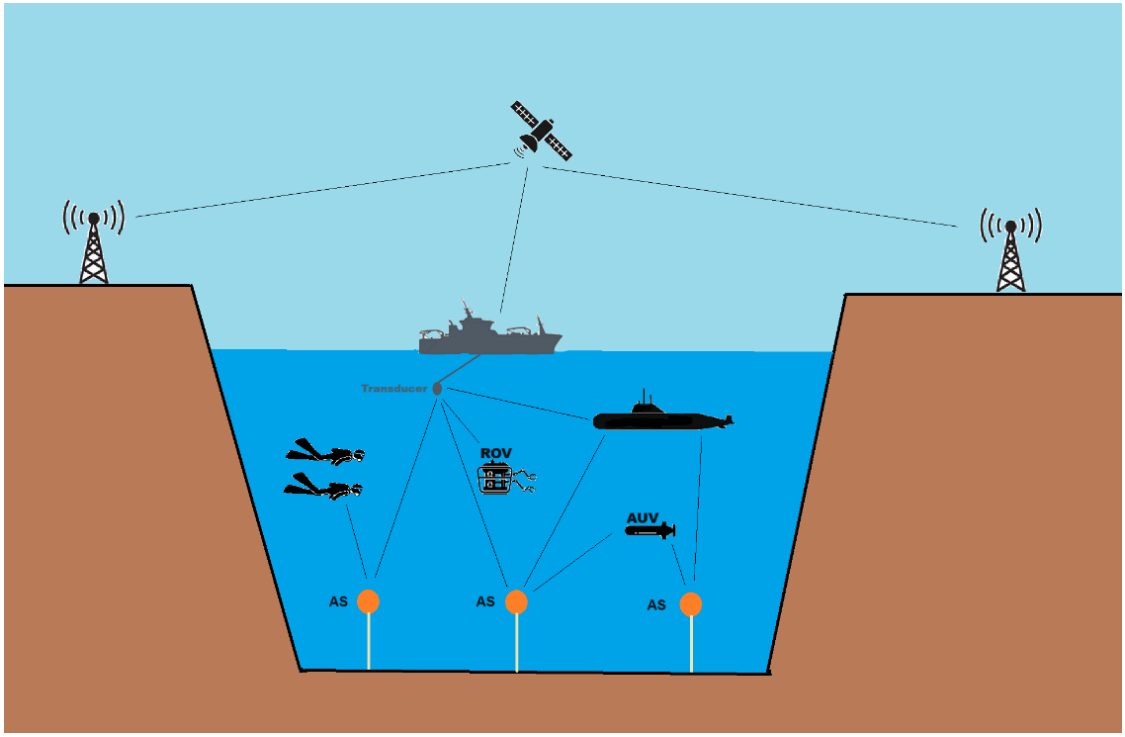


Figure 1. Illustration of marine and underwater communication through antennas, satellites and acoustic sensors (AS). ROV: Remote Operating Vehicle, AUV: Autonomous Underwater Vehicle.

Signal steganography has become a crucial technique in securing communications in IoT applications (Sharda & Budhiraja, 2013; Setiadi et al., 2023). In maritime and underwater systems, where secure and covert communication is critical due to operational and environmental constraints, steganography offers an important technique. Underwater communication systems face unique challenges due to the complexity of the environment, including high noise levels, limited bandwidth, and the need for robust data protection. The signal steganography helps address these challenges by embedding hidden information within communication signals. The acoustic steganography is particularly relevant in underwater systems where traditional radio frequency (RF) communication is impractical due to the attenuation of RF signals in water. The acoustic communication is commonly used for underwater data transmission, and steganography can be applied to these acoustic signals. Underwater environments can cause distortion and attenuation of acoustic signals, which may affect the integrity of the embedded data. The limited bandwidth available for acoustic communication can restrict the amount of data that can be hidden. RF Steganography is used in maritime environments where RF communication is feasible, such as in satellite communications and surface vessel communications. In these systems, steganography can be applied to various types of RF signals modifying the modulation scheme, such as phase-shift keying or amplitude modulation, to embed secret data (Khan et al., 2021; Subramanian et al., 2021). Slight adjustments in the modulation parameters can encode additional information. Data can be hidden within the shape of transmitted RF pulses. By altering the pulse characteristics subtly, hidden messages can be embedded without significant impact on the signal's primary function. RF communication generally supports higher data rates compared to acoustic systems, enabling the embedding of larger amounts of data. RF signals can be transmitted over longer distances compared to acoustic signals, providing greater flexibility for maritime applications.

Even if the steganography and the cryptography are both crucial techniques in data security, they serve different purposes and offer distinct advantages. While cryptography secures data by making it unreadable without the correct key, the steganography embeds the data within other data. This means that an observer cannot even detect that there is a hidden message, making it less likely to attract attention from potential attackers. Steganography can be used to transmit information within regular,

everyday data such as images, audio files, or text. Since the carrier data appears normal, it avoids drawing suspicion. In contrast, cryptographic methods often result in noticeable patterns that can signal to an observer that a message is being transmitted. The steganography offers a range of methods for embedding data, such as within images, audio files, or even network packets. This versatility allows for the integration of hidden messages into various types of digital content, making it adaptable to different communication scenarios and environments (Fabbri et al., 2018; Djebbar, 2021). While steganography offers several advantages, it also has notable disadvantages when compared to cryptography. Steganography often has limitations on the amount of data that can be effectively embedded within a source message. Furthermore, steganography can be susceptible to steganalysis, which involves techniques used to detect the presence of hidden data (Mishra & Bhanodiya, 2015). Sophisticated tools and methods can sometimes reveal hidden information by analyzing patterns or anomalies in the carrier data, potentially compromising the effectiveness of steganography. Embedding data within a carrier can lead to perceptible changes or degradation in the quality of the source message file, such as an image or audio file. Even small alterations can be detected through careful inspection, which can reveal the presence of hidden information. Cryptography does not inherently affect the quality of the data being encrypted (Mishra & Bhanodiya, 2015; Das & Das, 2016).

Designing and implementing effective steganographic methods can be complex and require careful consideration to avoid detection and maintain data integrity (Subhedar & Mankar, 2014; Tao et al., 2018). The process of embedding and extracting data must be precisely managed to prevent introducing detectable artifacts. In summary, while steganography provides unique benefits in hiding the existence of data, it has limitations compared to cryptography, such as smaller data capacity, vulnerability to detection, and lack of data integrity protection (Wani & Sultan, 2023; Yu et al., 2024). Cryptography offers robust data security with well-defined standards for encryption, key management, and data integrity, making it a complementary approach to steganography for comprehensive data protection (Das & Das, 2016; Khari et al., 2020).

Altaay et al. (2012) provided a comprehensive overview of various image steganography techniques. They reviewed the fundamental concepts and methods used to conceal information within digital images, detailing techniques such as Least Significant Bit (LSB) substitution, pixel value differencing, and frequency domain methods. They emphasized the importance of these techniques in ensuring secure communication by embedding secret data into image files in a way that is imperceptible to the human eye. They discussed the trade-offs between embedding capacity, image quality, and security, offering insights into the practical applications and challenges associated with image-based steganography. Alhaddad et al. (2020) explored the enhancement of secret data detection accuracy in audio steganography, particularly within the context of securing 5G-enabled IoT networks. The study focused on evolutionary algorithms to improve the reliability and precision of hidden data detection embedded within audio files. They discussed various techniques for optimizing the detection process, evaluating their effectiveness in maintaining data security and integrity amidst the high-speed, high-volume data exchange characteristic of 5G networks. Their findings highlight advancements in audio steganography methodologies that can be employed to safeguard confidential information in the evolving landscape of IoT security.

Amjath and Senthooran (2020) focused on steganographic techniques to be employed to obscure sensitive data within IoT communications, thereby improving data confidentiality and integrity. They evaluated various methods of embedding secret information in different types of digital media, such as images and audio, to prevent unauthorized access and eavesdropping. The study highlighted the importance of integrating steganography with IoT systems to address security challenges and ensure secure data transmission in a networked environment with numerous interconnected devices. Bachrach and Shih (2012) provided a comprehensive survey of image steganography and steganalysis within the context of multimedia security. They reviewed various techniques used for embedding secret information within digital images (steganography) and methods for detecting and analyzing such hidden data (steganalysis). The study covered a range of steganographic approaches, including spatial domain methods like Least Significant Bit (LSB) insertion and transform domain techniques such as Discrete Cosine Transform (DCT). They discussed the challenges and advancements in steganalysis, which aims to identify and extract hidden information, thus highlighting the ongoing efforts to enhance both the robustness of steganographic techniques and the effectiveness of detection methods.

Bairagi et al. (2016) presented an efficient steganographic method designed to enhance communication security within critical infrastructures of IoT. They introduced a novel approach for embedding secret information into digital media, specifically targeting the challenges posed by the high-stakes nature of IoT environments. Their approach highlighted the steganographic technique's ability to securely conceal data while maintaining the integrity and performance of IoT systems. Their study emphasized the importance of this method in safeguarding sensitive communications against unauthorized access and attacks, thus contributing to the overall security and resilience of IoT networks. (Das & Das, 2016) explored the integration of cryptography and steganography techniques to enhance secure data transfer in IoT environments. They proposed a hybrid approach that combines cryptographic methods for encrypting data with steganographic techniques for hiding the encrypted information within digital media. This dual-layered security strategy aimed to address the vulnerabilities of IoT systems by ensuring that data is both encrypted and concealed, thereby improving confidentiality and reducing the risk of unauthorized access or interception. They discussed the effectiveness of this combined approach in securing data transmission across IoT networks.

Djebbar (2021) presented a practical framework for enhancing the security of IoT data through the application of steganography. They discussed how steganographic techniques can be employed to conceal sensitive information within IoT communications, thereby providing an additional layer of security against potential cyber threats. They detailed a practical implementation approach, including methods for embedding data within various types of media and data streams used in IoT systems. The study highlighted the advantages of using steganography to obscure the presence of sensitive information, complementing traditional security measures like encryption. Khari et al. (2020) explored advanced methods for enhancing data security within IoT environments. They presented a comprehensive approach that integrates both cryptographic and steganographic techniques to protect sensitive data transmitted across IoT networks. The study emphasized the importance of using elliptic curve cryptography for robust public key authentication and confidentiality, alongside steganography to obscure data within otherwise benign communication channels.

Hassaballah et al. (2021) introduced a novel image steganography method on embedding sensitive data within digital images to enhance the security of IoT communications. By leveraging advanced steganographic techniques, the approach aimed to provide an additional layer of security against unauthorized access and data breaches in industrial environments. Their study demonstrated how the method effectively conceals information within image files while maintaining data integrity and operational efficiency. Jia-jia et al. (2018) explored bio-inspired steganography techniques designed to enhance the security of underwater acoustic communications. They proposed innovative steganographic methods inspired by biological systems to embed secret information within acoustic signals used in underwater communication. These bio-inspired techniques aimed to improve the robustness and stealth of data concealment, making it more difficult for potential eavesdroppers to detect hidden messages. Their study highlighted the advantages of using nature-inspired approaches to achieve secure and efficient underwater communication, addressing the unique challenges of the aquatic environment, such as signal degradation and noise. Pradhan et al. (2016) provided an in-depth evaluation of performance parameters for various image steganography techniques. They analyzed different steganographic methods by assessing key performance indicators such as embedding capacity, image quality, and robustness against detection and attacks. They emphasized the importance of these parameters in determining the effectiveness of steganographic techniques for securely hiding data within images while maintaining visual fidelity.

3. Material and Methods

The study starts with the acquisition of visual data. The underwater data steganographic encoding and decoding consists of two layers of image and audio signal processing as introduced in Figure 2 where the flowchart illustrates the proposed mechanism. The chaotic map is generated through Arnold’s cat algorithm. Thus, the image steganography step is achieved to generate relevant sound data. However, the media is not suitable for underwater communication since it is not an acoustic wave. Inverse MEL transformation is applied to generate sound file from encoded image file. The encoded data is sent to the receiver. When the receiver gets the message, the sound is transformed to shuffled

image. Finally, the original image is reconstructed with the inverse Arnold's cat algorithm. The flowchart of the study is given in Figure 2.

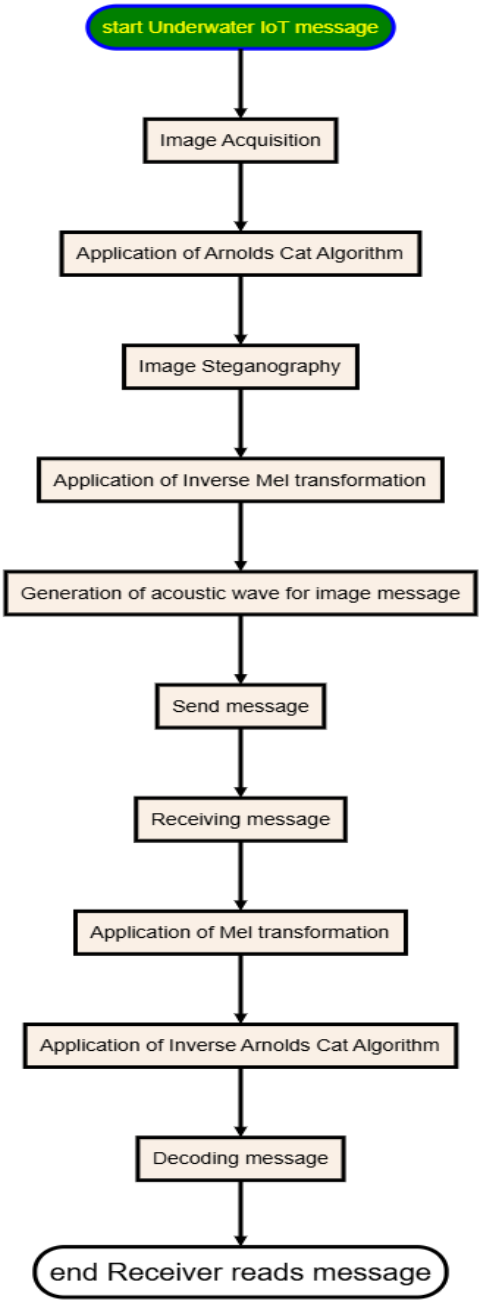


Figure 2. Flowchart of the proposed approach.

In this study, two different image datasets were chosen to perform image to acoustic wave transformation using steganography. The EUVP (Enhancing Underwater Visual Perception) dataset is a specialized collection of underwater imagery designed to advance research and development in underwater visual perception and computer vision (Islam et al., 2020). The dataset includes high-resolution underwater images captured in various environments and conditions, such as natural marine settings and artificial underwater structures. Images are annotated with labels for various objects and features, including marine life, coral reefs, and underwater equipment. The dataset covers a wide range of underwater conditions, including different lighting scenarios and depths. This variety helps in developing robust algorithms that can handle diverse real-world scenarios. It encompasses various types of underwater scenes, from shallow coastal waters to the deep-sea environments, providing a broad

spectrum of visual contexts. The dataset is used for developing and evaluating algorithms related to object detection, segmentation, and tracking in underwater environments. It focused on improving image quality and visibility in challenging underwater conditions, such as addressing issues with color distortion and low contrast. The underwater_imagenet dataset, introduced by Fabbri et al. (2018) is a specialized dataset designed to address challenges in underwater imagery enhancement. The dataset comprises a large collection of underwater images, which are derived from the ImageNet dataset but adapted to underwater conditions. This includes a variety of underwater scenes featuring marine life, objects, and environments. The dataset is specifically created to train and evaluate Generative Adversarial Networks (GANs) for improving underwater image quality. It focuses on enhancing features such as color correction, contrast, and overall clarity, which are often degraded due to the underwater environment. The images in the dataset are processed to simulate realistic underwater distortions, such as color fading and blur, which allows GAN models to learn how to generate high-quality images from degraded inputs. In a nutshell, the underwater_imagenet dataset provides a crucial resource for advancing underwater image processing through GANs, addressing specific challenges related to image quality and visual clarity in aquatic settings. 100 color JPEG images from each dataset were chosen as input messages in this study. 200 images have a spatial resolution of 256 x 256 pixels. The experiments were evaluated through mean images.

Arnold's cat map is a chaotic transformation used to scramble images, enhancing data security through mathematical manipulation. The process begins by representing an image as a matrix I with pixel values, where each pixel's position is denoted by coordinates (x, y) in the matrix. The Arnold's cat map applies the transformation defined by the matrix multiplication as follows;

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \tag{1}$$

(x', y') are the new coordinates of the pixel after transformation, and N is the size of the image matrix. This matrix multiplication results in a chaotic reorganization of the pixel positions. By repeatedly applying the transformation, the image undergoes multiple iterations, with each application scrambling the pixel positions further. The image then appears as random noise due to the chaotic nature of the transformation. In order to recover the original image, the inverse of Arnold's cat map is applied, given by;

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix} \tag{2}$$

This reverse procedure reconstructs the original image from the scrambled image, revealing the original content. Arnold's cat map's chaotic transformation effectively transforms the original image into a chaotic map, making it secure against unauthorized access.

In audio processing, a Mel spectrogram is a powerful tool for analyzing and visualizing the frequency content of an audio signal, particularly for tasks like speech recognition and audio classification. It provides a time-frequency representation of the signal, but with a frequency scale that is more aligned with human auditory perception. The first step in generating a Mel spectrogram is to compute the Short-Time Fourier Transform (STFT) of the audio signal. This involves dividing the signal into overlapping frames and applying a Fourier Transform to each frame. For an audio signal x(t), the STFT is given by;

$$X(t,f) = \int_{-\infty}^{\infty} x(\tau)\omega(\tau - t)e^{-j2\pi f\tau}d\tau \tag{3}$$

where $\omega(\tau - t)$ is a window function centered at time t, and f is the frequency variable. The magnitude spectrogram is obtained by taking the magnitude of the STFT result:

$$|X(t,f)| = \sqrt{Re[X(t,f)]^2 + Im[X(t,f]^2} \tag{4}$$

This gives us a time-frequency representation where each point indicates the amplitude of a particular frequency at a given time. The Mel scale is a perceptual scale of pitches that approximates human hearing. The Mel filter bank is used to map the frequency axis of the magnitude spectrogram to the Mel scale. The Mel scale is defined as follows;

$$Mel(f) = 2595log_{10}(1 + \frac{f}{700}) \quad (5)$$

where f is the frequency in Hertz.

In order to convert the frequency axis to the Mel scale, the magnitude spectrogram is multiplied by a set of triangular filters that cover the Mel frequency bands. The Mel-filtered spectrogram can be computed as:

$$S_m(t,m) = \sum_f |X(t,f)| \,.\, H_m(f) \quad (6)$$

where Hm(f) represents the Mel filter bank, which is a set of triangular filters spaced according to the Mel scale. The Mel spectrogram is converted to a logarithmic scale to better represent the perceptual differences in loudness. This is done by applying a logarithmic function;

$$LogMel(t,m) = \log\,(1 + S_m(t,m)) \quad (7)$$

This step compresses the dynamic range of the spectrogram, making it more suitable for machine learning applications. A Mel spectrogram thus combines the STFT for time-frequency analysis with the Mel scale for frequency scaling and optional logarithmic compression. The result is a time-frequency representation that better matches human auditory perception, making it an effective feature for various speech processing tasks.

Finally, Chroma feature extraction was integrated to our method to compare acoustic performance between pitch classes in acoustic wave transmission. Chroma computation using is a powerful tool in the analysis of speech processing, offering valuable insights into the harmonic structure of audio signals. This technique enables the extraction of tonal characteristics from speech by analyzing the chroma features. Briefly, it captures the intensity distribution across the twelve pitch classes of the chromatic scale. This is particularly useful in tasks such as pitch tracking, speaker identification, and emotion recognition, where understanding the underlying musicality or tonal variations in speech can enhance the accuracy of these processes.

During the design and the implementation, Python 3.11 programming language was used with OpenCV, Librosa, NumPy and Matplotlib libraries.

4. Results

Arnold's cat map takes a structured initial image and, after several iterations, transforms it into a highly scrambled form. An underwater image with a clear pattern becomes increasingly distorted with each application of the map. This behavior demonstrates the concept of chaos, where even simple deterministic rules can lead to highly unpredictable results. The transformation effectively randomizes the image, which is a key characteristic of chaotic systems.

Figure 3 presents the preprocessed images where 200 images were normalized in RGB channels and grayscale images were created. Even if RGB steganography are in use for IoT systems, grayscale images were preferred due to image to sound conversion to decrease data loss and bandwidth capacity in underwater environments. Figure 4 shows the histogram distribution for grayscale images. Histograms become important to ensure high quality data transmission and measure data loss during image-audio encoding. Three different experiments were evaluated to compare the efficiency of the proposed setup. Figure 5 illustrates the application of 10 times, 50 times and 500 times Arnold cat mapping on mean images. The map's periodicity is crucial for applications like image encryption. It means that the scrambling is not permanent; the original image can be recovered by applying the inverse

transformation. This feature is valuable in scenarios given in Figure 5 where reversible scrambling is required. The chaotic map essentially performs a shearing and stretching transformation on the image. Over iterations, this transformation can cause the image to stretch and fold in complex ways, leading to its eventual scrambling. The nature of the transformation reveals how spatial structures can evolve under linear mappings, giving insight into how complex patterns and textures can emerge from simple rules. When Arnold's cat map is applied to the image, the histogram distribution undergoes significant changes. After several iterations, the histogram of the scrambled image often becomes approximately uniform. This uniformity indicates that the pixel values are spread more evenly across the entire range of possible intensities. The map effectively redistributes pixel values, leading to a more uniform histogram. This characteristic is consistent with the behavior of chaotic systems, where initial structures become mixed and spread out over time.

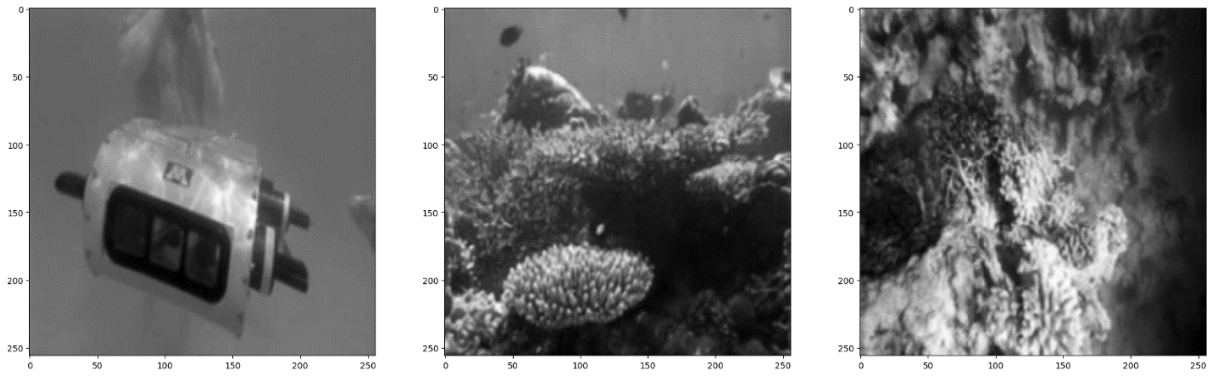


Figure 3. Preprocessed images.

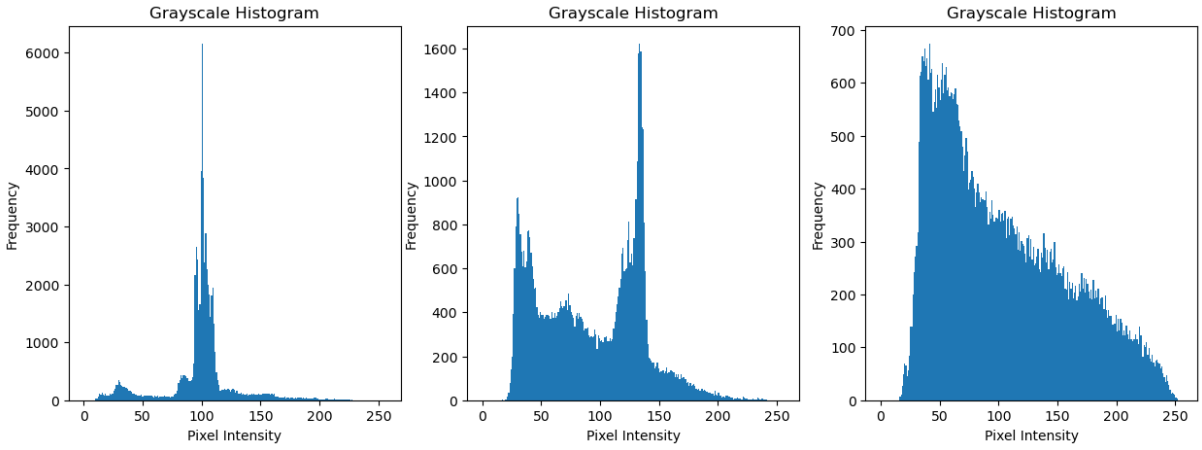


Figure 4. Histograms of preprocessed images.

The inverse Mel transformation provides an approximation of the original STFT magnitude spectrum from Mel features. While it can effectively reconstruct many aspects of the signal, there may be some loss of detail due to the compression and scaling performed by the Mel filter bank. The reconstruction quality depends on the accuracy of the inverse transformation and how well the Mel features capture the original frequency content. Some high-frequency details may be lost or approximated, especially if the Mel filters are coarse. The Mel transformation is inherently lossy because it maps the frequency spectrum to a lower-dimensional Mel scale. This process reduces the resolution of frequency information, which can impact the accuracy of the inverse Mel transformation. As a result, the reconstructed spectrum from Mel features may not perfectly match the original STFT magnitude spectrum, and some fine-grained frequency details may be lost. The inverse Mel transformation is useful in applications where approximate reconstruction of the audio signal is acceptable. This includes tasks such as speech synthesis, where the Mel features are used to generate new audio signals, and audio

enhancement, where the goal is to improve the quality of audio based on Mel features. Figure 6 presents the comparison of three scenarios and the loss of reconstructed mean images with STFT as residual errors in dB.

In underwater communication, the inverse Mel transformation can be used to create synthetic or enhanced audio signals that approximate the characteristics of the original signal. However, it is important to consider the trade-offs between reconstruction quality and the level of detail retained. The inverse Mel transformation involves mapping Mel-scaled features back to the original frequency domain using a procedure that approximates the inverse of the Mel filter bank. This often requires careful handling of the Mel scale and its associated parameters. The mathematical relationship between the Mel and frequency domains is complex, and the inverse transformation must account for the non-linear mapping between these domains to achieve accurate reconstruction.

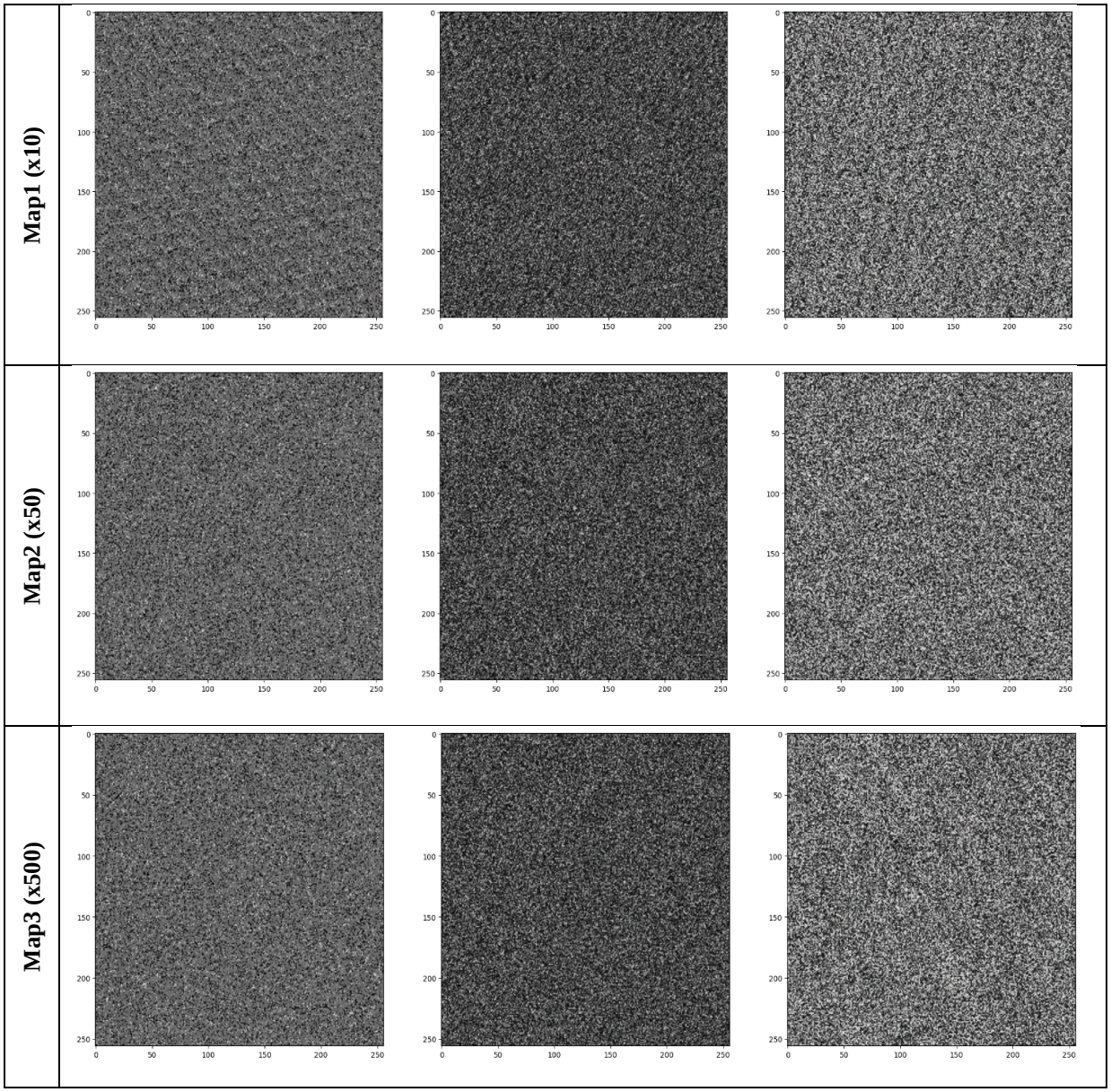


Figure 5. Application of three different Arnold cat maps on preprocessed images.

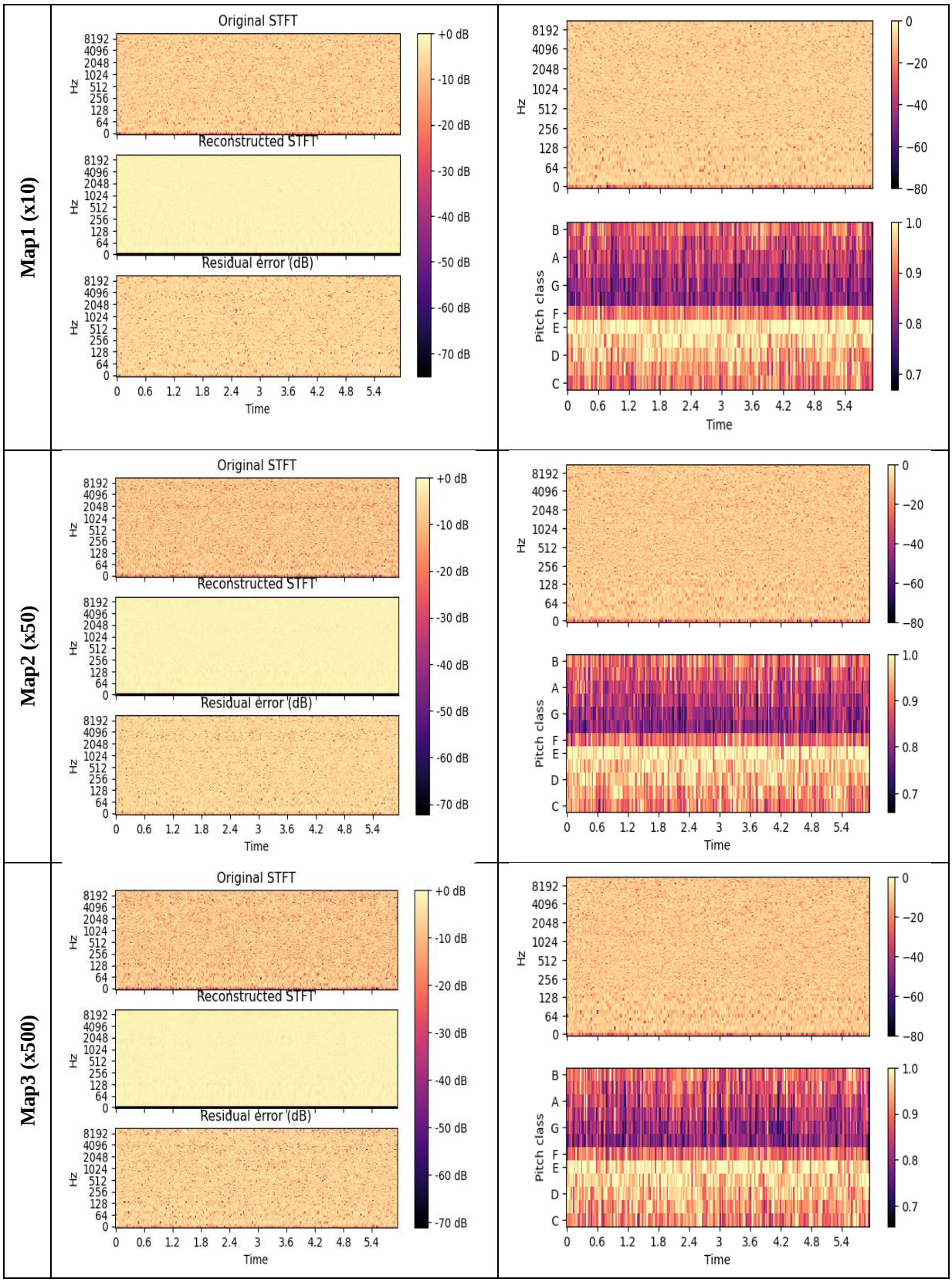


Figure 6. Comparison of three Arnold cat map techniques on reconstructed acoustic signals and chroma features through mean images.

5. Discussion and Conclusion

After a few iterations, the histogram of the scrambled image tends to approach a uniform distribution. This means that pixel values are distributed more evenly, as opposed to clustering around certain values. Uniform histograms are a sign that the map has successfully scrambled the image by removing any initial patterns or structures and achieving a high degree of randomness. This property is desirable in cryptographic applications where predictability needs to be minimized. The rate at which the histogram converges to uniformity depends on the number of iterations. Typically, after a sufficient number of iterations the histogram distribution of the scrambled image will closely approximate a uniform distribution. This convergence indicates that the map's effect on the pixel values is thorough, spreading out pixel intensities and reducing correlation between neighboring pixels. Given that Arnold's cat map is periodic, the histogram of the image will eventually return to its original distribution after a certain number of iterations. This periodicity implies that while the histogram becomes uniform during the scrambling process; it will revert to the initial histogram after completing one full cycle of iterations. This property is useful for applications where the ability to return to the original image is required.

The STFT provides a time-frequency representation of a signal by dividing it into overlapping segments, applying the Fourier transform to each segment, and then analyzing the resulting frequency components over time. The Mel transformation maps the frequency axis to the Mel scale, which is designed to approximate the frequency resolution of human hearing. This transformation is typically performed using a Mel filter bank applied to the magnitude spectrum obtained from the STFT. The inverse Mel transformation aims to approximate the original frequency-domain representation from Mel-scaled features. It involves mapping the Mel features back to the original frequency domain.

The Mel scale reduces frequency resolution, especially at higher frequencies. The Mel filter bank groups frequencies into broader bands, which means fine-grained frequency information is lost. When performing the inverse Mel transformation, the loss of detailed frequency information can result in discrepancies between the reconstructed spectrum and the original STFT magnitude spectrum. The Mel filter bank approximates the human auditory system’s frequency resolution and maps the continuous frequency spectrum to discrete Mel bands. This approximation introduces quantization errors. The inverse transformation must approximate the original frequency content based on these quantized Mel features, leading to errors in the reconstructed spectrum. The Mel scale involves a non-linear mapping of frequencies, which complicates the inverse transformation process. The inverse operation approximates the mapping rather than perfectly reversing it. The complexity of reversing a non-linear transformation can result in residual errors, as the process may not perfectly reconstruct the original frequency content. The design of the Mel filter bank, including the number and width of filters, affects the fidelity of the transformation. A limited number of filters or suboptimal filter design can introduce errors. The resolution and characteristics of the Mel filter bank influence the accuracy of the inverse transformation. If the filter bank does not capture the signal’s frequency content adequately, the reconstructed spectrum will be inaccurate. During the inverse Mel transformation, certain artifacts may appear due to the approximation process and the inherent limitations of the Mel scale.

Image steganography presents both significant opportunities and notable challenges in the context of IoT systems for underwater applications. This technique, which involves embedding secret data within digital images, offers a novel approach to securing communications in an environment where traditional methods face severe constraints. The primary advantage of using image steganography in underwater IoT is its ability to provide an additional layer of security by concealing sensitive information within seemingly safe images. This can greatly reduce the risk of interception and unauthorized access, which is particularly important in underwater environments where communication channels are vulnerable to eavesdropping and interference.

However, image steganography in underwater applications is not without its limitations. The constrained bandwidth and signal quality in underwater environments can restrict the amount of data that can be effectively hidden within images. Additionally, implementing robust steganographic techniques requires careful design to avoid detection by sophisticated steganalysis methods, which can undermine the security benefits. The complexity of integrating steganographic methods into existing underwater IoT systems also presents a challenge, as it demands a balance between security and system performance. As promising application areas in underwater IoT systems, image steganography can be used to secure the transmission of data collected by underwater sensors, ensuring that sensitive research

information in marine biology and environmental monitoring. Moreover it can enhance communication between underwater vehicles and surface stations, safeguarding mission-critical data in defense and security. For underwater exploration and navigation, steganography can facilitate secure data transfer between exploration robots and surface control stations. Furthermore, during emergency response and disaster management, steganographic techniques can ensure secure communication among rescue teams and underwater sensors, improving coordination and security.

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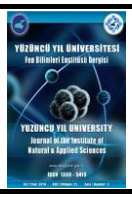
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Research Article

Improving Residential Marketing Campaigns via Customer Data Clustering

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Abstract: As the construction industry struggles to develop effective marketing plans for residential projects, using rich datasets to understand customer demand helps builders of residential complexes with complex use cases. Decision-makers often struggle to understand big data. Solving this problem begins with relevant data being mined and collected. Multi-criteria decision-making (MCDM) models are used to rank the data or alternative options according to their importance to decision-makers. The weights of the criteria, obtained according to their importance, are essential to reveal the relative value of different criteria. To understand and analyze big data, cluster analysis within the data mining discipline is used to segment and score data. This analysis is an effective tool for determining marketing strategies and understanding customer behavior. This study was conducted to determine the marketing strategy appropriate for customer segmentation. For this, the Rank Order Centroid (ROC) criterion weight method gives weights to the criteria according to their relative importance. The K-means cluster analysis algorithm uses the values obtained from the ROC method. By combining ROC and K-means methods, this study will contribute to extracting information from large data sets and simplifying decision-making processes in the residential sector. As a result of the study, customers were divided into groups, and it was concluded that the groups with the highest scores should be prioritized in marketing strategies.

Keywords: Clustering, Data mining, Marketing, Multicriteria decision-making, Resident

Müşteri Verilerinin Kümelenmesi Yoluyla Konut Pazarlama Kampanyalarının İyileştirilmesi

Öz: İnşaat sektörü, konut projeleri için etkili pazarlama planları geliştirmekle uğraşırken, müşteri taleplerini anlamak için zengin veri kümelerini kullanmak, karmaşık kullanım alanlarına sahip konut komplekslerinin inşa edicilerine yardımcı olmaktadır. Karar vericiler genellikle büyük verileri anlama konusunda zorluklarla karşılaşırlar. Bu sorunu çözmek, ilgili verilerin madenciliği ve toplanmasıyla başlar. Çok kriterli karar verme (MCDM) modelleri, verileri veya alternatif seçenekleri karar vericiler için önemlerine göre sıralamak için kullanılır. Önem derecelerine göre elde edilen kriterlerin ağırlıkları, farklı kriterlerin göreceli değerini ortaya çıkarmak için esastır. Büyük veriyi anlamak ve analiz etmek için, veri madenciliği disiplini içinde kümeleme analizi kullanılır; bu analiz, pazarlama stratejilerini belirleme ve müşteri davranışını anlama konusunda etkili bir araçtır. Bu çalışma, müşteri segmentasyonu için uygun pazarlama stratejisini belirlemek amacıyla yapılmıştır. Bunun için Rank Order Centroid (ROC) kriter ağırlığı yöntemi kriterlere göreceli önemlerine göre ağırlıklar vermektedir. K-ortalama kümeleme analizi algoritması ROC yönteminden elde edilen değerleri kullanır. Bu çalışma, ROC ve K-ortalama metotlarını bir arada kullanarak, büyük veri setlerinden bilgi çıkarılmasına ve konut sektöründe karar alma süreçlerinin basitleştirilmesine katkı sağlayacaktır. Çalışma sonucunda müşteriler gruplara ayrılmış ve en yüksek puanı alan grupların pazarlama stratejilerinde önceliklendirilmesi gerektiği sonucuna varılmıştır.

Anahtar Kelimeler: Çok kriterli karar verme, Konut, Kümeleme, Pazarlama, Veri madenciliği

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1. Introduction

In the business world and the construction industry, creating the right marketing strategies is not only important for the success of housing projects but also necessary to understand and fully meet customer needs. In this context, having rich and diverse information, such as bank customers' data, can be a great advantage in building mixed-use residential complexes.

With the growth of civilization and the development of technology, housing construction and basic consumer goods keep pace with this and increase the quality of living space with additional features. The housing need arising from rapid population growth, structural changes in agriculture, social and cultural development, and migration from rural to urban areas has made the housing sector particularly useful (Tacoli et al., 2015). In the business world and the construction industry, decision-makers often face difficulties understanding big data. Solving this problem begins with relevant data mined and collected. Data mining is a discipline that aims to extract meaningful information from large data sets. This process includes collecting, cleaning, analyzing, and finalizing data. Data mining helps businesses, organizations, and researchers better understand data and make more informed decisions. For this reason, data mining has become a useful research and business field today (Bilici & Özdemir, 2022). After data is collected, decision-makers may encounter differences in the weights of the collected data. In this case, Multicriteria Decision-Making (MCDM) methods come into play to resolve these weight differences.

Multiple criteria are included in many real-world decision-making situations. The criteria weights play a critical role in determining the relative importance of various criteria. In this way, information is given to decision-makers regarding which factors, when assessing the data, they should give more weight to. One of the MCDM methods is Rank Order Centroid (ROC) weight. This method is a straightforward way to assign weights to criteria based on their relative relevance (Roszkowska, 2013). To understand and analyze big data, cluster analysis within the data mining discipline is used to segment and score data. This analysis is a useful tool for understanding the structure and relationships in data sets, and one of the most widely used clustering algorithms is the K-means clustering algorithm (Pande et al., 2012). K-means cluster analysis divides the data into several clusters and calculates the centroids that define these clusters. Data are assigned to relevant clusters, considering their distance to these centers. This way, data with similar traits are grouped in one cluster to make different clusters. K-means analysis helps us better understand patterns and clustering in the dataset (Singh et al., 2011). K-means clustering analysis, which is used especially in marketing strategy, geographical analysis, and customer segmentation, plays a useful role in data mining projects. This clustering analysis simplifies the decision-making process by reducing the complexity of large data sets and providing valuable information to businesses (Ali & Kadhum, 2017).

This study uses the ROC method to give criteria weights according to their relative relevance using the Microsoft Excel program and the K-means algorithm for cluster analysis using the IBM SPSS Statistics program.

The main objective of this study is to develop a methodology that will assist decision-makers in the construction industry in the more effective analysis of large data sets and the subsequent development of marketing strategies. The following section presents a summary of the contributions made by this study.

1) Presents a novel approach that combines Multi-Criteria Decision-Making (MCDM) with data mining techniques, with the aim of assisting decision-makers in the construction industry in the analysis of large datasets and the formulation of marketing strategies.

2) Illustrates the practical integration of the ROC (Rank Order Centroid) method for the weighting of criteria and K-means clustering for the segmentation of customers, thereby enhancing the effectiveness of marketing strategies.

3) Demonstrates how the ROC method can enhance decision-making by prioritising pivotal factors in the marketing processes of housing projects, thereby offering more transparent guidance to stakeholders.

4) Demonstrates the efficacy of K-means clustering for customer segmentation, thereby facilitating the development of more targeted and efficient marketing strategies within the construction industry.

2. Literature Review

Cluster analysis techniques are valuable in marketing research, particularly for market segmentation. These techniques have been successfully applied in the marketing sector, particularly in data mining, where it has been used to segment markets or segment customers and predict future trends (Chiang, 2011; Tleis et al., 2017; Maciejewski et al., 2019; Kuo et al., 2020). For instance, Heryati and Herdiansyah used student data and were divided into five groups using the K-means clustering method according to regional origin and study programs; these groups were formed based on different promotional strategies (Heryati & Herdiansyah, 2020). Hutagalung used the K-means clustering method to determine the market segmentation of Indonesia Digital Home (Indihome), a leading digital fiber optic service package (Hutagalung et al., 2022). In customer segmentation, it has been found that K-means clustering is the most efficient algorithm (Maulina et al., 2019). Bai used the Fuzzy C-means algorithm; this study states that this methodology is applied to managerial insight and decision-making processes. Using a two-stage technique, companies were first divided into four clusters and then ranked within these clusters using MCDM (Bai et al., 2014).

The importance of criteria weighting in marketing decision-making is highlighted in several studies. Gürbüz and Hung both emphasize the use of MCDM methods, with Gürbüz specifically using a fuzzy metric distance and analytic hierarchy process (AHP) hybrid method (Hung et al., 2012; Gürbüz et al., 2014). Singh and Pant further review three weighing methods, highlighting their function in establishing the relative weight of the criteria in MCDM (Singh & Pant, 2021). These studies collectively underscore the usefulness of criteria weighting in marketing decision-making. The ROC method, a popular model for criteria weight estimation in MCDM in marketing, has been the focus of many studies. Pandiangan, in determining the location of minimarkets, the ROC method allows for obtaining an objective and precise result by focusing on various criteria (Pandiangan et al., 2023). Lastly, Wijaya used the ROC method to determine the most appropriate online sales platform. It evaluated the relationships and weights, determined the min and max values, and analyzed the effect of the criterion weights on the result (Wijaya et al., 2022). Studies underscore the versatility and effectiveness of the ROC method in various decision-making and marketing applications.

Table 1 lists the articles examined during the literature review and the methods they used. The table was made so readers could see the resolved problems and methods applied to this study and other studies.

The topic has attracted more attention recently than in past years, and the literature review conducted under the direction of the relevant subject and its subheadings has revealed techniques that could be applied to many sectors. This study aims to make clustering methods and criteria weighting methods accessible to a broader audience and serve as a resource for analyzing customer data and determining the right marketing strategy. There are a limited number of studies on integrating data clustering techniques, particularly the K-means algorithm, with Multi-Criteria Decision Making (MCDM) methods for developing marketing strategies. Existing studies address these methods separately but do not focus enough on the deeper and more precise marketing insights that can be gained by using these two methods together. This study, which determines criteria weights using the ROC method and performs customer segmentation with the K-means algorithm, aims to fill this gap. The integration of these two methods contributes to the development of more targeted and effective marketing strategies through the analysis of large data sets.

Table 1. Methods used in literature

Study	Problem	Criteria Weight Methods					Cluster Analysis Methods			
		ROC	AHP	ANP	BWM	DANP	K-means	Ward's	K-medoids	Fuzzy C-means
(Tleis et al., 2017)	Market segmentation						✓			
(Maciejewski et al., 2019)	Customer segmentation							✓		
(Kuo et al., 2020)	Market segmentation									✓
(Chiang, 2011)	Market segmentation							✓		
(Heryati & Herdiansyah, 2020)	Determine the promotion strategy						✓			
(Hutagalung et al., 2022)	Market segmentation								✓	
(Maulina et al., 2019)	Customer segmentation						✓			✓
(Bai et al., 2014)	Evaluating the performance of organizations									✓
(Gürbüz et al., 2014)	Marketing strategies and marketing decision processes analysis		✓							
(Hung et al., 2012)	Evaluating performances and improving professional services					✓				
(Singh & Pant, 2021)	The performance of weighing methods in MCDM		✓	✓	✓					
(Pandiangan et al., 2023)	Determination of mini market location	✓								
(Wijaya et al., 2022)	Selection of online sales platforms	✓								
This study	Customer segmentation	✓					✓			

3. Material and Methods

In this section, the methods used in the study are explained. The dataset used is introduced and how the methods are applied is explained step by step.

3.1. Marketing strategies

Developing a sound marketing strategy is beneficial to succeed in today's competitive business environment. Marketing strategies are plans and tactics that enable a product or service to reach its target audience, increase demand, and achieve long-term business goals. A business's marketing approach is key in determining its future, expanding its customer base, differentiating from competitors, and ensuring profitability.

There are numerous things to consider when developing a marketing strategy. The first thing to do is to determine who our target market is. Understanding who our customers are and how we can meet their needs and preferences is the foundation of a successful marketing strategy. Market research, customer feedback, and data analysis are useful (Rohmawati & Winata, 2021). The next action is to make a unique offer. Consider how to differentiate our business's products or services from competitors. We must offer our customers a value proposition explaining why they should choose us (Phillips-Wren et al., 2016). A marketing strategy can include many different tactics, including communication. Advertising, social media, content marketing, promotions, events, and many other tools can help our business engage with our target audience. When deciding which communication channels and tactics to use, we must consider where our target audience is and their preferred communication methods (Bajpai et al., 2012). Marketing strategies should be designed not only for short-term benefits but also for long-term growth. We should consider our business's future growth potential and adjust our marketing plan according to these goals. Finally, we should regularly review and adjust our marketing strategies to adapt to customer needs and market conditions (Wirtz & Daiser, 2018).

In addition to increasing a company's profits, marketing strategies also increase customer satisfaction, increase brand value, and provide a competitive advantage. Therefore, creating and implementing marketing strategies for businesses is extremely useful.

3.2. Data mining

The development of technology produces copious amounts of data, making data mining even more useful. Data mining aims to obtain meaningful information from copious amounts of data by combining statistics, artificial intelligence, and computer science. Contribute to strategic decision-making processes in business and science by identifying patterns in data using analytical techniques such as classification, regression, and clustering. Data mining is used in many fields, such as finance, health, and marketing (Madni et al., 2017).

3.2.1. Concept of data mining

Data mining is a procedure that combines fields such as statistics, mathematics, artificial intelligence, and computer science to find patterns, information, and relationships in big data sets (Sharma, 2014). In this field, various techniques are used to analyze complex and large data sets where information is inaccessible. Data mining analyzes data for purposes such as extracting information, making predictions, classifying, clustering, and identifying patterns of relationships. As such, it is used in many application areas in the business world, such as strategic decision-making, understanding customer behavior, and optimizing marketing strategies (Guo & Qin, 2017). Data mining is also a useful research area for developing artificial intelligence and machine learning. The stages of data mining are as follows (Wu et al., 2021):

1. Identification of the problem and definition of the goal: The aims and objectives of the project are determined.
2. Data Collection: Required data is collected from various sources.
3. Data preprocessing: Data is organized, and missing information is completed.

4. Data Discovery and Exploratory Analysis: Patterns and relationships are discovered within a data set.
5. Modeling: Create learning algorithms or statistical models.
6. Evaluation: Evaluate the created model using test data.
7. Deployment: Success models are integrated into business processes.
8. Monitoring and Maintenance: Model performance is monitored, updated, or maintained as necessary.

The development of artificial intelligence and machine learning, as well as well-informed decision-making processes, are facilitated by this organized approach to data mining.

3.3. Data mining methods

Data mining techniques refer to techniques and methods used to extract patterns from copious amounts of data and obtain meaningful information. These techniques can be applied to various fields, such as classification, regression, clustering, relational analysis, time series analysis, and anomaly detection. Data mining techniques aim to reveal hidden information in data sets by using fields such as mathematics, statistics, machine learning, and artificial intelligence (Papakyriakou & Barbounakis, 2022).

3.3.1. Clustering analysis

Understanding the patterns hidden in data sets is critical for the business and scientific worlds. Cluster analysis combines data points with similar characteristics in a data set to identify homogeneous groups. This analysis method is an excellent tool in data mining and is used in many areas (Zou, 2020).

3.3.1.1. Concept of clustering analysis

Cluster analysis is a statistical technique that divides similar data points in a data set into specific groups, or "clusters." These groups contain data points with similar characteristics. Cluster analysis aims for homogeneity within groups, but heterogeneity between different groups should be maximized (Zou, 2020).

3.3.1.2. Process order of clustering analysis

Cluster analysis typically follows the following sequence of operations (Oyelade et al., 2019):

1. Collecting and preparing data: The first step is to collect the data set for analysis and prepare this data using preprocessing steps. Operations such as filling in missing data, processing outliers, and cleaning unnecessary features are performed at this stage.
2. Feature Selection: Selecting the features to be used for analysis reduces the complexity of the dataset and allows the clustering algorithm to work more efficiently.
3. Data standardization: The data set is standardized to compensate for different scales between features and to obtain values of similar size.
4. Selection of clustering algorithm: The clustering algorithm appropriate to the data set is selected. K-means, Hierarchical clustering, DBSCAN, etc. Appropriate algorithms, such as popular algorithms, are preferred.
5. Determine the ideal number of clusters: Knowing the ideal number of clusters for k-means and similar algorithms is useful.
6. Clustering process: According to the selected algorithm, the data set is divided into clusters. Each cluster contains data points with similar characteristics.
7. Evaluation of the results: Clustering results are visualized and analyzed. At this stage, we must ensure that the clusters created are meaningful and consistent.
8. Applications of business results: The clustering results obtained can be used in various areas, such as optimizing business strategies, segmenting customers, and developing marketing strategies.

This process provides general steps for successfully performing cluster analysis. However, these steps can be changed or adjusted depending on the standard of the data set and the analysis goal.

3.4. Clustering analysis methods

Clustering involves dividing information into a data set and dividing it into groups based on certain proximity criteria. Each group is called a "cluster" (Gülagiz & Sahin, 2017). The methods of clustering analysis are as follows:

3.4.1. Hierarchical clustering methods

Hierarchical clustering best suits small samples (typically n < 250). Researchers can use these methods to identify similarities and decide to merge/split clusters. The methods of hierarchical clustering analysis are as follows (Dabhi & Patel, 2016):

1. Associative/Additive methods:
- Connection techniques: Single, Full, Average connection
- Variance techniques: Ward's method
- Centralization techniques: Median, Centroid
2. Discriminative/Divided methods:
- Split averages
- Automatic interference identification

Hierarchical clustering methods include addition (joining) and division (separation). Aggregation combines similar clustering techniques; partitioning, on the other hand, is based on large clusters representing all data points.

3.4.2. Non-hierarchical clustering methods

When the number of clusters is known, non-hierarchical clustering is employed. The methods of Non-hierarchical clustering analysis are as follows (Gülagiz & Sahin, 2017):

- K-means clustering
- K-medoids clustering
- Partitioning around medoids (PAM)
- Fuzzy C-means (FCM) method

These clustering techniques should be selected based on the specific problem context and data set characteristics. Knowing the number of clusters in advance can increase the accuracy of our analysis and give us more meaningful clustering results.

3.4.2.1. K-means algorithm

K-means analysis is a clustering algorithm that groups data points into a certain number of clusters. This algorithm aims to achieve uniform clustering by assigning data points with similar characteristics in the dataset to the same cluster. Since K-means is a grouping process performed without using labeled data, it falls into the unsupervised learning category (Ali & Kadhum, 2017). Implementation of this algorithm includes the following steps (Singh et al., 2011):

1. Initial estimate of cluster centers: A certain number of K cluster centers are randomly selected.
2. Each data point should be assigned to the closest cluster center: Based on the distance between K cluster centers, each data point is assigned to the closest cluster center.
3. Calculation of new cluster centers: New centers are calculated for each cluster. The cluster's center represents the mean of all the data points.
4. New centers are calculated: The second and third steps are repeated until the cluster's center is fixed. These steps are repeated until the data point is permanently assigned to the last assigned cluster.
5. Evaluation of the results: Clustering results should create meaningful clusters compatible with the determined K number.

This analysis is an effective research method used in many areas, especially data mining and segmentation.

3.5. ROC weight method

Using the rank order centroid (ROC) weigh method is a straightforward way to assign weights to criteria depending on their relative relevance. It is frequently easier for decision-makers to rank criteria than to weigh them. These ranking ranks are the input for this algorithm, which uses them to create weights for each criterion (Tamba et al., 2021). The following are the steps involved in this method (Roszkowska, 2013):

Step 1. All factors are ranked by decision-makers in order of relative relevance, from most to least useful.

Step 2. Equation (1) is employed to calculate the anticipated value of the weights when there are more than two criteria. The formula considers the rank positions of the criteria. For each criterion j, the weight is calculated using the formula:

$$wj(ROC) = \frac{1}{n}\sum_{k=j}^{n}\frac{1}{r_k} \quad (1)$$

Where n is the total number of criteria, r_k represents the rank position of the criteria, and $wj\ (ROC)$ is the weight assigned to the j-th criterion. The criteria weights are as follows: $w_1 \geq w_2 \geq ... \geq w_n$. The total of the criterion weights is 1.

Step 3. The arithmetic mean of the predicted values is calculated to determine the final criterion weights.

In this study, ROC and K-means algorithms were used synthetically. How these two methods are used together is explained with the flow chart in Figure 1.

4. Experimental Studies

On the " UC Irvine Machine Learning Repository" site, there is data related to direct marketing campaigns of a Portuguese banking institution. Telemarketing initiatives depended on calls. Often, multiple contacts with the same customer were required to assess whether to subscribe (yes) or not (no) to the product (term deposit at a bank) (Moro et al., 2014). Based on these data, the weight and importance of the criteria were calculated using the ROC method and the Microsoft Excel program. Then, data analysis was performed, and customers were divided into groups with the K-means clustering algorithm using the IBM SPSS Statistics program. These groups were created to conduct a residential complex marketing campaign. The study aims to analyze customer behavior and divide customers into groups for marketing purposes.

Input Variables, bank customer's data:

1. No: Customer
2. Age: (Numeric)
3. Job: Kind of work (admin., unknown, unemployed, management, housemaid, entrepreneur, student, blue-collar, self-employed, retired, technician, services)
4. Marital: Marital status (married, divorced, single; note: "divorced" denotes a widow or divorce)
5. Education: (Unknown, secondary, primary, tertiary)
6. Default: Possesses defaulted credit (yes, no)
7. Balance: Average annual sum, expressed in euros (numeric)
8. Housing: Possesses a mortgage (yes, no)
9. Loan: Possesses a personal loan (yes, no)
10. Previous: Quantity of connections made both for this client and before this campaign (numeric)
11. Poutcome: The outcome of the previous advertising effort (unknown, other, failure, success)

The original data for the customers are shown in Table 2 before they have been amended.

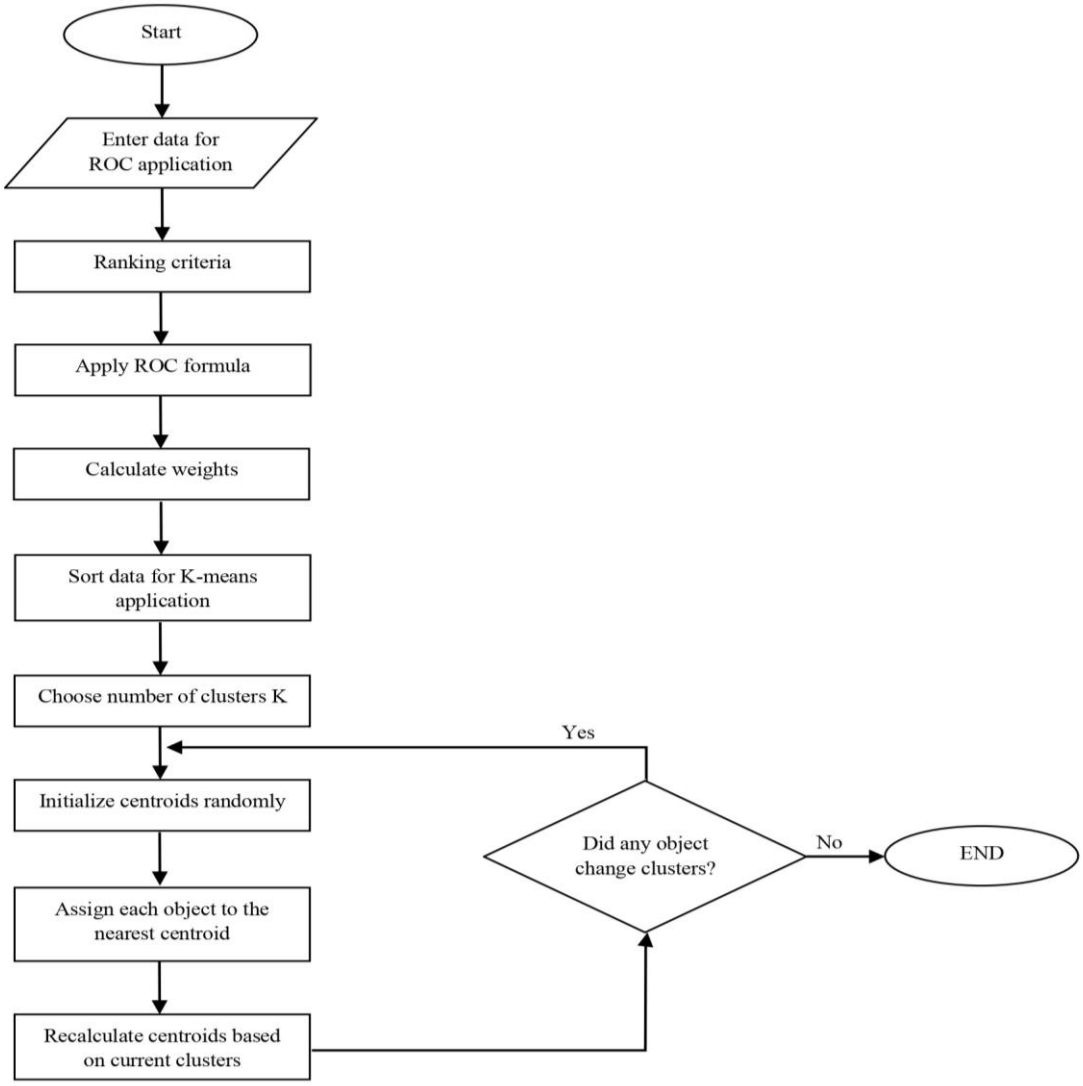


Figure 1. Flow chart of ROC method and K-means algorithm.

Table 2. Original customer data

No	Age	Job	Marital	Education	Default	Balance	Housing	Loan	Previous	Poutcome
1	30	unemployed	married	primary	no	1 787	no	no	0	unknown
2	33	services	married	secondary	no	4 789	yes	yes	4	failure
3	35	management	single	tertiary	no	1 350	yes	no	1	failure
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
4 519	57	technician	married	secondary	no	295	no	no	0	unknown
4 520	28	blue-collar	married	secondary	no	1 137	no	no	3	other
4 521	44	entrepreneur	single	tertiary	no	1 136	yes	yes	7	other

The verbal concepts applied in this analysis were converted into numerical values to begin the analysis. The variable numbers for which this change was made are 6, 8, 9, and 11. “1” was used for “No” and “0” for “Yes” responses. As for the 11th variable, Poutcome, has been calculated as 1 for "success" responses and 0 for other cases. Table 3 shows a list of analyzable customer data.

Table 3. Analyzable customer data

No	Age	Job	Marital	Education	Default	Balance	Housing	Loan	Previous	Poutcome
1	30	unemployed	married	primary	1	1 787	1	1	0	0
2	33	services	married	secondary	1	4 789	0	0	4	0
3	35	management	single	tertiary	1	1 350	0	1	1	0
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
4 519	57	technician	married	secondary	1	295	1	1	0	0
4 520	28	blue-collar	married	secondary	1	1 137	1	1	3	0
4 521	44	entrepreneur	single	tertiary	1	1 136	0	0	7	0
		MAX			1	71 188	1	1	25	1

4.1. ROC method application

The ROC method calculates the importance and weight of the criteria. It can be summarized in three steps:

Step 1. Using the linear normalization matrix, the decision matrix is normalized by considering the benefit or cost-oriented nature of the criterion. All values entered in this study were applied as benefits by dividing each value by the highest value among them. The result of the process is shown in Table 4 below.

Table 4. Normalized decision matrix

No	Age	Job	Marital	Education	Default	Balance	Housing	Loan	Previous	Poutcome
1	30	unemployed	married	primary	1	0.025103	1	1	0	0
2	33	services	married	secondary	1	0.067273	0	0	0.16	0
3	35	management	single	tertiary	1	0.018964	0	1	0.04	0
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
4 519	57	technician	married	secondary	1	0.004144	1	1	0	0
4 520	28	blue-collar	married	secondary	1	0.015972	1	1	0.12	0
4 521	44	entrepreneur	single	tertiary	1	0.015958	0	0	0.28	0

Step 2. In this step, the importance of the criteria was determined by reviewing the literature and choosing the best ranking. The arrangement is as follows. 1. Balance, 2. Poutcome, 3. Default, 4. Housing, 5. Loan, 6. Previous.

The weights are analyzed using the ROC method, and the results are sorted in Table 5.

Table 5. ROC weighting results

Criteria(C)	C1	C2	C3	C4	C5	C6	Total
Alignment	1	2	3	4	5	6	
Weight (W)	0.408333	0.241667	0.158333	0.102778	0.061111	0.027778	1

Step 3. The criterion weights acquired by the ROC method are multiplied by the normalized matrix to calculate the weight of the matrix in Table 6.

Table 6. Weighted normalized ROC matrix

					W					
					0.1583	0.4083	0.1027	0.0611	0.0277	0.2416
No	Age	Job	Marital	Education	Default	Balance	Housing	Loan	Previous	Poutcome
1	30	unemployed	married	primary	0.1583	0.0102	0.1027	0.0611	0	0
2	33	services	married	secondary	0.1583	0.0274	0	0	0.0044	0
3	35	management	single	tertiary	0.1583	0.0077	0	0.0611	0.0011	0
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
4 519	57	technician	married	secondary	0.1583	0.0016	0.1027	0.0611	0	0
4 520	28	blue-collar	married	secondary	0.1583	0.0065	0.1027	0.0611	0.0033	0
4 521	44	entrepreneur	single	tertiary	0.1583	0.0065	0	0	0.0077	0

4.2. K-means algorithm application

K-means algorithm, a non-hierarchical clustering method, is used. The algorithm identifies a certain number of 'K' clusters depending on the problem. At the start of the algorithm, an object representing each cluster is randomly selected. Each object is assigned to the nearest cluster, and the cluster mean is calculated using the clustering criteria. These calculated averages are used as new cluster points, and each object is placed in the cluster most closely resembles it. This process continues until no further changes are observed in the cluster. Customers were divided into groups using the K-means clustering algorithm using the IBM SPSS Statistics program. Part of the dataset in the IBM SPSS Statistics program is shown in Table 7.

Table 7. Part of the dataset in the IBM SPSS Statistics program

No	Age	Job	Marital	Education	Default	Balance	Housing	Loan	Previous	Poutcome	Mean
1	30	unemployed	married	primary	0.1583	0.0102	0.1027	0.0611	0	0	0.06
2	33	services	married	secondary	0.1583	0.0274	0	0	0.0044	0	0.03
3	35	management	single	tertiary	0.1583	0.0077	0	0.0611	0.0011	0	0.04
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
4 519	57	technician	married	secondary	0.1583	0.0016	0.1027	0.0611	0	0	0.05
4 520	28	blue-collar	married	secondary	0.1583	0.0065	0.1027	0.0611	0.0033	0	0.06
4 521	44	entrepreneur	single	tertiary	0.1583	0.0065	0	0	0.0077	0	0.03

Each customer's score was averaged, and then the IBM SPSS Statistics program was used to distribute customers into four groups. Finding each cluster's initial center is one of the most important steps, and the program does this automatically. Depending on the method used, these initial centers may be predefined or determined according to specific criteria or random selection. Initial Cluster Centers are shown in Table 8.

Table 8. Initial cluster centers

	Cluster			
	1	2	3	4
Mean	0.00	0.12	0.01	0.11

These starting points represent the beginning of the cluster creation process within the clustering algorithm running on the data set. Algorithms such as K-means clustering determine these starting centers, update them repeatedly, assign data points to clusters, and perform the clustering process.

In Table 9, the distance to the cluster center determined by the clustering algorithm when creating each cluster is a useful measure of the elements of the cluster. This distance measure describes the location of a data point within a given cluster relative to the center of that cluster. This analysis is useful to understand the distribution of elements in each cluster and their relationship to the cluster center.

Table 9. Cluster membership

Case number	NO	Cluster	Distance
1	4 518.00	1	0.028
2	857.00	1	0.026
3	1 959.00	1	0.026
.	.	.	.
.	.	.	.
.	.	.	.
4 519	1 604.00	2	0.017
4 520	1 217.00	2	0.019
4 521	3 701.00	2	0.031

Table 10 refers to the final center of each cluster determined by the clustering algorithm. This is the stage when the clustering process ends and cluster centers stabilize.

Table 10. Final cluster centers

	Cluster			
	1	2	3	4
Mean	0.02	0.09	0.04	0.06

The final center of each cluster is an intermediate point determined by the applied clustering algorithm and fixed in the final stage of the clustering process. Especially when iterative algorithms such as K-means clustering are used, cluster centers are updated at each iteration, and these updates form the final centers when the clustering process reaches a stable result. The final centroid is useful for understanding each cluster's features, the distribution of data points, and the relationships within the

cluster. These final centers are used to analyze and interpret the clustering results after completing the clustering process, as they reflect the characteristics that represent each cluster.

The number of items in each cluster in Table 11 reflects the group size determined by the clustering algorithm. This information is important for understanding clustering results and assessing the representation of each cluster in the dataset. Item counts are used to evaluate the heterogeneity or homogeneity of clustering results, understand group spacing, and evaluate the performance of clustering algorithms.

Table 11. Number of cases in each cluster

Cluster	Number of groups	Groups sorted by score
1	452	4
2	133	1
3	2 308	3
4	1 628	2
Total	4 521	-

Figure 2 shows the distribution of customers into four diverse groups based on data analysis using the K-means algorithm. Each section in the circle represents a certain percentage of customers in each group.

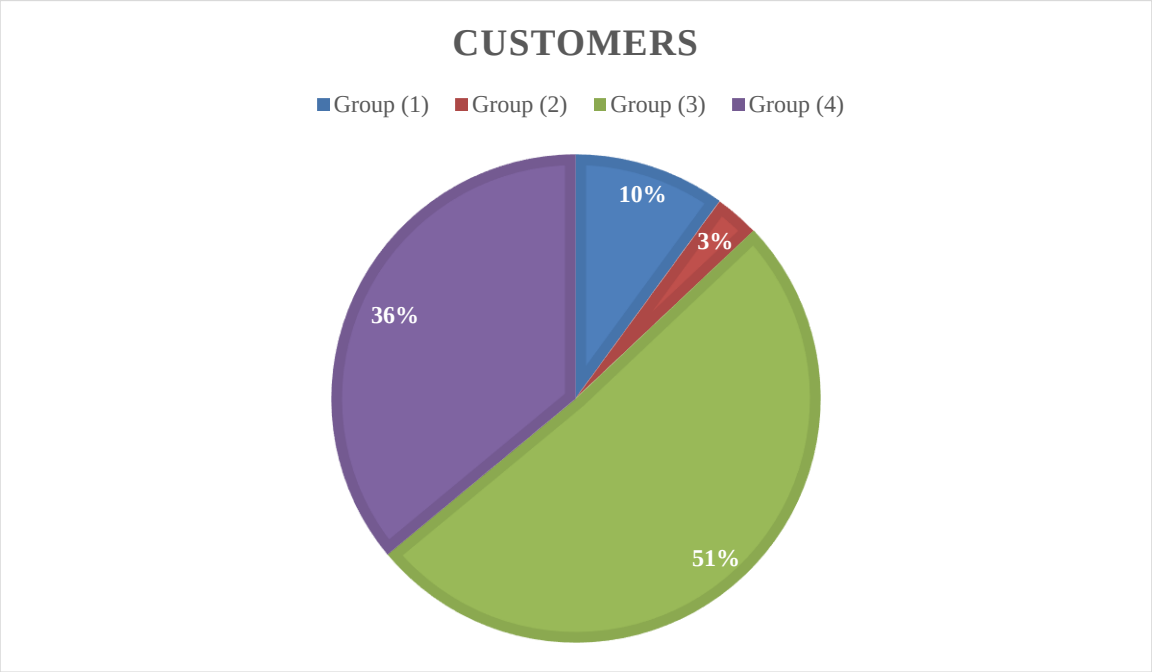


Figure 2. Percentage of customers in each group.

After analyzing the bank customers' data and dividing them into four diverse groups, all members of each group were identified. It has been observed that the members of Group (2), Group (4), Group (3) and Group (1) are ordered from highest to lowest in descending order according to the scores collected for each. In this context, the classification obtained by dividing customers into segments and recording each segment provides valuable information regarding understanding customer behavior and characteristics and executing and focusing marketing campaigns suitable for each group. High-scoring groups can be used specifically to develop specific and miscellaneous marketing strategies and manage Marketing campaigns management more effectively.

5. Conclusions and Recommendations

This study presents an integrated methodology utilizing the ROC (Rank Order Centroid) method for weighting decision criteria and the K-means clustering algorithm for customer segmentation, tailored specifically for the construction industry. By combining these two approaches, the research aims to simplify decision-making processes and optimize marketing strategies in residential projects. The results demonstrated that the most effective marketing strategies can be achieved by focusing on high-scoring customer segments identified through this integrated approach.

As a result of analyzing the data of banking customers and dividing them into four distinct groups, each group's members were identified. According to the scores obtained, Groups (2), (4), (3), and (1) were ranked from the highest to the lowest, respectively. High-scoring groups, particularly Group (2), with 133 customers, and Group (4), with 1 628 customers, represent high-value customer segments that can be prioritized in marketing strategies to achieve efficiency. By focusing on these groups, can conduct more precise and efficient marketing campaigns. This classification provides valuable insights into customer behavior, allowing for customized marketing campaigns tailored to the characteristics of each group.

The practical application of this methodology underscores the critical role of big data analysis in modern marketing. Using large datasets and advanced analytical techniques provides a deeper understanding of customer behaviors and preferences, paving the way for more precise and efficient marketing strategies. This approach not only enhances decision-making capabilities but also contributes to better financial performance and customer satisfaction in the construction sector.

Future research could further explore the potential of integrating additional data mining methods with other multi-criteria decision-making approaches to enhance the precision of customer segmentation. Additionally, applying this methodology to different industries or combining it with predictive analytics techniques could yield deeper insights and contribute to the development of dynamic marketing strategies that adapt in real-time to changes in customer behavior and market trends.

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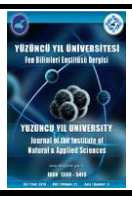
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Araştırma Makalesi

Sorgun İlçesi Geri Dönüştürülebilir Atık Envanterinin Hazırlanması

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Öz: Bu araştırmada Sorgun İlçesi'nde geri dönüştürülebilir atıkların verimli bir şekilde toplanması ve yönetilmesi için envanter çalışması amaçlanmıştır. İlk olarak atık yönetimi kavramları, çevre hukuku ve AB standartları gibi temel prensipler incelenmiştir. Ardından atık türleri detaylı bir şekilde ele alınmış ve geri dönüşüm potansiyeli olan atıklar ile geri dönüştürülemeyen atıklar arasındaki temel farklar vurgulanmıştır. Çalışmada, özellikle kâğıt-karton ve plastik gibi belirli atık türlerinin geri dönüşüm süreçleri detaylıca irdelenmiştir. Ayrıca sıfır atık projesi ve benzeri yenilikçi atık azaltma yaklaşımları üzerine odaklanılmıştır. Sorgun Belediyesi, geri dönüşüm için toplama ve ayırma tesisini 5 yıllığına özel bir geri dönüşüm firmasına kiralamıştır. Firma devlet kurumlarına özel sıfır atık kutuları ve kafesler temin etmektedir. Çoğunlukla kâğıt, karton ve plastik atıkları toplama ve ayırma yapmaktadır. Tesiste ikincil hammaddeye dönüşüm yapılmamakta, ayrılıp preslenen atıklar geri dönüşüm tesislerine satılmaktadır. Sorgun ilçesinin 33 noktasında bulunan atık kutularından toplanan atıklar baz alınarak yapılan çalışmada 2020-2023 yılları arasındaki yıllık veriler tablo halinde, 2022-2023 yıllarındaki veriler mevsimsel dağılımda gösterilmiştir. 2022 yılında ilkbahar mevsiminde %25, yaz mevsiminde %30, sonbahar mevsiminde %25 ve kış mevsiminde %20 oranında kâğıt-karton toplanmıştır. 2023 yılında ilkbahar mevsiminde sırasıyla bu oranlar: %31, %25, %21 ve %23'tür. Plastik atık verileri de 2022-2023'te mevsimsel bazda sunulmuştur. Verilerin olası sonuçları üzerine tartışmalar yapılmıştır.

Anahtar Kelimeler: Atık yönetimi, Geri dönüşüm, Sıfır atık

Preparing of Recyclable Waste Inventory in Sorgun District

Abstract: This research aims to develop inventorying methods for the efficient collection and management of recyclable waste in Sorgun district. It begins by exploring fundamental concepts of waste management, environmental law, and EU standards. Subsequently, it extensively examines diverse types of waste, highlighting the essential differences between recyclable and non-recyclable Waste. In the study, recycling processes and specific Waste types such as paper-cardboard and plastic were examined extensively. Additionally, it emphasizes innovative waste reduction approaches like the zero-waste project. Sorgun Municipality hired to collection and sorting facility for recycling to a private recycling company for 5 years. The firm provides special zero-waste boxes and cages to governmental institutions. The company has been collected and separated mostly paper, cardboard and plastic waste. There is no conversion into secondary raw materials at the facility, and the separated and pressed wasted are sold to other recycling facilities. In the study based on the wastes collected from the waste bins located at 33 points of Sorgun district, the annual data between 2020-2023 are shown in table form, and the data in 2022-2023 are shown in seasonal distribution. Annual data between 2020-2023 are shown in table form, data in 2022-2023 are shown in seasonal distribution. In 2022, 25% of paper-cardboard was collected in spring, 30% in summer, 25% in autumn and 20% in winter. In the spring season in 2023, these rates are: 31%, 25%, 21% and 23% respectively. Plastic waste data was also presented on a seasonal basis in 2022-2023. Discussions were held on the possible outcomes of the data.

Keywords: Recycle, Waste management, Zero waste

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1. Giriş

Sıfır atık terimi, dünyada ilk kez kimyager Paul Palmer tarafından Sıfır Atık Sistemleri (Zero Waste Systems Inc (ZYC)) firması altında kullanılmıştır. Zaman içinde dünya genelinde birçok kuruluş sıfır atık kavramını benimseyerek atık azaltma ve bertaraf hedefleri belirlemiştir. Avustralya'nın başkenti Canberra'daki belediyeler 1995'ten 2010'a kadar No Waste (Atıksız) tasarısını önerdiler ve Canberra, dünyadaki resmi atık azaltma hedefini benimseyen ilk şehir haline geldi (Zaman, 2014).

1977'de Yeni Zelanda'da sıfır atık hareketinin temelleri atıldı. Sıfır Atık Yeni Zelanda Vakfı ile bu hareketi destekleyen vakıf, atıkların azaltılmasını teşvik ederek döngüsel ekonomiyi destekledi; yani ürünlerin yeniden kullanılması, onarılması ve geri dönüştürülmesi yoluyla atıkları minimize eden ve sonunda ortadan kaldıran bir ekonomi hedefledi. Ayrıca 2000 yılında ABD'nin Kaliforniya eyaletinde Del Norte County, kapsamlı bir sıfır atık planı benimseyerek 2001'de Kaliforniya Entegre Atık Yönetim Kurulu tarafından stratejik atık yönetimi planı olarak kabul edildi (Zaman, 2014).

Sıfır atık olabildiğince az atık üretmeyi hedef alıp çıkan atıkları geri dönüşümle çevirmeyi hedef alır. Dolayısıyla insanların bilinçli olması sıfır atık için en önemli ve öncelikli basamaktır (Johnson, 2013).

Ülkemiz de sıfır atık çalışmalarına 2018'de başlamıştır. Çevre Şehircilik ve İklim Değişikliği Bakanlığı, 12 Temmuz 2019'da Sıfır Atık Yönetmeliği'ni yayınlayarak devletin bütün kamu ve özel kurumlarında Sıfır Atık Projesi'ni zorunlu hale getirmiştir. Bu proje ile atıkların ayrı ayrı toplanması, geri dönüştürülmesi, bertaraf edilmesi amaçlanmaktadır (Türkiye Belediyeler Birliği, 2021).

Sıfır Atık Yönetmeliği; büyükşehir ilçe belediyeleri, il-ilçe belediyeleri, belediye birlikleri, il özel idareleri, kamu kurum ve kuruluşları, organize sanayi bölgeleri, havalimanları, limanlar, iş merkezleri ve plazalar, alışveriş merkezleri, 100 oda ve üstü konaklama kapasiteli işletmeler, sağlık işletmeleri, petrol istasyonları ve dinlenme tesisleri, 300 ve üzeri konuta sahip siteler, zincir marketler, tren ve otobüs terminalleri, eğitim kurumları ve yurtlar, 50-99 aralı oda konaklamalı kapasiteli işletmeler, serbest bölgeler, sanayi siteleri, laboratuvarlar, hukuk büroları, dernekler, kooperatif, çevre danışmanlıkları ve meslek kuruluşları, tüzel kişiliğe sahip kuruluşlar, kafeterya ve restoranlar, kargo şirketleri, ambalajlı ürün satışı yapan yerleri kapsar. Kurumlardan sıfır atık yönetim sistemi için istenen bütün belgelerde Sıfır Atık Yönetmeliği kullanılır. Atıkların diğer atıklarla karıştırılmadan toplanması, geri dönüşümlerinin sağlanması ve atık miktarının önlenmesi sağlanır (Sıfır Atık Yönetmeliği, 2019)

Atık yönetimi yalnızca ülkemiz için değil, tüm ülkeler için önemli bir konudur. Ancak ülkemizde sıfır atık uygulamasının geç fark edilişi diğer ülkelerden geride kalmamıza sebep olmuştur. Sıfır Atık Yönetimi'nin özünü oluşturan geri kazanım anlayışında Almanya %56, Avusturya ve Güney Kore %54 değerleri ile öncü ülkeler olarak sıralanmaktadır (Gray, 2017). Fakat diğer ülkelerden geri kalsak da çalışmalar hızlı bir şekilde devam etmiştir ve Sıfır Atık Projesi kapsamında 12 tane atık türünün geri kazanımı/dönüşümü sağlanmıştır. Bunlar; plastik atık, ahşap atık, metal atık, atık pil, bitkisel atık yağ, cam atık, elektronik atık, kâğıt atık, organik atık, tekstil atığı, kompozit atık ve tıbbı atıktır (Demir, 2019).

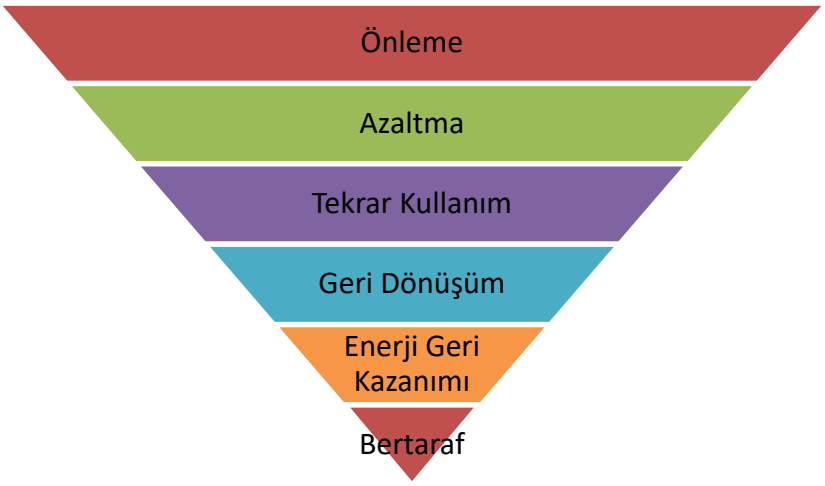
Gün geçtikçe artan bu atıkların önüne geçilmesi, doğal kaynakların tükenmemesi ve çevreye zararın en aza indirilmesi için Katı Atık Yönetim sistemi belirlenmiştir. Bu sistem atıkların oluşumundan bertarafına kadar oluşan süreci kapsamaktadır. Atık yönetimi ile kaynakların uzun vadeli kullanılması için israfa son vermek, ekonomik değeri olan maddeleri geri kazanmak ve tekrar kullanıma kazandırmak mümkün hale gelmiştir (Demir, 2019).

Çevresel olarak düşündüğümüzde sıfır atık, hammaddelerin kaynağından tasarruf edilmesini teşvik ederek canlı veya cansız çevre için oluşturulan tehlikeleri azaltır ve sera gazı emisyonlarını depolama sahalarında azaltır. Ayrıca üretimde kullanılan enerji miktarını azaltarak hem ekonomik hem de çevresel olarak avantaj sağlar. Mevcut atık malzemelerinin ekonomik bir şekilde yönetilmesi gereken bir gerçektir. Çünkü atık depolama sahaları ve yakma tesisleri yüksek maliyetler içerir. Ancak döngüsel bir sistemde geri dönüştürülebilir atıklar birçok ülkede önemli faydalar sunar (Elgizawy ve ark., 2016).

Dünyada ve ülkemizde tek bir atık türü için yönetim sistemi oluşturmaktansa bütün atık türlerini kapsayan Entegre Yönetim Sistemi kurulmuştur. Entegre atık yönetimi; atık türünün belirlenmesi, bu atık türüne yönelik yönetim sisteminin seçilmesi ve uygulanması olarak tanımlanabilir (Bozkurt, 2012).

Atıkların kaynağından itibaren ayrı ayrı toplanması ve işlenmesi gereklidir. Böylece çevreye ve insan sağlığına zarar vermeyecek yöntemler kullanarak atıkların tekrar kullanılması, geri dönüşümü, enerji üretimi veya güvenli bertarafı sağlanmalıdır (ÇŞİDB, 2023). Atık yönetim hiyerarşisi; atık

yönetim stratejilerini, atıkların oluşum kaynağından bertaraf edilmesine kadar olan süreçte en az miktarda atığın meydana gelmesini hedefleyerek sıralar. Bu hiyerarşinin etkili bir şekilde uygulanması atıkların kaynağında oluştuğu andan son bertaraf edildiği ana kadar olan süre içinde sağlanır, Buradaki süreçler Şekil 1'de belirtilmiştir:



Şekil 1. Atık yönetimi hiyerarşisi (ÇŞİDB, 2020).

2. Materyal ve Yöntem

Sorgun ilçesi, Yozgat ilinin 80 618 (Türkiye İstatistik Kurumu, 2023) kişiyle en fazla nüfuslu ve en gelişmiş ilçesidir. İlçe nüfusunun artması sebebiyle orantılı olarak tüketim ve atık oluşumu da artmıştır. Sorgun belediyesi düzen ve temizlik açısından giderek kendini geliştirmiş ve 2020'den beri sürdürülen Sıfır Atık Projesi kapsamında yürütülecek faaliyetlere önem vermektedir.

Sıfır Atık kapsamında ilçenin belirli noktalarına sıfır atık kutuları konulmuş ve birçok kurum tarafından atıkların toplanmasına özen gösterilmiştir. Belediye toplama işini 2020 yılından beri lisanslı bir geri dönüşüm firması üzerinden yapmaktadır. Tesis toplama-ayırma tesisi olup preslenen atıklar, ikincil hammadde üreten geri dönüşüm firmalarına satılmaktadır. İlçenin sanayi yapısının gelişmemiş olması sebebiyle kâğıt, karton ve plastik atık dışında çok fazla atık oluşmamaktadır. Ekonomik getirisi ön planda tutulmakta ve bunun yanı sıra kâğıt, karton, plastik atıkların toplanması, taşınması, ayrılması daha kolay olduğu için bu üç atığa önem verilmektedir.

Mevsimlere ve okulların açık olup olmama durumuna göre değişkenlik gösterse de günlük karton atık miktarı ve plastik atık miktarı ayrı ayrı bir tonu bulmaktadır. Hem sokak toplayıcılarının çok olması hem de kurumlara verilen teşviklerin olması sebebiyle geri dönüşüm kolu sıkıntısız ilerlemektedir. Ayrıca marketler kendi sistemlerini yürütmek adına sıfır atık projesine büyük önem vermekte ve en çok atık çıkan yerler de zincir marketler olmaktadır.

Belediye, lisanslı firmaya okullara geri dönüşümle ilgili verilecek eğitimi zorunlu tutup denetlemektedir. Haliyle verilen eğitimler ve okullara konulan geri dönüşüm kutuları sayesinde ayrı ayrı atıklar toplanabilmektedir. Bu da geri dönüşümün ilk basamağı olarak çok önemlidir.

2.1. Yöntem

Sorgun ilçesinin tam 33 noktasında geri dönüşüm-toplama firmasının atık kutuları bulunmaktadır. Bunlar;

- Bütün büyük marketler (A101, BİM, ŞOK, MİGROS, BİZİM MARKET) (29),
- Emniyet ilçe müdürlüğü (1),
- Huzurevi (1),
- Devlet Hastanesi (1),
- PTT (1)'dır.



Şekil 2. Market önü atık kafesleri.



Şekil 3. Kurum içi atık kutuları.

Kurum içlerine ve dışlarına konulan atık kutuları/kafesleri üretilen atığın miktarına göre verilir. Örneğin günde 1 ton kâğıt-karton-plastik çıkarabilecek potansiyelde bir kurum ise mutlaka kurum dışına (Şekil 2) bir kafes konulur. Eğer hastane gibi büyük ve çok çalışanlı bir kurum ise hem kurum içine (Şekil 3) hem de kurum dışına toplamak için atık kutuları konulur.

Bunun haricinde Sorgun Belediyesinin geri dönüşüm firması, belediye adına ilçenin belirli noktalarına atık kutuları yaptırmakla görevlendirilmiştir. Bunlardan bazıları Şekil 4'te verilmiştir.



Şekil 4. İlçenin bazı noktalarındaki atık kutuları.

3. Bulgular

3.1 Verilerin analizleri ve % dağılımları

Sorgun ilçesinde yapılan çalışmaya; PTT, Emniyet İlçe Müdürlüğü, Huzurevi, Devlet Hastanesi, tüm zincir marketler (BİM, A101, ŞOK, BİZİM MARKET, SEÇ vs.) dâhil edilmiştir. Ayrıca zincir marketlerin bütün şubeleri bu çalışmaya dâhildir. Sadece kâğıt-karton ve plastik atıklar toplanmıştır. 2022 yılında mevsimlere göre toplanan Kâğıt karton atıklarının dağılımı Şekil 5'te sunulmuştur.



Şekil 5. 2022 yılı kâğıt-karton atıklarının mevsimlere göre % dağılımı.

2022 yılında toplanan kâğıt-karton atık miktarı ilkbahar mevsiminde toplam 161.08 ton ile %25, yaz mevsiminde toplam 194.70 ton ile %30, sonbahar mevsiminde 160.21 ton ile %25, kış mevsiminde 128.88 ton ile %20 oranına denk gelmektedir.

Benzer şekilde yine 2022 yılına ait plastik atıkların mevsimlere göre dağılımları Şekil 6'da verilmiştir.



Şekil 6. 2022 yılı plastik atıkların mevsimlere göre % dağılımı.

2022 yılında toplanan plastik atık miktarı ilkbahar mevsiminde 119.53 ton ile %27, yaz mevsiminde 130.01 ton ile %29, sonbahar mevsiminde 122.13 ton ile %27, kış mevsiminde 77.47 ton ile %17 oranına denk gelmektedir.



Şekil 7. 2023 yılı kâğıt-karton atıkların mevsimlere göre % dağılımı.

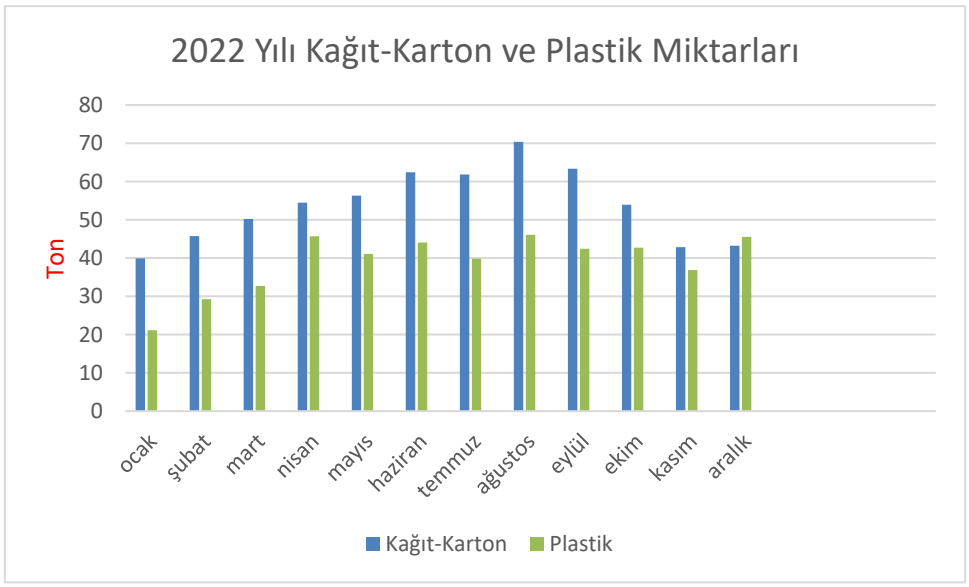
2023 yılına ait Kâğıt karton verileri Şekil 7'de gösterilmiştir. Bu dönemde toplanan kâğıt-karton atık miktarı ilkbahar mevsiminde toplam 163.90 ton ile %31, yaz mevsiminde 128.98 ton ile %25, sonbahar mevsiminde 111.65 ton ile %21, kış mevsiminde 118.62 ton ile %23 oranına denk gelmektedir.



Şekil 8. 2023 yılı plastik atıkların mevsimlere göre % dağılımı.

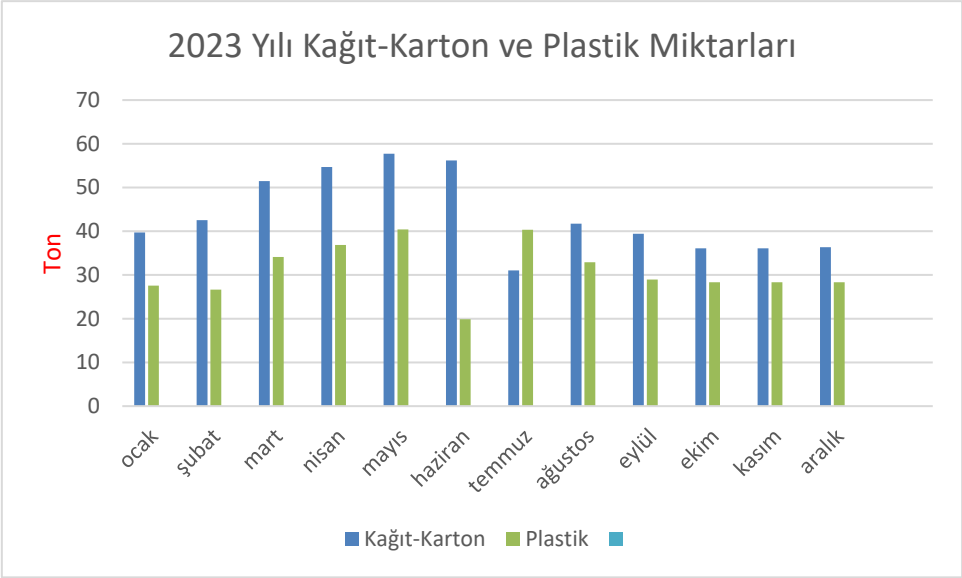
Şekil 8'de 2023 yılında toplanan plastik atık miktarı görülmektedir. İlkbahar mevsiminde toplam 111.40 ton ile %29, yaz mevsiminde 93.12 ton ile %25, sonbahar mevsiminde 92.79 ton ile %24, kış mevsiminde 82.52 ton ile %22 oranına denk gelmektedir.

2022 yılında toplanan kâğıt-karton ve plastik atıklar, Şekil 9'da tüm aylara göre gösterilmiştir.



Şekil 9. 2022 yılı kâğıt-karton ve plastik miktarları.

2023 yılında toplanan kâğıt-karton ve plastik atıklar, Şekil 10'da tüm aylara göre gösterilmiştir.

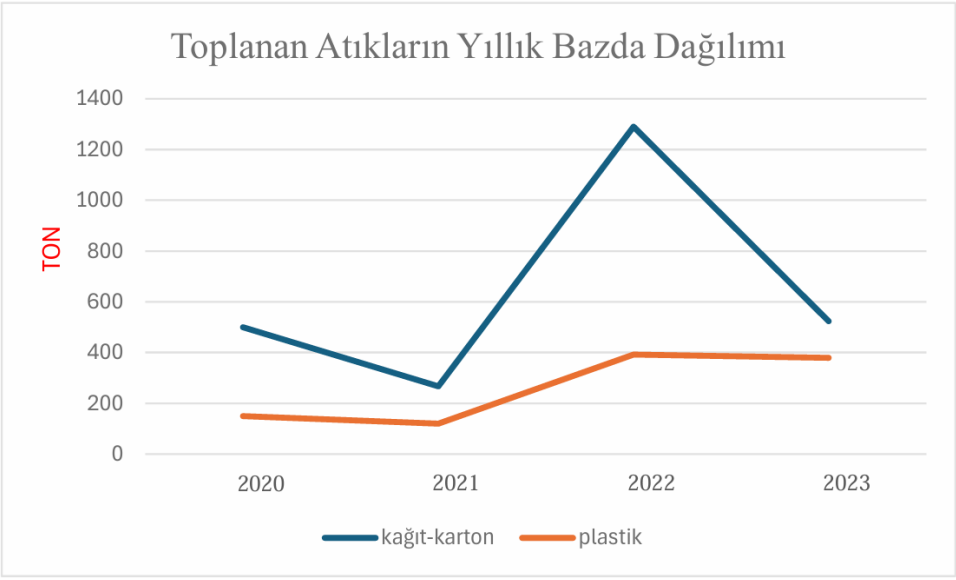


Şekil 10. 2023 yılı kâğıt-karton ve plastik miktarları.

Çizelge 1. Verilerin yıllık miktarları (Ton)

	KAĞIT-KARTON (Ton)	PLASTİK (Ton)
2020	500	150
2021	267	120
2022	1 289.8	392.17
2023	523.1	379.8

Çizelge 1’ de 2020-2023 yılları arasında toplanan kâğıt karton ve plastik atık miktarları görülmektedir.



Şekil 11. Toplanan atıkların yıllık bazda dağılımı.

Benzer şekilde 2020-2023 dönemine ait yıllık bazda toplanan Kâğıt karton ve plastik miktarları Şekil 11'de verilmiştir.

4. Bulgular ve Tartışma

Geri dönüştürülebilir atıklar, ekonomik değeri açısından birçok kurumun dikkatini çeker hale gelmiştir. Bazı kesimler yasal olmayan bir şekilde daha fazla kâr elde etmek için şehir dışına satmaya çalışmaktadır. Belediyenin lisanslı firmaya bu görevi vermesi sebebiyle dışarıya ya da başka firmalara geri dönüşüm atıklarını satmak yasaktır. Belediye bu konuda gerekli denetlemelerini yapıp cezalarını kesmektedir.

Zaman zaman kesilen cezalar sosyal açıdan baş kaldırmalara sebep olmuştur. Toplayıcıların ya da bazı kurumların geri dönüşüm fiyatlarını pahalı bulması ve yasal olmayan yollarla satışa kalkması hem ilçe kalkınması hem de firma açısından tehlikeli bir hal almaya başlamıştır.

Toplanan veriler göz önüne alındığında mevsimlere göre değişiklik söz konusudur. 2022 ve 2023 yıllarında toplanan atıklarda inişler çıkışlar olduğu gözlemlenmiştir. Genel olarak sonbahar-kış mevsiminde yüzdesel olarak her iki atık türünden de en az miktarda atık toplanmış, ilkbahar-yaz mevsiminde ise bu miktarlar daha fazladır (Şekil 5 ve 6). Kış mevsiminden ilkbahar mevsimine ve ilkbahar mevsiminden yaz mevsimine geçişte bir artış vardır. Sonbahar mevsiminden kış mevsimine geçerken bir azalış söz konusu olup yaz mevsiminden sonbahar mevsimine geçerken atık miktarlarında azalma gözlemlenmiştir (Şekil 5). Buna bağlı olarak yaz mevsiminde artmasının sebebini, ilçeye yapılan ziyaretler olarak gösterebilir. Bu sebeple artan nüfus, daha fazla atık üretimine sebep olmuştur. Görünür de atık üretiminin artması olumsuz bir sonuç gibi görünse de atık toplayıcılarına ekonomik bir fayda sağlamıştır.

Yaz aylarında toplanan atık miktarından sağlanan gelir kış aylarında toplanan miktara göre fazladır.

Sonbahar ve ilkbahar mevsimleri sabit ilerlemekte bazen artışlar gözlemlenmektedir.

Bunun yanı sıra kâğıt-karton atıklar, plastik atıklara göre daha çok toplanmaktadır. Çünkü kâğıt-karton atıklardan sağlanan ekonomik gelir plastik atıklardan daha fazladır. Bu yüzden toplamada öncelik kâğıt-karton atıklara verilmektedir. Toplanıldıktan sonra sadece preslenen kâğıt-karton atıklar, fire vermemektedir. Fakat plastik atıklar (su şişeleri, yiyecek içecek kutuları vs.) işleme tabii tutulması gerektiği için işletmeler kâğıt-karton atıkları toplamayı tercih etmektedirler.

Tüm odak noktası marketlerin önündeki kafesler haline gelmiş ve sitelerde atık yönetimi uygulamaları yapılmamaktadır. İnsanlar tembelliğe yönelmekte ve zaten atacak yerleri olmadığı için atıklarını ayırmamaktadır. Bu soruna acilen bir çözüm bulunmalıdır. Çünkü her insanın barındığı bir yer vardır genel olarak da ilçe halkının en kalabalık yaşadığı yerler site halindeki yapılar olduğu için buralara mutlaka bir düzenleme yapılması şarttır.

Yapılan benzer bir çalışmada, atık toplamada rota optimizasyonu belirlenmiş ve taşıma sistemindeki verim artırılmak istenmiştir. Ekonomi ön planda tutulmuş ve tasarruf elde edilmiştir. Bizim çalışmamızda atık toplama belirli bir rotasyon ile yapılmamıştır (İrdemez ve ark., 2021).

Gelişi güzel istiflenen atıklar toplanırken hem zaman kaybı yaşanmasına hem de tesis açısından yüksek maliyetlere sebep olmaktadır. Bu kapsamda akıllı sistemlerin kullanılması yerel yönetimlerin zamandan ve yüksek maliyetlerden kaçınmasına olanak sağlar. Bu çalışmada ele alınan konunun önemi bizim çalışmamızda da vurgulanmıştır. Fakat çalışma atık kumbaraları, bulut bilişim, sunucu ve son cihazdan oluşmaktadır. Kumbaralara belirli bir ağırlık geldiğinde sensörler, bulut bilişime bilgi aktarmakta ve anlık olarak kumbaralar takip edilmektedir. Böylece atık toplama rotasyonu bir gün önceden hesaplanabilir (Sevinç ve ark., 2021).

Elâzığ Belediyesi'nin yürüttüğü çalışmada, tekstil kutuları şehrin farklı farklı noktalarına konmuştur ve halk geri dönüşüm basamağına dahil edilmiştir. Sıfır Atık Projesi kapsamında yürütülen bu çalışmanın aynısı ilçemizde de yapılmaktadır. Halkımız kullanmadıkları giysilerini, eşyalarını bırakarak geri dönüşüme katkı sağlamaktadır. Geri dönüşüm, neredeyse tüm türlerde ilerleme sağlamıştır (Akarsu, 2022).

Kayseri'de yürütülen benzer bir çalışmada; evsel atıklar, katı atıklar, plastik atıklar, cam atıklar, metal atıklar ve diğer atıklar olmak üzere 6 türde çalışma yapılmıştır ve bu atıkların aritmetik ve geometrik ortalamaları, standart sapmaları hesaplanmıştır. Bizim yaptığımız çalışmada; kâğıt-karton ve plastik atıklar toplanmıştır. Bunun sebebi her iki atık türünün de ekonomiye diğer atıklardan fazla gelir sağlamasıdır. Çalışmamıza benzer bir şekilde verilerin yüzde dağılımları grafikler halinde gösterilmiştir. Ayrıca personel maliyetleri, ulaşım maliyetleri de hesaba katılarak gelir-gider tablosu yapılmış, fayda maliyet analizleri yapılmıştır (Aydın, 2019).

Bir araştırma makalesinde, ambalaj atıkları toplama sistemlerini geliştirmek amaçlanmıştır. 6 farklı toplama sistemi incelenmiş ve analizler sonucunda kontrolsüz toplamanın ciddi bir dezavantaja sahip olduğu saptanmıştır. Yapılan çalışma incelendiğinde atıkların; ayrıştırma şekli, depolama şekli ve toplama şekline göre sistematik bir şekilde ayrıldığını görebiliriz. Mevcut durumda raporlarda resmi olarak çalışan toplamada 50 kişi çalışıyorken, kayıt dışı 800 toplayıcı olduğu belirlenmiştir. Buradan yola çıkarak çalışmamızdaki verilerde oransal bir değişim olmamasının sebebini açıklayabiliriz (Geyhan ve ark., 2021).

Sorulması Gereken Sorular

1. Atıkların ayrı ayrı toplanması sorunsuz ilerlemekte midir?

Evet. Bunun sebebi insanların bir nevi zorunda kalması ve atık noktalarının çok uzak noktalarda olmamasıdır. Yerel halk bilinç ve görsel olarak atık ayırmaya maruz bırakılmıştır.

İlçede eğitim seviyesi yüksek insanlar bulunmaktadır. Eğitim seviyesi arttıkça farkındalık da artmaktadır. Dolayısıyla insanlar çevre bilincine önem vermekte ve bilinçlendirildikçe de geri dönüşüm konusuna önem vermeye başlamıştır.

Farkındalıktan ziyade geri dönüşümün en önemli kısmı ekonomi boyutudur. Toplayıcılar artık bu işten elde edilen geliri gördükleri için buraya yönelmişler ve yeni bir iş kolu doğmuştur. Hem küçük bir ilçe hem de toplayıcı sayısı fazla olunca atıkların ayrı ayrı toplanması basamağı sorunsuz ilerlemektedir.

2. Kesilen cezalar ne gibi sonuçlara yol açmaktadır?

Toplayıcılar belediyenin yetkilendirdiği firmaya atıkları satmak zorundadır. İsterlerse firma için de çalışabilirler fakat her iki durum da olmadığında bir yaptırım uygulanmaktadır. Bu yaptırım bazen uyarı bazen de para cezası şeklindedir. Para cezası uygulanmaya kalkıldığında sosyal açıdan başkaldırmalar olmakta ve günümüz ekonomi şartlarına göre geçinemediklerini öne sürüp isyan etmektedirler. Aslında önce farkındalık ile başlayan bu proje, zamanla iş koluna döndüğü için insanlar tatmin edici paralar kazanmayı istemektedirler. Firmayla anlaşamadıklarında da bu mevzu çatışmaya dönmektedir.

3. Sorgun ilçesinde atık yönetimi nasıl ilerlemektedir?

Belediye ve firmalar görevlerini yerine getirdikleri için ilçede oldukça temiz bir görünüm vardır. Hem belediye hem de yetkili firmalar işinin gereğini yapmakta ve bütün basamaklara uyarak atık yönetimini yürütmektedirler. Belediye-yetkili firma ve toplayıcılar iş birliği ile çalışmaktadırlar. Fakat bazı bilinçsiz kesimler yasal olmayan bir şekilde biriktirmeler yapmakta hatta bunların bertarafını yine bilinçsizce kendileri sağlamaya çalışmaktadır.

4.1. Öneriler

İnsanların bilinçsiz olması, geri dönüşümden ziyade sadece ekonomiyi düşünmeleri geri dönüşüm basamaklarını sekteye uğratmaktadır. Marketler ve bazı kurumların kendi sistemleri olduğu için çalışanlarına geri dönüşüm konusunda gerekli bilinci yüklediğini görmekteyiz. Fakat sokak toplayıcılarında bu durum yoktur. Eğer geri dönüşüm basamaklarına dâhil edilirler ise bu sorun ortadan kalkabilir.

Sıfır atık ilkeleri doğrultusunda gerçekleştirilecek her türlü faaliyet toplumun her kesimini ilgilendirdiğinden herhangi bir paydaşın sistem dışı kalmasını önlemek gerekir. Bu sebeple sokak toplayıcılarının da bu basamaklara dâhil olduğu bir kapsamda ilerlemek daha yararlı olacaktır. Onlara çeşitli eğitimler verilmeli ve bu işe sadece parasal açıdan bakılmaması gerektiği anlatılmalıdır.

Bazı teşvik uygulamaları yapılabilir. Geri dönüşüm, halkın gözünde ilgi çekici hale getirilmeli.

Site yönetimlerinde pilot bir site seçilmeli ve bir süre gözlemlenerek çıkan atığın miktarı hesaplanmalı, kontrollü bir şekilde yerel halk sistemin merkezinde tutulmalıdır.

İyi olan şey de şudur: sıfır atık kutuları ilçenin yüzölçümü bakımından küçük olması sebebiyle herkesin ulaşabileceği noktalardadır. Halkın sürekli gözünün önünde bulunması ve normal çöp kutuları yerine bu noktaların bulunması onları tanımlanan atığın olduğu kutulara atmaya itmiştir. Bu şekilde geri dönüştürülebilir atıkların ayrı ayrı toplanması basamağı neredeyse eksiksiz ilerlemektedir.

Süreçte önce bir rota organizasyonu belirleyip ardından toplamaya çıkılması yönünde bir plan çizilmeli ve toplayıcılar da bu basamağa dâhil edilmelidir.

Akıllı şehirlerde kullanılan yapay zekâ uygulamalarını ilçeye entegre etmek için uğraşılmalı, gerekirse yerel yönetimlere proje dahilinde sunulmalıdır.

Çalışmaya ek olarak bir anket hazırlanıp ilçe sakinlerine dağıtılmalıdır. Bu süreçte ilçedeki insanların geri dönüşüm basamağına hangi ölçüde katkı sağladıkları ölçülebilir.

Teşekkür

Çalışılan konu üzerinde verilerini sunan Sorgun Belediyesi'ne teşekkürlerimizi sunarız.

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Research Article

Hydrogel Balls Developed for Use in the Detection of Heavy Metals in Wastewater

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Abstract: The study highlights the development of hydrogel beads for the detection of Nickel (Ni(II)) and Chromium (Cr(VI)) in industrial wastewater, providing an innovative solution to heavy metal pollution in a cost-effective and environmentally friendly manner. The beads change color when exposed to metals, making detection fast and simple. This technique makes a significant contribution to occupational health and safety by providing real-time detection of harmful heavy metals, thereby reducing the risk of exposure to workers. Additionally, the hydrogel beads aim to protect both worker health and surrounding ecosystems by helping industries meet environmental standards. Key findings include detection limits of 2.5 mg/mL for nickel and 1 mg/mL for chromium, and color changes stabilizing within 10 min. The hydrogels exhibited excellent swelling behavior with equilibrium swelling ratios of 72.65% for nickel and 64.18% for chromium, providing high efficiency in moisture absorption and retention. These features, combined with their ability to function without pretreatment or pH adjustment, offer an accessible and effective solution for managing metal pollution in industrial environments. Overall, the hydrogel beads demonstrated a success rate of 90.56% for nickel and 91.60% for chromium in detecting and measuring metal ions, providing an accessible and effective method for managing metal contamination in industrial environments while protecting both worker health and environmental integrity.

Keywords: Colorimetric analysis, Heavy metal, Hydrogel, Occupational health and safety

Atık Sularda Bulunan Ağır Metallerin Tespitinde Kullanılmak Üzere Geliştirilmiş Hidrojel Toplar

Öz: Çalışma, endüstriyel atık sularda Nikel (Ni(II)) ve Krom (Cr(VI)) tespiti için hidrojel boncuklarının geliştirilmesini vurgulayarak, ağır metal kirliliğine uygun maliyetli ve çevre dostu bir şekilde yenilikçi bir çözüm sunmaktadır. Boncuklar metallere maruz kaldığında renk değiştirerek tespiti hızlı ve basit hale getirmektedir. Bu teknik, zararlı ağır metallerin gerçek zamanlı tespitini sağlayarak iş sağlığı ve güvenliğine önemli bir katkı sağlamaktadır ve böylece çalışanların maruz kalma risklerini azaltmaktadır. Ek olarak, hidrojel toplar endüstrilerin çevre standartlarını karşılamasına yardımcı olarak hem çalışan sağlığını hem de çevre ekosistemlerini korumayı hedeflemektedir. Ana bulgular arasında nikel için 2,5 mg/mL ve krom için 1 mg/mL'lik tespit limitleri ve renk değişimlerinin 10 dakika içinde sabitlenmesi yer almaktadır. Hidrojeller, nikel için %72,65 ve krom için %64,18'lik denge şişme oranlarıyla mükemmel şişme davranışı göstererek nem emilimi ve tutulmasında yüksek verimlilik sağlamıştır.. Bu özellikler, ön işlem veya pH ayarlaması olmadan işlev görme yetenekleriyle birleştiğinde, endüstriyel ortamlarda metal kontaminasyonunu yönetmek için erişilebilir ve etkili bir çözüm sunmaktadır. Genel olarak hidrojel boncuklar, metal iyonlarını tespit etme ve ölçmede nikel için %90,56, krom için %91,60 başarı yüzdesi sergileyerek hem işçi sağlığını hem de çevresel bütünlüğü koruyarak endüstriyel ortamlarda metal kirliliğini yönetmek için erişilebilir ve etkili bir yöntem sunmaktadır.

Anahtar Kelimeler: Ağır metal, Hidrojel, İş sağlığı ve güvenliği, Kolorimetrik analiz

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1. Introduction

The analysis of nickel and chromium in water drawn from organized industrial zones is crucial from an occupational health and safety perspective. Nickel (Ni) and chromium (Cr) are metals frequently used in industrial processes, and their introduction into water can have adverse effects on worker health. Water containing high concentrations of nickel and chromium, which can enter the body through inhalation, may lead to serious health issues over time. Regular analysis of workplace water can identify potential hazards and reduce the risk of workers being exposed to these metals. The results of these analyses serve as an important data source for the development and implementation of occupational health and safety policies. Furthermore, actions taken based on the analysis results can lead to the development of effective strategies aimed at protecting worker health and ensuring a safe working environment. Therefore, the regular examination of industrial water sources in organized industrial zones is critical for both environmental sustainability and worker health (Shi &Wang, 2021).

Metal analysis in industrial waters can be conducted using various methods that play a significant role in monitoring water quality and enforcing environmental regulations. Key methods include metal analysis using instruments such as atomic absorption spectrophotometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and inductively coupled plasma optical emission spectrometry (ICP-OES). While AAS is used to accurately measure the concentration of specific metals, ICP-MS and ICP-OES allow for rapid and precise multi-metal analysis (Wysocka, 2021; Douvris et al., 2023). These methods offer appropriate sensitivities and detection limits for the determination of various metals, providing essential tools for assessing the environmental compliance and health impacts of industrial waters. Analysis results not only help companies comply with environmental regulations but are also crucial for worker health and safety. However, these methods can be time-consuming in terms of labor requirements (Ali et al., 2023). Sample collection, preparation, analysis, and interpretation of results must be carefully conducted by experts, which can increase labor costs (Baralkiewicz et al., 2007).

Consumables are another significant cost factor. The chemicals required for instrument maintenance, calibration standards, and consumables increase the cost of analysis. Moreover, to obtain accurate and reliable results, these materials must always be fresh and of high quality. When fresh materials are used, the accuracy and reliability of the experimental results are enhanced. For example, the chemical properties of a reagent can change over time; therefore, it is recommended to use a reagent that has been stored in new and suitable conditions. In this context, the term "fresh" is important for ensuring the quality of the materials and the validity of the experiments.

Therefore, metal analysis in industrial waters has disadvantages such as high costs, labor requirements, and the need for consumables. As a result, less costly alternatives or more efficient management strategies should be developed to minimize analytical costs and processes.

Cross-linked polymers capable of swelling by retaining more than 20% of their mass in solvent are known as xerogels. When the solvent is water, these cross-linked structures are referred to as hydrogels (Laftah et al., 2011). Hydrogels are physically or chemically cross-linked hydrophilic polymer matrices that swell upon absorbing large amounts of water (or biological fluids) but do not dissolve in water in the short term (Peppas et al., 2000; Kopecek, 2002). Due to their biocompatibility and biodegradability, hydrogels are widely used in industries such as food, pharmaceuticals, and biomedicine (Jayakumar et al., 2011). Owing to their swelling properties in aqueous environments, hydrogels find applications in contact lenses, wound dressings (Jayakumar et al., 2011), tissue engineering (Lee & Mooney, 2001), water treatment, heavy metal removal (Li et al., 2010), controlled drug release (Qiu & Park, 2012), agriculture (Arbona et al., 2005), ion exchange applications, chromatography applications, solvent extraction, and the manufacturing of healthcare products (Zohuriaan-Mehr et al., 2009). Researchers are also used to remove moisture from industrial waste containing oil and grease and to prevent corrosion (Juang & Shiau, 2000).

The characterization of cross-linked polymers that exhibit swelling behavior necessitates the examination of their swelling properties. For this purpose, a swelling curve must first be constructed. Swelling curves are created by monitoring the change in mass or volume of polymers over time in appropriate solvents (Dolbow et al., 2004). Additionally, monitoring dehydration and saturation values is essential.

In this study, we developed f with a diameter of 0.5 mm, which are insoluble in water and unaffected by metal interferences, for the colorimetric detection of the heavy metals nickel and chromium, which pose risks to human, environmental, and animal health. The hydrogel beads are immersed in liquid for 5 minutes, during which a color change within the beads is observed. The metal concentration is determined by reading from a color scale.

The aim of this study is to present a new method for colorimetric and photometric color change-based analyses in liquids, providing a faster and more accessible alternative to the currently used test strips and colorimetric sensors.

From an occupational health and safety perspective, this study plays a crucial role, as industrial wastewater often contains various harmful chemicals that can pose health risks to workers and damage the environment.

Key contributions of this study to occupational health and safety include; Workers in industrial facilities must be protected from the harmful effects of heavy metals in wastewater. These hydrogel beads can quickly detect heavy metals in wastewater, reducing the risk of exposure for workers.

Industrial wastewater can cause significant environmental damage. The leakage of heavy metals can contaminate water sources and harm ecosystems. The use of these hydrogel beads enables the early detection of heavy metal contamination, thereby protecting the environment.

In the event of a heavy metal leak in industrial facilities, a rapid and effective response is necessary. These hydrogel beads can be used as a tool for the quick detection and removal of heavy metals in wastewater, thus improving the emergency response process.

The innovative aspect of this study lies in both the material used and the experimental method employed. The application of biodegradable and environmentally friendly hydrogel beads for the detection of toxic heavy metals, such as Ni(II) and Cr(VI), presents a notable approach. The ability of these hydrogels to be applied directly in industrial wastewater without the need for pre-treatment or pH adjustment makes the material both practical and efficient. Experimentally, the rapid color change of the hydrogel beads, reaching equilibrium within 10 minutes, offers significant advantages in terms of time and cost compared to traditional metal analysis methods. This colorimetric approach provides a fast and cost-effective solution for the detection of heavy metals, which is particularly valuable for ensuring occupational health and safety in industrial settings. Thus, this study highlights the use of hydrogel beads as an environmentally friendly, economical, and efficient tool for detecting heavy metals, offering substantial contributions to both occupational health and environmental protection.

This study can serve as a foundation for educational programs aimed at industry workers regarding the handling of industrial wastewater and the detection of heavy metals. By learning the procedures for wastewater treatment and the use of hydrogel beads, workers can contribute to maintaining a safe working environment.

In conclusion, this study provides a significant contribution to occupational health and safety by enabling the rapid and effective detection of heavy metals in industrial wastewater, thereby protecting worker health and the environment.

2. Material and Methods

The materials used include sodium alginate, sodium carboxymethyl cellulose, calcium lactate, dimethylglyoxime, sodium thiocyanate, ammonia, 1-10 phenanthroline, sodium citrate, ascorbic acid, diphenylcarbazide, acetic acid, and cuprizone.

The detection of Nickel (Ni(II)) and Chromium (Cr(VI)) in industrial wastewater was performed using a spectrophotometer (model XYZ), which was calibrated according to the manufacturer's guidelines prior to each series of measurements to ensure accuracy and precision in detecting the colorimetric changes of the hydrogel beads. Water samples were collected from various industrial sites using clean, sterilized containers and were stored at 4°C to minimize degradation or contamination before analysis. Before testing, each sample was filtered using a 0.45 μm membrane filter to remove any particulate matter that could interfere with the colorimetric analysis.

For the colorimetric detection of metals, hydrogel beads were prepared by dissolving sodium alginate and sodium carboxymethyl cellulose in distilled water. For Nickel detection, 0.5 g of calcium lactate was dissolved in 20 mL of water and mixed with 0.25 g of dimethylglyoxime (DMG) dissolved in 20 mL of ethanol, along with 5 mL of 10% sodium thiocyanate (NaSCN) and 5 mL of ammonia. For

Chromium detection, 0.5 g of calcium lactate was combined with 0.1 g of diphenylcarbazide (DFK) in 20 mL of ethanol, 4 mL of acetic acid, and 1 mL of 1% NaSCN.

The hydrogel beads were immersed in the prepared metal solutions for 10 minutes to allow for the establishment of equilibrium. Color changes were observed and quantified using a colorimeter, where RGB and ΔE values were recorded to assess the intensity of the color change corresponding to the concentration of the metals present. RGB stands for Red, Green, Blue in English. It is a color model used in various electronic systems, including computer displays, where different combinations of red, green, and blue light are used to create a broad array of colors. All experiments were conducted at a controlled room temperature of 25°C, and the pH of the samples was monitored and maintained within a neutral range (pH 6-7) to ensure optimal performance of the hydrogel beads. Each test was repeated three times to confirm the repeatability and reliability of the results.

The data obtained from the colorimetric measurements were analyzed using appropriate statistical methods. Detection limits for Nickel and Chromium were determined through calibration curves created from standard solutions, allowing for accurate quantification of metal concentrations in the samples.

2.1. Metal colorimetric analysis studies

Dimethylglyoxime (DMG) was used for nickel analysis. Ammonia was used to enhance color intensity, and 10% sodium thiocyanate (NaSCN) was used to prevent metal interferences. Diphenylcarbazide (DFK) was used for chromium analysis, with acetic acid to enhance color intensity and 1% NaSCN to prevent metal interferences.

2.2. Production of reactant-containing hydrogels

To create nickel hydrogel beads, 1 g of sodium alginate and 0.5 g of sodium carboxymethyl cellulose were dissolved in 60 mL of water. For the nickel solution, 0.5 g of calcium lactate was dissolved in 20 mL of water and mixed with 0.25 g of DMG dissolved in 20 mL of ethanol. This mixture was then combined with 5 mL of 10% NaSCN and 5 mL of ammonia.

For the chromium solution, 0.5 g of calcium lactate was dissolved in 20 mL of water and mixed with 0.1 g of DFK dissolved in 20 mL of ethanol, along with 4 mL of acetic acid and 1 mL of 1% NaSCN. The prepared reactant-containing mixture was then stirred using a magnetic stirrer. A suspension of sodium alginate and sodium carboxymethyl cellulose was added dropwise into the mixture using a dropper. After the dropping process was completed, the beaker was covered with parafilm, and stirring was continued for 30 minutes, after which the mixture was filtered.

The reaction between sodium alginate and calcium lactate in the drops causes the mixture to gel immediately upon contact. Approximately 2000 hydrogel beads can be obtained from 60 mL of the reactant mixture.

2.3. Dehydration rate test

The hydrogel beads were immersed in distilled water until they reached their swelling capacity. After removal, excess moisture was absorbed using filter paper. The hydrogels were weighed, and the results were recorded. Fully swollen hydrogels were then dried at 50°C for 15, 30, 60, 75 minutes, and 24 hours, with weights recorded after each time point. The dehydration rate was calculated using the Equation (1):

$$\text{Dehydration Rate} = (m_e - m_b)/(m_e - m_a) \times \%100 \quad (1)$$

where m_e is the weight at equilibrium swelling, m_b is the weight at various time points, and m_a is the weight after 24 hours (Li et al., 2020). Separate measurements were taken for each time point to determine the dehydration rate over time.

2.4. Equilibrium swelling ratio test

The equilibrium swelling ratio of hydrogels, which indicates the amount of air and water content, is a critical factor in determining the behavior of hydrogels in water. For example, hydrogels with a low equilibrium swelling ratio may exhibit higher floating speeds, while those with a high ratio may have greater stability. The equilibrium swelling ratio is calculated using the mass equilibrium water content (EWC(m)) (2):

$$\text{Equilibrium swelling ratio} = m_{max} - m_o / m_{max} \quad (2)$$

where m_{max} is the mass at maximum swelling, and m_o is the initial weight (Li et al., 2020).

2.5. Saturation test

The saturation coefficient measures the amount of liquid a hydrogel can absorb relative to its own weight, indicating the hydrogel's absorption capacity. A high saturation coefficient signifies a high absorption rate. For example, if a hydrogel has a saturation coefficient of 0.3, it can absorb liquid up to 30% of its own weight. In the saturation test, hydrogel beads were placed in solutions with pH levels of 2, 6, 8, and 11 and monitored at 5, 10, 20, and 30-minute intervals. The initial and post-exposure diameters of the hydrogel beads were recorded, and the saturation variability coefficient was calculated for each pH and duration (3).

$$\text{Saturation} = (R_o - R_1) / (R_o * 100) \quad (3) \quad (3)$$

where R_o is the initial diameter of the hydrogel bead, and R_1 is the diameter after the exposure. The Saturation Variability Coefficient (SVC) is given by (4):

$$\text{Saturation Variability Coefficient} = S_t / avr_t \quad (4)$$

where S_t is the standard deviation of saturation percentages across all measurements, and avr_t is the average saturation percentage (Li et al., 2020; Li et al., 2022).

2.6. Metal interference and stability test

For interference studies, metal ions, including Ni(II), Fe(III), Cu(II), Cr(VI), Al(III), Zn(II), and Co(II) were selected. The color intensities of hydrogels containing masking agents and buffer solutions were measured in analyte solutions containing different metal ions.

3. Results

In this study, the experiments utilizing hydrogel beads for the detection of heavy metals were conducted with careful attention to ensuring repeatability. The experiments were repeated multiple times in accordance with established protocols, consistently yielding similar results. For instance, the color change duration of the hydrogel beads remained constant for specific metal concentrations, demonstrating the reliability of the hydrogels as effective detectors.

These repeated experiments indicate that the hydrogel beads exhibited consistent performance both in practical applications and laboratory settings, confirming the reliability of the results. Consequently, the experimental design and methods employed in this study enhance repeatability, thereby validating the effectiveness of hydrogel beads in the detection of heavy metals.

3.1. Physical analysis of hydrogel beads

The results obtained for the nickel and chromium hydrogel beads are presented in Table 1 and Table 2.

Table 1. Physical analysis results of nickel hydrogel beads

Test Name	Test Result
Dehydration (24 hours)	58.34
Equilibrium Swelling Ratio (ECW%)	72.65
Saturation Variability Coefficient (pH = 2)	0.20
Saturation Variability Coefficient (pH = 6)	0.34
Saturation Variability Coefficient (pH = 8)	0.20
Saturation Variability Coefficient (pH = 11)	0.30

The test results provide valuable insights into the properties of the tested material under various conditions. The material exhibited a dehydration rate of 58.34%, indicating a significant loss of water content over a 24-hour period. This suggests that the material has a moderate to high rate of dehydration, which could be relevant for applications requiring controlled moisture release.

The equilibrium swelling ratio was recorded at 72.65%, demonstrating the material's ability to absorb and retain a substantial amount of liquid relative to its dry weight. This high swelling capacity indicates that the material could be effective in applications where moisture absorption and retention are crucial, such as in hydrogels or wound dressings.

The saturation variability coefficient was measured at different pH levels (2, 6, 8, 11) to assess the material's stability and performance in varying acidic and alkaline environments. The coefficients were relatively low, with values of 0.20 at pH 2, 0.34 at pH 6, 0.20 at pH 8, and 0.30 at pH 11. These results suggest that the material maintains a stable saturation level across a wide range of pH conditions, indicating its potential suitability for diverse applications where pH stability is important, such as in drug delivery systems or biosensors.

Overall, the material's properties, including its dehydration rate, swelling capacity, and pH stability, make it a promising candidate for applications that require controlled water content, high absorbency, and consistent performance across different pH environments.

Table 2. The results obtained for the chromium hydrogel beads

Test Name	Test Result
Dehydration (24 hours)	63.74
Equilibrium Swelling Ratio (ECW%)	64.18
Saturation Variability Coefficient (pH = 2)	0.17
Saturation Variability Coefficient (pH = 6)	0.34
Saturation Variability Coefficient (pH = 8)	0.15
Saturation Variability Coefficient (pH = 11)	0.29

The test results provide important information about the material's behavior under specific conditions, particularly in terms of dehydration, swelling capacity, and pH stability.

The material showed a dehydration rate of 63.74% over a 24-hour period, indicating a substantial loss of water content. This relatively high dehydration rate suggests that the material has a strong tendency to release moisture, which may be advantageous in applications where rapid drying or moisture control is required.

The equilibrium swelling ratio was recorded at 64.18%, reflecting the material's ability to absorb and retain water relative to its dry weight. This moderate swelling capacity suggests that while the material can absorb a significant amount of moisture, it does so to a lesser extent compared to materials with higher swelling ratios. This could be relevant for applications where moderate moisture absorption is desired.

The saturation variability coefficient was measured across a range of pH levels (2, 6, 8, 11) to evaluate the material's stability in different acidic and alkaline environments. The coefficients were low, with values of 0.17 at pH 2, 0.34 at pH 6, 0.15 at pH 8, and 0.29 at pH 11. These low variability coefficients indicate that the material maintains consistent saturation across various pH levels,

suggesting good stability and reliability in environments with fluctuating pH levels. This characteristic is particularly valuable for applications in which pH stability is critical, such as in biomedical devices or environmental sensors.

In summary, the material exhibits a significant dehydration rate, a moderate swelling capacity, and stable performance across a broad pH range. These properties make it a potential candidate for applications that require moisture management and consistent functionality in varying pH conditions.

Hydrogels are moisture-containing materials, and their moisture content decreases during dehydration. This decrease is determined by comparing the hydrogel's moisture content with an initial value. For example, if the initial moisture content of the hydrogel is 100% and it drops to 58%, the hydrogel has undergone 42% dehydration. This means that the hydrogel's moisture content has decreased by 42% from its initial value. The degree of dehydration is measured by the percentage reduction in moisture content.

In this study, the hydrogel beads prepared for nickel showed a moisture loss of 41.66% over 24 hours, while for chromium, this value was 36.26%.

Dehydration graphs with time for nickel and chromium hydrogels are shown in Figure 1 and Figure 2.

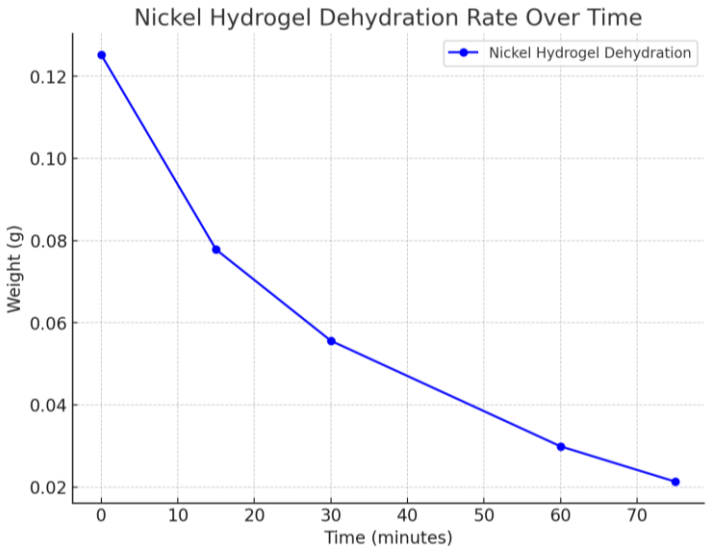


Figure 1. Nickel dehydration rate.

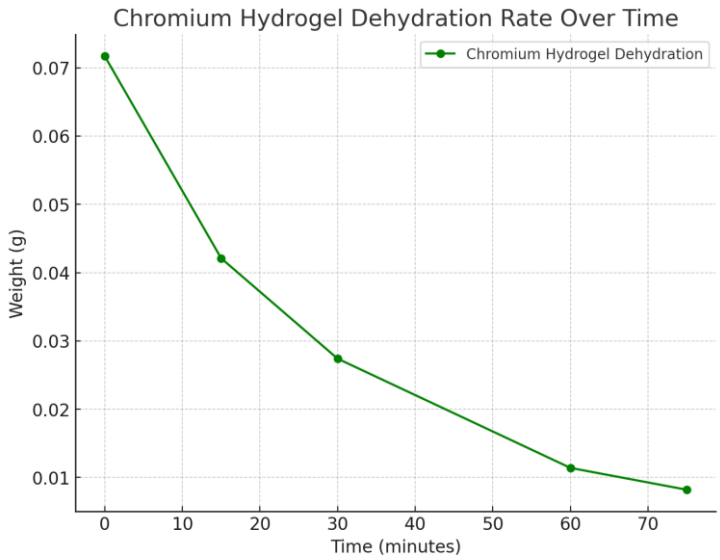


Figure 2. Chromium dehydration rate.

The equilibrium swelling ratio of a hydrogel varies with its moisture content. As the moisture content increases, the hydrogel swells, and as the moisture content decreases, the hydrogel contracts. Therefore, maintaining a certain level of moisture content is crucial for achieving the equilibrium swelling ratio of the hydrogel. If the moisture content is low, the hydrogel may become compact and brittle. Conversely, if the moisture content is high, the hydrogel may become swollen and light. An increased equilibrium swelling ratio is important for the effective use of the hydrogel.

For nickel hydrogel beads, the equilibrium swelling ratio is 72.65%, while for chromium, it is 64.18%.

The swelling change coefficient varies with the hydrogel's moisture content. As the moisture content increases, the degree of swelling increases, and as the moisture content decreases, the degree of swelling decreases. Therefore, the swelling change coefficient of the hydrogel reflects changes in its moisture content. When hydrogels are used in waste and industrial waters, the pH value is a critical variable. Changes in pH can affect the swelling behavior of the hydrogel, which may lead to variations in the results. Hydrogels may exhibit different behaviors at different pH levels, which can affect the efficiency of the results.

The pH/time and % swelling change for nickel hydrogel beads are illustrated in Figure 3.

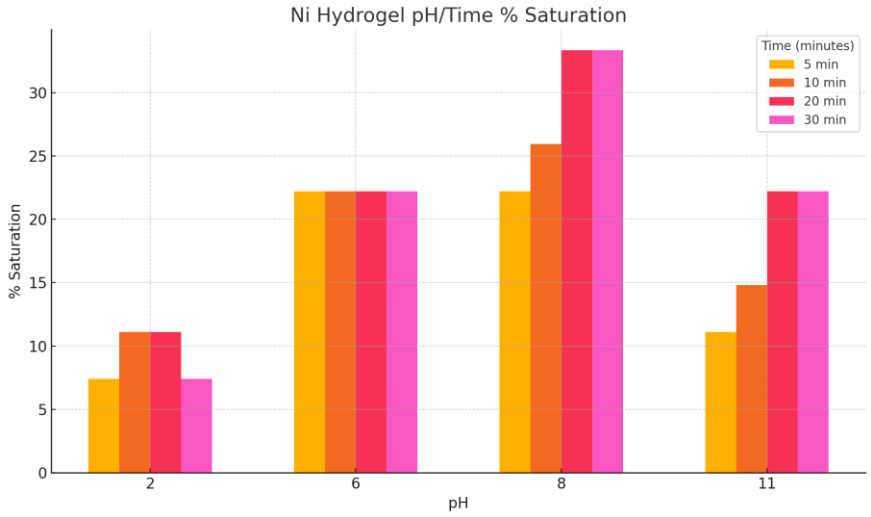


Figure 3. pH/time and % swelling change of nickel hydrogel beads.

The pH/time and % swelling change for chromium hydrogel beads are illustrated in Figure 4.

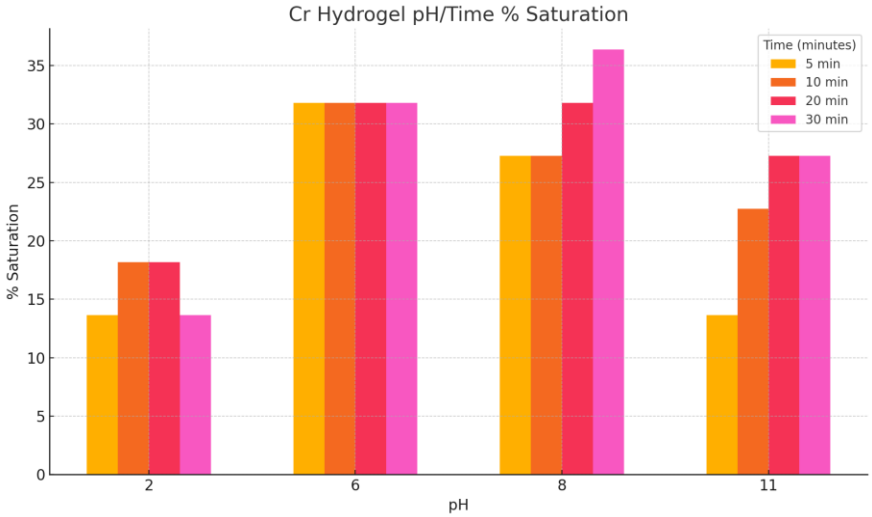


Figure 4. pH/time and % swelling change of chromium hydrogel beads.

The hydrogels exhibit color changes starting at the 2nd minute after being added to the solution to be analyzed, reaching equilibrium by the 10th minute. Thus, the duration for which the hydrogel remains in the solution during use is also crucial for its effectiveness.

3.2. Verification with colorimeter device

RGB is an abbreviation for "Red, Green, Blue," and it is a color model used to represent colors in digital imaging systems. This model operates by combining the three primary color components—red, green, and blue light—which are fundamental to the creation of various colors. Each color component typically has a value ranging from 0 to 255, which determines the overall color combination in a pixel. For instance, an RGB value of (255, 0, 0) indicates that the pixel is entirely red.

The importance of RGB lies in its ability to facilitate color perception and measurement. Colorimeter devices utilize RGB measurements to quantify color changes, which aids in identifying the presence of specific metal concentrations. This approach allows the color changes observed in hydrogel beads during metal detection to be expressed numerically in RGB format. Consequently, the accuracy and repeatability of experimental results are enhanced.

In this study, RGB measurements were employed to validate the effectiveness of hydrogel beads in metal detection. The RGB values of the color changes were analyzed in comparison to metal concentrations, enabling an objective assessment of the performance of hydrogel beads in detecting metals.

In studies aimed at verifying the color differences observed in hydrogels, which were developed for the analysis of nickel and chromium metals and used in real water samples, a comprehensive evaluation was conducted to include intermediate values for nickel and chromium. The differences in ΔE values were determined. All color analyses and RGB readings performed within the scope of this study were conducted using a colorimeter device.

3.3. Metal ınterference and stability studies

Interference studies were conducted with metal ions Ni(II), Fe(III), Cu(II), Cr(VI), Al(III), Zn(II), and Co(II), each at a concentration of 10 mg/mL. The resulting color intensities were compared, as shown in Figure 5. As expected, the color intensities of the analytes containing the target metal ions were similar to those of the target metal ions mixed with the interference ions, while the color intensities of the interference ions alone were significantly lower. This indicated that these interfering ions had minimal impact on the colorimetric detection of the target metal ions.

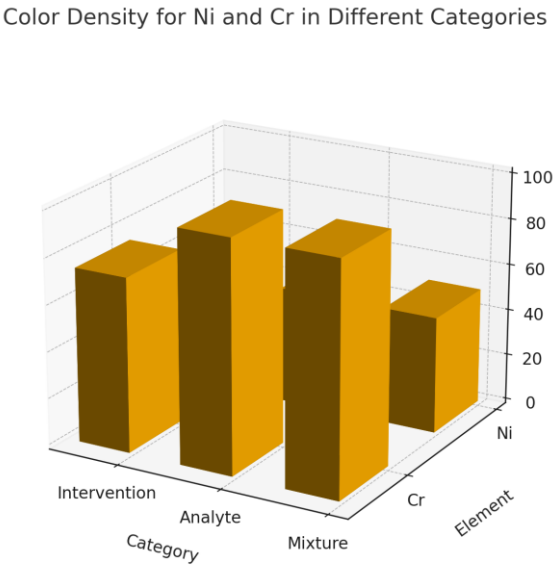


Figure 5. Interference studies with metal ions in hydrogel beads. Color intensity is represented by the ΔE value.

Figure 5 illustrates the results of interference studies conducted with various metal ions using hydrogel beads. The graph represents color intensity changes, quantified by Δ E values, to assess the impact of different metal ions on the colorimetric response of the hydrogel beads.

The graph shows the Δ E values for hydrogel beads exposed to a range of metal ions, including Ni(II), Fe(III), Cu(II), Cr(VI), Al(III), Zn(II), and Co(II). These values reflect the extent of color change induced by each metal ion. The results indicate that the Δ E values for target metal ions (such as Ni(II) and Cr(VI)) are significantly higher compared to those for interference ions.

The hydrogel beads exhibit pronounced color changes (higher Δ E values) when interacting with target metal ions, such as Ni(II) and Cr(VI). This suggests that the hydrogel beads are highly responsive to these specific ions, which is essential for accurate detection and quantification.

The graph shows that interference ions (e.g., Fe(III), Cu(II), Al(III), Zn(II), and Co(II)) result in lower Δ E values. This indicates that these ions have minimal effect on the hydrogel beads' colorimetric response. The low Δ E values for these interference ions suggest that the hydrogel beads maintain their sensitivity to target ions despite the presence of other metal ions.

The minimal interference from other metal ions highlights the robustness of the hydrogel beads in detecting specific target ions. This characteristic is crucial for practical applications, as it ensures that the beads can accurately measure target metal ions even in complex sample matrices containing multiple metal contaminants.

The results underscore the potential of hydrogel beads for reliable metal ion detection in various environmental and industrial settings. The ability of the hydrogel beads to distinguish between target and non-target metal ions makes them valuable tools for precise and accurate analysis, minimizing the risk of false results due to interference.

Figure 5 effectively demonstrates the interference studies with metal ions using hydrogel beads. The high Δ E values for target metal ions and the low Δ E values for interference ions confirm the beads' specificity and sensitivity. This indicates that hydrogel beads are well-suited for accurate metal ion detection, even in the presence of other metal contaminants, enhancing their applicability in diverse analytical and environmental monitoring scenarios.

3.4. Application in real samples

In this study, the "treated wastewater samples taken from the Dudullu OSB Boğaziçi University Technology Development Zone and the processed wastewater samples taken from the Ankara Chamber of Industry 2nd and 3rd Organized Industrial Zones" were found to have low heavy metal concentrations. Particularly, the water samples obtained from Ankara, while classified as industrial wastewater, were insufficient in terms of the specified metal concentrations. Therefore, to address this deficiency, contaminated water samples used in the study were simulated by adding Ni(II), Fe(III), Cu(II), Cr(VI), Al(III), Zn(II), and Co(II) ions to the water samples.

The prepared hydrogel beads were tested with environmental samples. The study was conducted using tap water from Dudullu OSB Boğaziçi University Technology Development Zone and processed wastewater samples from Ankara Chamber of Industry 2nd and 3rd Organized Industrial Zones. The concentrations of Ni (II), Fe (III), Cu (II), Cr (VI), Al (III), Zn (II), and Co (II) in both the tap water and processed wastewater samples were found to be very low and undetectable. As a result, to simulate contaminated water samples, Ni (II), Fe (III), Cu (II), Cr (VI), Al (III), Zn (II), and Co (II) ions were added to the water sample at final concentrations of 10 mg/mL and 25 mg/mL from a standard metal solution used for ICP-MS (Merck-1.11355.0100). The added metal ions, Ni (II) and Cr (VI) were subsequently detected with hydrogel beads (Figure 6, Figure 9).



Figure 6. Results when using nickel hydrogel beads with standards at concentrations of 2.5, 5, 10, 25, and 50 mg/mL.

After the hydrogel beads were placed in solutions containing Ni (II) and Cr (VI), a color change from transparent to pink for nickel and from transparent to magenta for chromium was observed. The color intensity (ΔE) increased proportionally with the concentration. This increase is shown for nickel in Table 3 and for chromium in Table 5.

Table 3. RGB values and ΔE values for nickel hydrogel beads tested with standards

Concentration (mg/mL)	RGB Value	Δ E Value
2.5	220,206,213	17.15
5	212,178,196	28.82
10	231,151,205	49.52
25	198,69,112	75.02
50	193,39,75	85.20

Standard graphs for nickel and chromium metals using hydrogel beads were prepared based on color intensity measurements. The standard graph for nickel is shown in Figure 7, and the standard graph for chromium is shown in Figure 10.

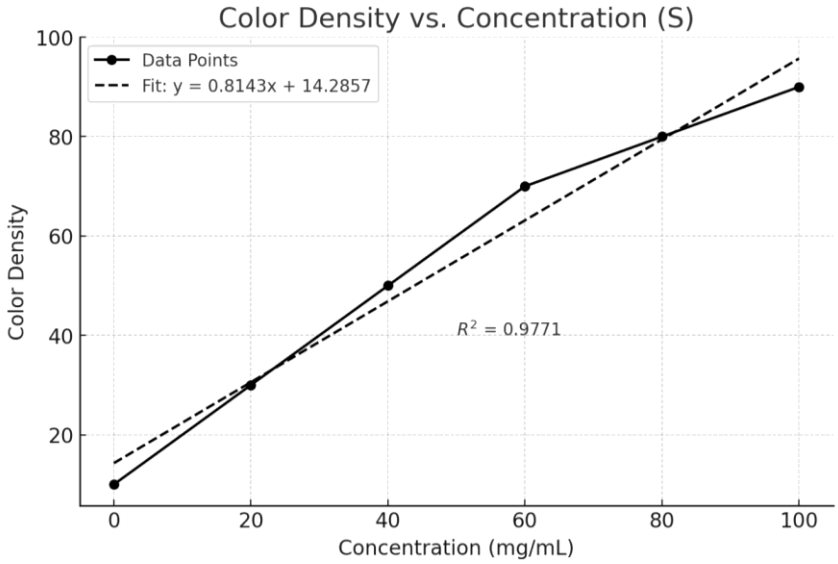


Figure 7. Standard graph prepared from color intensity (ΔE) values of hydrogel beads applied to nickel standards.

The hydrogel beads were tested with real water samples. The test results are presented for nickel in Figure 8 and for chromium in Figure 9.

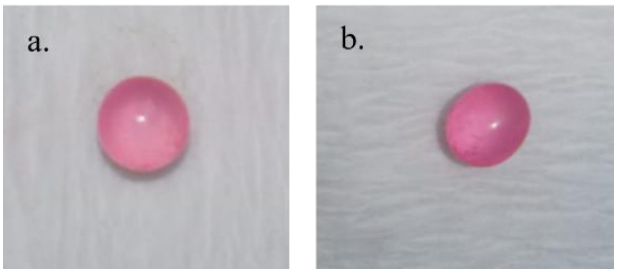


Figure 8. Color changes of nickel hydrogel beads applied to tap water (a) and wastewater (b) containing 25 mg/ml nickel.

Using standard graphs for metal concentrations and color intensity values the concentrations in mg/mL of the hydrogel beads tested in tap water and wastewater were determined. The results for nickel are shown in Table 4, and the results for chromium are shown in Table 6.

Table 4. RGB values and ΔE values for nickel hydrogel beads were tested with tap water and wastewater

Sample	Added	RGB Value	Δ E Value	Found (mg/mL)	%RSD
Tap Water	10	221,157,191	49.224	10.63	1.21
Wastewater	10	215,153,192	43.08	26.32	2.57



Figure 9. Results of nickel hydrogel beads with standards at concentrations of 1, 2.5, 5, 10, 25, 50, and 100 mg/mL.

Table 5. RGB values and Δ E values obtained from testing chromium hydrogel beads with standards

Concentration (mg/mL)	RGB Value	Δ E Value
1	220,200,195	19.59
2.5	215,190,208	24.4
5	228,170,216	40.06
10	230,130,214	65.08
25	210,55,152	85.81
50	216,10,136	96.96
100	213,6,28	101.36

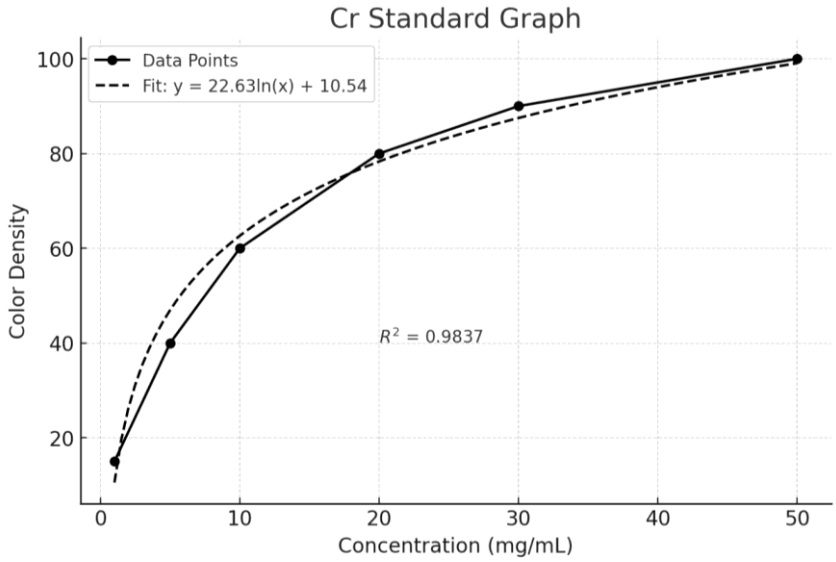


Figure 10. Standard graph prepared based on color intensity (Δ E) values for chromium hydrogel beads applied to chromium standards.

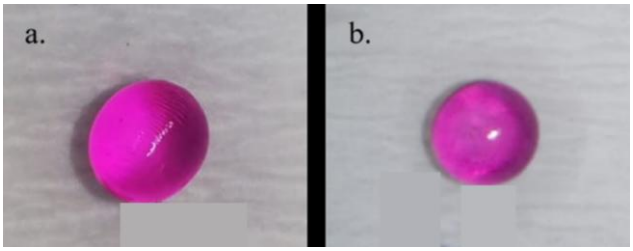


Figure 11. Color changes of chromium hydrogel beads applied to tap water (a) and wastewater (b) containing 25 mg/mL chromium.

Table 6. RGB values and Δ E values obtained from testing chromium hydrogel beads with tap water and wastewater

Sample	Added	RGB Value	Δ E Value	Found (mg/mL)	%RSD
Tap Water	25	202,72,186	86.92	26	7.2
Wastewater	25	195,69,183	87.14	29	7.4

The RGB values and Δ E values reflect the color changes observed in the hydrogel beads when exposed to chromium ions. The high Δ E values in both samples indicate a significant color change corresponding to the presence of chromium, confirming that the hydrogel beads are responsive to chromium ions and can effectively detect their presence in both tap water and wastewater.

Both tap water and wastewater samples showed similar concentrations of chromium, approximately 29 mg/mL, despite the initial added concentration being 25 mg/mL. This consistency suggests that the hydrogel beads effectively capture and quantify chromium ions across different water matrices.

The %RSD values of 7.4% for both tap water and wastewater indicate a relatively low level of variation in the results, signifying good repeatability and precision in the detection process. This low %RSD suggests that the hydrogel beads provide reliable measurements across various sample types.

The similarity in RGB and Δ E values between tap water and wastewater implies that the presence of other substances in wastewater does not significantly interfere with chromium detection. This indicates that the hydrogel beads maintain their performance in complex sample matrices, which is essential for environmental monitoring, where samples often contain multiple contaminants.

Overall, the hydrogel beads have proven to be effective for on-site chromium detection in both clean and contaminated water sources. The consistent detection levels in different water types enhance the versatility of the hydrogel beads, making them suitable for a wide range of applications, including environmental monitoring and wastewater treatment. The high Δ E values and consistently found concentrations confirm the effectiveness of the beads, while the low %RSD underscores their reliability and precision in practical applications.

Hydrogels developed for the analysis of Ni(II) and Cr(VI) demonstrate high efficiency in fluids with varying pH levels. The optimal pH for maximum efficiency is 6.0, at which the hydrogels absorb up to 34% of their own mass in fluid, reaching saturation. Due to their high dehydration rate, the storage and preservation conditions of the hydrogel beads are crucial. Throughout the study, ten hydrogel beads were stored in a 1.5 mL Eppendorf tube at room temperature. However, when exposed to an open environment, the hydrogels began to degrade after one day due to moisture loss, losing about half of their moisture content.

The hydrogel beads operate with high efficiency and accuracy in fluids, exhibiting minimal sensitivity to different pH levels, ions, and substances. They have a detection range of 2.5, 5, 10, 25, and 50 mg/mL for nickel and 1, 2.5, 5, 10, 25, 50, and 100 mg/mL for chromium. The color stability of the hydrogel beads lasts for at least one week when stored in a closed environment.

Measurement of changes in metal concentration during 6 months shelf life is given in Table 7.

Table 7. Measurement of metal concentration changes over a 6-month shelf life

Sample	Added	Found (mg/mL)	6 Month After Found (mg/mL)	Difference
Tap Water	10	10.63	10.95	-0,32
Wastewater	10	26.32	25.86	-0.46

This table presents the changes in metal concentration for tap water and wastewater samples during a 6-month storage period. The initial detected concentrations are compared with the measurements taken after 6 months, with the differences shown both in absolute values.

4. Discussion and Conclusion

This study underscores the significant role of hydrogel beads in the detection of heavy metals, specifically Nickel (Ni(II)) and Chromium (Cr(VI)), in industrial wastewater. The key findings highlight the effectiveness of these hydrogel beads in providing a rapid, cost-effective, and environmentally friendly solution to heavy metal contamination. The established detection limits of 2.5 mg/mL for nickel and 1 mg/mL for chromium emphasize the capability of hydrogel beads to identify hazardous metal concentrations that pose serious risks to both occupational health and environmental safety.

One of the remarkable aspects of this research is the ability of the hydrogel beads to undergo a color change within just 10 minutes upon exposure to metal ions. This rapid response time is crucial in industrial settings where timely detection can significantly mitigate workers' exposure to toxic substances, thereby enhancing workplace safety. Moreover, the hydrogel beads demonstrate robustness by functioning effectively without the need for pre-treatment or pH adjustment, making them suitable for diverse industrial environments where conditions may vary.

Repeated experiments conducted on wastewater samples revealed that the nickel hydrogels demonstrated a success rate of 90.56% in metal detection, while the chromium hydrogels exhibited a success rate of 91.60%. These findings indicate that both hydrogels possess high sensitivity and consistency in detecting heavy metals.

The findings from this study align well with existing literature on colorimetric detection methods, which emphasize the importance of rapid identification of contaminants for effective waste management. However, the unique application of hydrogel technology offers a novel approach to heavy metal detection, contributing to the development of more sustainable industrial practices. When compared to traditional methods, which often involve complex procedures, high operational costs, and skilled personnel, the use of hydrogel beads presents a more user-friendly alternative that can be deployed directly on-site.

The implications of this research extend beyond mere detection of heavy metals. By facilitating compliance with environmental regulations, the application of hydrogel beads not only protects worker health but also safeguards surrounding ecosystems from contamination. The capacity for these beads to provide real-time monitoring enables industries to take immediate corrective actions, reducing the likelihood of hazardous substances entering the environment. Consequently, integrating such technologies into industrial operations can lead to more responsible management of wastewater, ultimately benefiting public health and environmental sustainability.

Despite the promising results, certain limitations of the proposed approach warrant discussion. The specificity of the hydrogel beads to Ni(II) and Cr(VI) may pose challenges in environments where multiple heavy metals or other contaminants are present. Interference from other ions could potentially affect the accuracy of the colorimetric detection. Furthermore, while the hydrogel beads demonstrated robustness, their performance in highly variable conditions, such as extreme pH levels or high concentrations of competing ions, requires further investigation. Addressing these limitations will be essential for enhancing the applicability of hydrogel beads in diverse industrial contexts.

Looking ahead, further research should focus on exploring the scalability of hydrogel bead applications across various industrial contexts. It would be beneficial to investigate the performance of these beads in the presence of other contaminants, such as heavy metals and organic pollutants, as well as under varying environmental conditions, including changes in temperature and pH levels. Such studies will be crucial for optimizing the utility of hydrogel beads in real-world settings and enhancing their sensitivity and specificity for a broader range of heavy metals.

Additionally, future research could explore the potential for functionalizing hydrogel beads with other materials to improve their detection capabilities or to enable the simultaneous detection of multiple contaminants. Such advancements would significantly expand the applicability of hydrogel beads in environmental monitoring and remediation efforts.

Sodium alginate-based hydrogel beads have garnered significant attention in various fields, including environmental monitoring, drug delivery, and food technology, due to their unique properties. These hydrogel beads exhibit several advantages. Firstly, sodium alginate is a naturally occurring polysaccharide that is biocompatible and biodegradable, making it an ideal candidate for applications in biomedical fields, as it minimizes adverse reactions in biological systems (Jayakumar et al., 2011). Additionally, hydrogel beads made from sodium alginate can be easily prepared through simple methods

such as ionotropic gelation, allowing for the formation of beads without the need for complex equipment (Li et al., 2020; Li et al., 2022).

Another notable advantage is their high swelling capacity. Sodium alginate hydrogels can absorb significant amounts of water, which enhances their ability to retain and release substances, making them suitable for various applications, including drug delivery systems (Lee & Mooney, 2001, Zou et al., 2020). Furthermore, hydrogel beads can be modified to selectively bind specific ions or molecules, allowing for targeted applications in metal ion detection and removal from wastewater (Idrees et al., 2020).

However, sodium alginate-based hydrogels also have certain disadvantages. One limitation is their sensitivity to environmental conditions; the performance of these hydrogels can be affected by changes in pH and ionic strength, which may influence their swelling behavior and binding capacity (Idrees et al., 2020; Chen et al., 2023). Additionally, while sodium alginate hydrogels exhibit good swelling properties, their mechanical stability may be lower than that of synthetic hydrogels, leading to structural breakdown under stress and potentially limiting their application in load-bearing environments (Peppas et al., 2000). Furthermore, achieving precise control over the release rates of encapsulated substances can be challenging, impacting their effectiveness in drug delivery systems where controlled release is critical (Qiu & Park, 2012; Adepu & Ramakrishna, 2021).

In summary, sodium alginate-based hydrogel beads offer a range of advantages that make them appealing for various applications, particularly in environmental and biomedical fields. However, their limitations in terms of sensitivity to environmental conditions, mechanical stability, and control over release rates warrant further research (Radoor et al., 2024). Future studies should focus on developing strategies to enhance the performance and stability of these hydrogels, thereby expanding their applicability in diverse settings.

In conclusion, this study provides compelling evidence for the effectiveness of hydrogel beads in detecting heavy metals in industrial wastewater. The findings contribute valuable insights to the field of occupational health and safety, highlighting the potential of innovative materials in addressing the environmental challenges associated with heavy metal pollution. By adopting such solutions, industries can not only enhance safety measures but also fulfill their environmental responsibilities, thereby promoting a healthier and more sustainable future.

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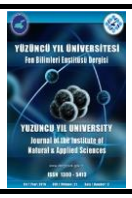
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Araştırma Makalesi

Rüzgâr Enerji Santrallerinin Kuruluş Yeri Seçiminde CBS, Çok Kriterli Karar Verme Analizi ve Bulanık Mantık Yönteminin Kullanılması: Kastamonu ili Örneği

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Öz: İnsan nüfusunun hızla artması birçok problemi ortaya çıkarmaktadır. Bu problemlerden birisi temiz, ucuz ve yenilenebilir enerji kaynaklarına olan erişimdir. Rüzgâr gücünün dünyanın hemen her yerinde bulunması ve erişiminin de diğer enerji kaynaklarına göre daha kolay olması bu kaynağa olan talebi artırmaktadır. Bu talebi karşılayabilmek için santral kurulumuna uygun yerleri tespit edebilecek araştırmalara ihtiyaç duyulmaktadır. Bu çalışmada Kastamonu İl'inde çok kriterli karar verme analizlerinden AHP ve bulanık mantık yöntemleri kullanarak rüzgâr enerji santrali (RES) kurulumu yer seçimi analizi gerçekleştirilmiştir. Parametrelerin birbirine göre önem derecelerinin belirlenmesinde AHP yöntemi kullanılmıştır. Sonrasında çalışma sahasının niteliklerine ve RES kurulum yeri şartlarına göre parametre alt sınıfları oluşturulmuş ve yeniden sınıflandırılmıştır. Ağırlıklandırılan parametre alt sınıflarına bulanık mantık üyelik değerleri atanmıştır. Ağırlıklı çakıştırma yöntemi hem AHP hem de bulanık üyelik sınıfları için kullanılmıştır. Sonuçta iki farklı uygunluk değer haritası üretilmiştir. Araştırmadan elde edilen bulgulara göre Kastamonu İl'inin rüzgâr enerji santrali kurulumu uygunluk yerleri ilin kuzeyinde yoğunlaşmaktadır. Cide, Doğanyurt, Devrekani, Bozkurt ve Pınarbaşı ilçelerinde RES santrali kurulumuna uygun yerler bulunmaktadır. Çalışmadan elde edilen sonuçlar rüzgâr enerjisi potansiyeli (REPA) ile karşılaştırılmıştır. Elde edilen sonuçların REPA atlasındaki bulgularla büyük ölçüde benzerlik gösterdiği belirlenmiştir. Çalışma alanı için yer seçimi analizinde bulanık mantık yönteminin kullanılmasının literatüre katkı sunacağı kanaatindeyiz.

Anahtar Kelimeler: Analitik hiyerarşi yöntemi (AHP), Bulanık mantık, Coğrafi bilgi sistemleri (CBS), Rüzgâr enerji santrali

The Use of GIS, Multi-Criteria Decision-Making Analysis, and Fuzzy Logic Method for Site Selection of Wind Power Plants: The Case of Kastamonu Province

Abstract: The growing human population presents numerous challenges, one of the most significant being the need for access to affordable, clean, and renewable energy sources. Wind power is increasingly favoured over other energy sources due to its widespread availability and accessibility around the globe. To meet this demand, it is essential to conduct research that identifies optimal locations for constructing wind power plants (WPPs). This study uses fuzzy logic and the Analytical Hierarchy Process (AHP) to analyze site selection for WPPs in Kastamonu Province. The AHP method was employed to assess the relative importance of various factors influencing site selection. Following this, parameter subclasses were defined and categorized based on the characteristics and conditions relevant to the study area, particularly the potential WPP installation sites. Membership values were assigned to the weighted parameter subclasses using fuzzy logic. The weighted overlay method was then applied to both the AHP and fuzzy membership classes, resulting in two distinct suitability maps. The findings of the study indicate that the northern part of Kastamonu Province is the most suitable area for wind power plant installations.

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Kabul Tarihi: 28.02.2025

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Specifically, the districts of Cide, Doğanyurt, Devrekani, Bozkurt, and Pınarbaşı were identified as the ideal locations. When compared with the wind energy potential map (REPA), a strong alignment was observed between the study's conclusions and the REPA atlas. We believe that the use of fuzzy logic method in the site selection analysis for the study area will contribute to the literature.

Keywords: Analytical hierarchy process (AHP), Fuzzy logic, Geographic information systems (GIS), Wind power plant

1. Giriş

Fosil yakıtların yenilenemez olmasına ve ciddi çevresel ve sağlık problemlerine yol açmasına rağmen, insan nüfusunun hızla artmasıyla beraber küresel enerji talebinde çok hızlı bir büyüme gerçekleşmiştir (Olabi & Abdelkareem, 2022). Küresel enerjiyle ilişkili karbon emisyonları %1.1'lik bir büyüme gerçekleştirerek 410 milyon ton artmıştır. Karbondioksit emisyonları bu haliyle Paris Anlaşması'nda tespit edilen iklim hedeflerini tutturmak şöyle dursun, 2023'te 37.4 gigatonla yeni bir rekor seviyeye gelmiştir (IEA, 2024). Paris Antlaşması'nın hedeflerini sürdürmek, hava ve su kirliliği, arazi kullanımı ve talebi gibi potansiyel çevresel etkileri en aza indirmek için enerji sektörü şebekesinin karbondan arındırılması (Sıfır karbon emisyonunu sağlayacak) olası bir çözümdür. Bu amaçların gerçekleştirilmesinde yenilenebilir enerji kaynakları önemli bir role sahiptir (Mello ve ark., 2020).

Günümüzde yenilenebilir enerji küresel düzeyde karbon emisyonlarını azaltma potansiyeli olduğu için kamuoyunun artan bir ilgisine sahiptir. Bu ilginin çoğunluğu ise elektrik gücü elde etmeye ve biyoyakıtların üzerine odaklanmıştır (Taibi ve ark., 2010). Rüzgâr gücü çok eski çağlardan bu yana enerji elde etmek için kullanılan yenilenebilir kaynaklardan birisidir. Teknolojinin gelişmesiyle beraber rüzgâr enerjisi rüzgâr gücünün bulunduğu birçok yerde kullanılmaktadır. Rüzgâr enerjisinin ekonomik değer kazanması, yaşam için bir ümit kaynağı olmuştur. Dünyada bulunan 2 milyar megawattlık rüzgâr gücünün çok az bir kısmının kullanılması da gelecekte ilgiyi bu alana yönlendirecektir (Yerebakan, 2001). Rüzgâr enerjisi üretilirken herhangi bir fosil yakıt kullanılmaz. Elektrik üretimiyle ilgili herhangi bir emisyona da sahip değildir (Towler, 2014). Rüzgâr enerjisi temiz ve yenilenebilir bir enerji çeşididir. Yerel ekonomiye katkı sağlar. Rüzgâr gücü elektrik bağlantısı olmayan yerlerde bile vardır. Santralleri arazide çok az yer kaplar. Çevresel etkileri oldukça azdır. Bakımları da gayet kolaydır (Enel Green Power, 2024). Küresel elektrik üretiminin karbon yoğunluğuyla 2022'de 436 gCO_2/kWh ile şimdiye kadarki en temiz kaynaklardan üretilen elektrik oranıdır. Bu durum rüzgâr ve güneş enerjisindeki %12'ye varan rekor büyümeden kaynaklanmıştır. Altmıştan fazla ülke şimdi elektrik üretimlerinin %10'undan fazlasını rüzgârdan sağlamaktadır (EMBER, 2023).

Rüzgâr gücü son zamanlarda hem araştırmacıların hem de enerji sektörü çalışanlarının dikkatini çekmeye başlamıştır. 2023 yılında dünyada en büyük rüzgâr enerjisi projelerinden beş tanesi şu şekildedir: 1. Dogger Bank rüzgâr çiftliği, 2. Baltık açık kıyı rüzgâr enerjisi çiftliği, 3. BP's Morgan ve Mona açık kıyı projesi, 4. Sarıçam, 5. RWE Kuzey deniz rüzgâr projeleri. Bu projelerde üretilen ve üretilecek enerji milyonlarca kişiye ulaşacak ve yerel ekonomilere de büyük katkıları olacaktır (McGuire, 2023). Avrupa Birliği'nde de rüzgâr enerjisi üretimiyle ilgili projeler yapılmaya devam etmektedir. Rüzgâr sektörü Avrupa ekonomisi için büyümeyi teşvik etmekte ve uzun dönemli sürdürülebilir meslekleri ortaya çıkarmaktadır. 2022'de Avrupa Birliği'nde rüzgâr enerjisiyle ilgili işçi sayısı 300.000 civarında iken, 2030'a kadar bu sayının 936.000 kişi kadar olması beklenmektedir (EU, 2024). Rüzgâr enerjisi dünyanın hemen hemen her yerinde bulunabilen bir enerji çeşididir. Açık denizlerde, kıyılarda, yüksek yerlerde, yazın veya kışın birçok mevsimde rüzgâr çeşitli atmosferik şartlara, yerel ya da küresel iklim ve hava şartlarına bağlı olarak oluşur. Ancak rüzgâr enerjisinin kullanılabilir olması için bazı niteliklere ihtiyaç duyulmaktadır. Bazı çalışmalarda korunaklı alanlar, havalimanları, yol ağı gibi parametreler ele alınmıştır (Solbrekke & Sorteberg, 2024). Bazı nitelikler de arazinin topografik yapısıyla alakalıdır. Yükselti, eğim ve bakı bu faktörlerdendir. Bu faktörlerin bileşimi rüzgâr enerji santrallerinin kuruluş yerinin seçiminde etkili olan parametrelerdir. Farklı araştırmalarda farklı parametreler de ele alınabilmektedir. Parametrelerin belirlenmesi ve birbirine göre önem derecesinin ortaya çıkarılmasında, bu faktörlerin tespiti ve enerji santrallerinin yer seçiminde Coğrafi Bilgi Sistemleri (CBS) ve çok kriterli karar verme analizleri birçok çalışmada kullanılmıştır

(Barzehkar ve ark., 2024; Can ve ark., 2024; Gherboudj, 2024; Hall, 2024; Ioannidis & Vagiona, 2024; Placide & Lolchund, 2024; Sahin ve ark., 2024; Solbrekke & Sorteberg, 2024; Vasudevan ve ark., 2024; Yaman, 2024; Yildiz, 2024). Yapılan bu çalışmalar dünyanın birçok bölgesinin rüzgâr enerji potansiyelinin ortaya çıkarılmasını amaçlamıştır.

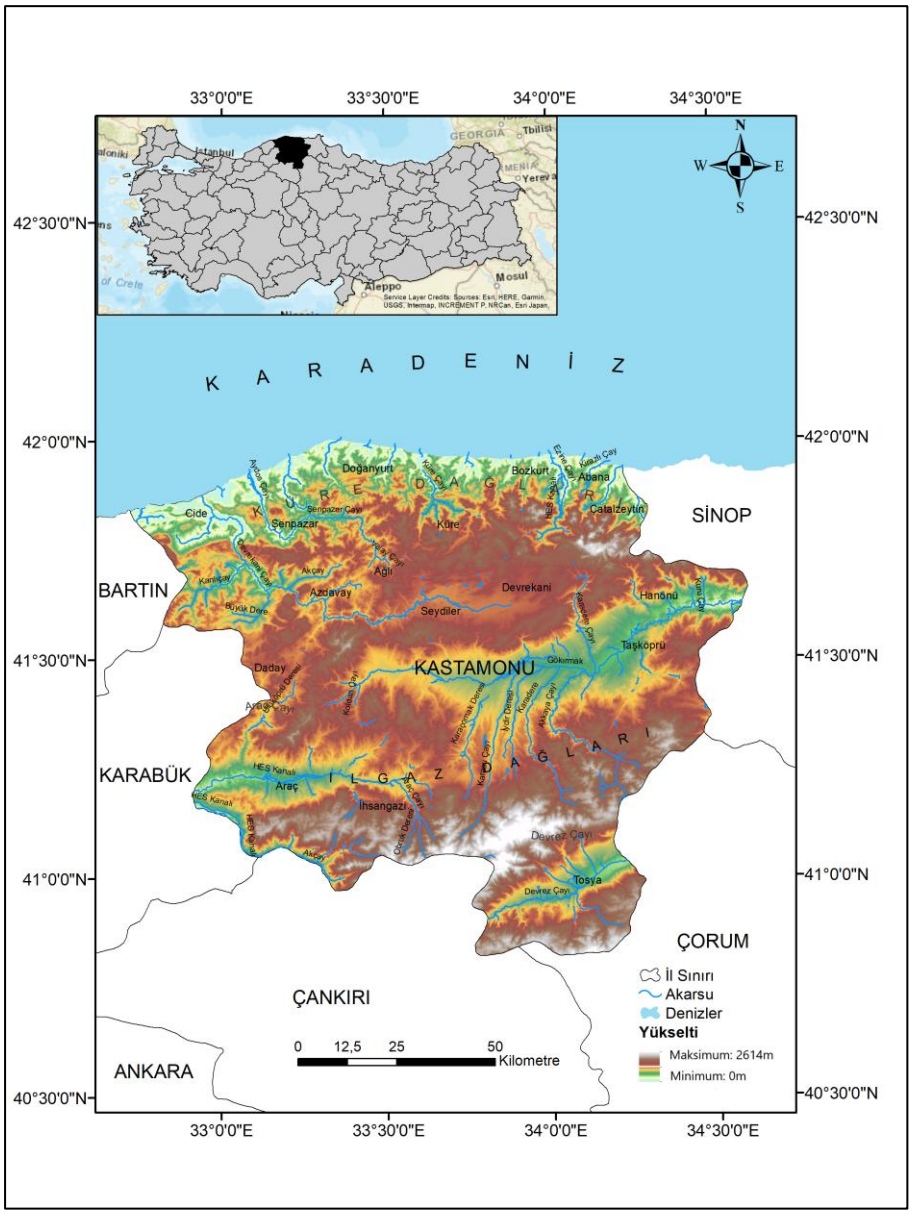
Kastamonu ilinin elektrik santrali gücü 163 Mwe'dir. İldeki 17 elektrik santralinden yılda takribi 328 GWh elektrik üretilmekte ve bu elektriğin büyük kısmı hidroelektrik santrallerinden karşılanmaktadır (Enerji Atlası, 2024). Kastamonu ilinde kurulu rüzgar enerji santrali bulunmamasına rağmen 10 MW'lık rüzgar enerji santrali için lisans alınmıştır. Bu durum ilin rüzgâr enerji potansiyeline sahip olduğunu göstermektedir (KUZKA, 2025). Kastamonu ilinin rüzgar enerji potansiyeli farklı çalışmalarda ele alınmıştır. Bunlardan Kaya ve ark. (2016), Kastamonu ilinin rüzgâr enerji potansiyeli rüzgâr türbin modelleri kullanarak rüzgâr enerjisi elektrik üretim potansiyeli tahminini gerçekleştirmiştir. Köse & Güneser (2019)'in yaptığı çalışmada Batı Karadeniz'de yer alan 7 farklı kentteki (Zonguldak, Bartın, Kastamonu, Bolu, Karabük, Düzce ve Sinop) rüzgâr enerjisi karakteristikleri ve potansiyeli belirlenmiştir. Şener (2017), Türkiye kıyılarının yenilenebilir enerji kaynağı potansiyelini tespit etmiştir. Araştırmadan elde edilen bulgulara göre Kastamonu ili kıyılarındaki rüzgar enerjisi güç yoğunluğu potansiyelinin İstanbul, Hatay ve Çanakkale gibi illerle benzerlik gösterdiği ortaya çıkmıştır. Bahsedilen çalışmalar rüzgar enerji potansiyelini ortaya çıkarırken, rüzgar enerji santrali yer seçimine yönelik herhangi bir analiz içermemektedir. Rüzgar enerji santrallerinin verimli çalışması için santralin kurulacağı yeri önemlidir. Rüzgar enerjisi verimini tespit etmek rüzgardan elde edilen enerji verimini artıracaktır (Kaya ve ark., 2016). Çalışmada Kastamonu ilinde rüzgar enerjisi santrali kurulabilecek alanların yer tespiti CBS, Analitik Hiyerarşi ve Bulanık mantık yöntemleriyle tespit edilmiştir. Yer tespiti için 13 farklı parametre kullanılmıştır. Bu parametrelerin önem sırası AHP yöntemine göre belirlenmiş ve ağırlıklı çakıştırma yöntemine göre bindirme analizleri gerçekleştirilmiştir. Sonuçta iki farklı şekilde yer seçimi analizi yapılarak sonuçlar karşılaştırılmıştır. Farklı yöntemler kullanarak sonuçların elde edilmesi ve karşılaştırmaların yapılması çalışmanın özgünlüğünü oluşturmaktadır. Bu yaklaşım, yer seçimi analizi için alternatifleri artırırken karşılaştırmaları daha kolay ve etkili hale getirmektedir.

2. Materyal ve Yöntem

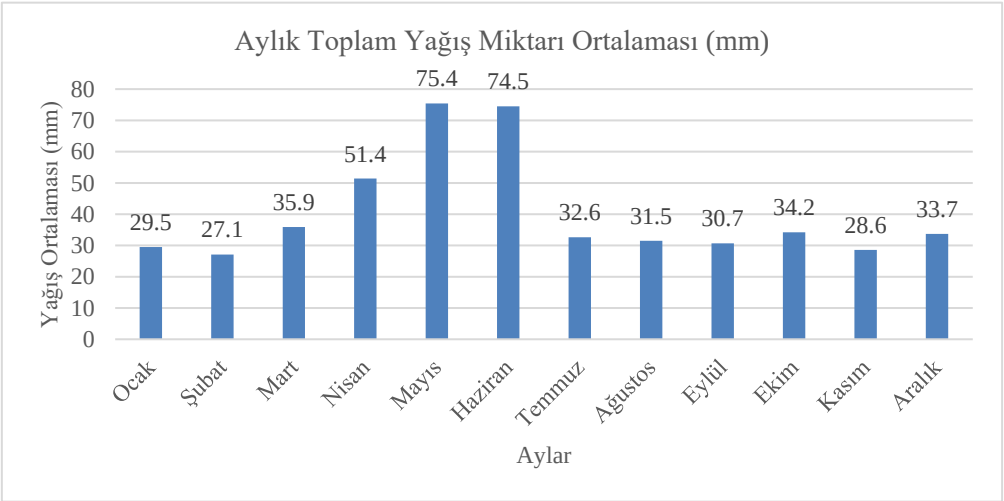
2.1. Çalışma alanı

Çalışma alanı Kastamonu ilidir (Şekil 1). İlde iki büyük dağ sistemi bulunur. Bunlardan Küre Dağları (İsfendiyar Dağları) Alp-Himalaya kıvrım dağ sisteminin bir parçasıdır. Doğu-batı yönlü olarak Karadeniz'in ardında uzanır. Bu sistemin batısında Bartın Çayı, doğusunda ise Kızılırmak nehri vardır (Duran, 2021). Küre Dağları denizle iç kesim arasında bir set teşkil eder. Küre Dağları fazlaca parçalanmıştır. Değişik seviyelerde var olan plato düzlükleri ve kıyının ardında olması nedenleriyle iklim niteliklerinden farklılıklar ortaya çıkar (Kurter, 1982). Örneğin kıyıda bulunan İnebolu meteoroloji istasyonunda yağış en fazla sonbahar mevsiminde görülür. Kastamonu merkez ilçesinde ise en fazla yağış karasallık etkisiyle ilkbahara kaymıştır (Şekil 2).

Engebeye bağlı olarak kıyıdan iç kesime doğru iklim değişimi ortaya çıkar. Küre Dağları sayesinde kıyıda Karadeniz ikliminin özellikleri belirgin olarak görülürken, iç kesimlerin iklimi karasallığa kaymıştır (Duran, 2017). Kastamonu Merkez ilçesinde bulunan Meteoroloji Genel Müdürlüğü'nden elde edilen uzun yıllar (1930-2023) meteorolojik verilerine göre ortalama sıcaklık 9.9 ºC iken en düşük sıcaklık ortalaması -1.0 ºC olarak ocak ayında, en yüksek sıcaklık ortalaması temmuz ayında 20.2 ºC'dir. Kıyıda bulunan İnebolu, Cide gibi yerleşim merkezlerinin rüzgâr hızları Kastamonu merkez istasyonundan daha fazladır. Bu durumun oluşmasında kıyıda rüzgâr hızını kesebilecek herhangi bir engelin olmaması, iç kesimde ise Küre Dağları engelinin rüzgarları kesmesinden dolayıdır (Coşkun, 2021).



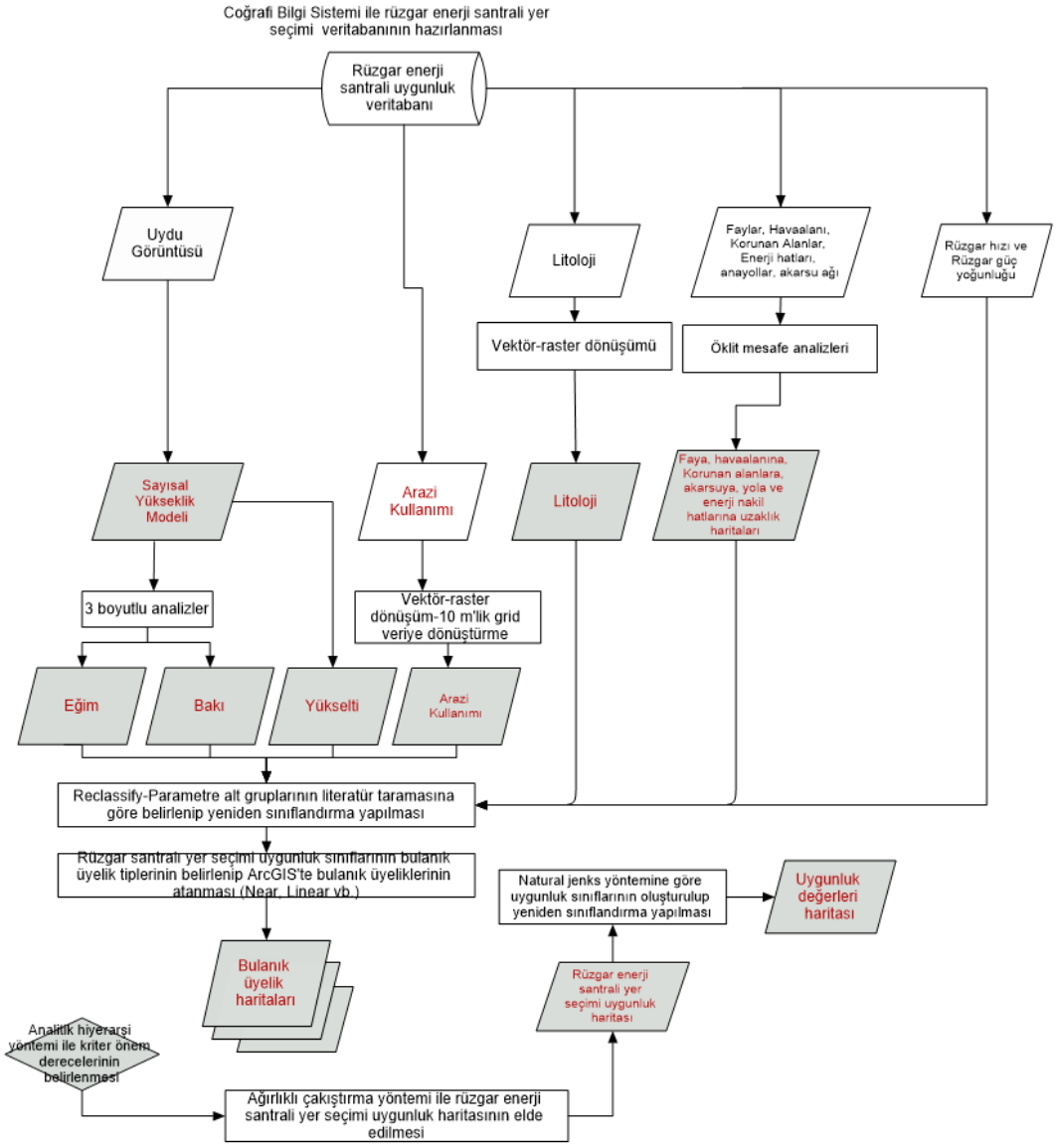
Şekil 1. Çalışma alanının konum haritası.



Şekil 2. Kastamonu ili merkez ilçesi uzun yıllar yağış değerleri ortalaması (MGM, 2024).

2.2. Çalışmada kullanılan veriler ve metot

Çalışmada Kastamonu ili rüzgâr enerjisi kurulabilecek alanlar CBS, çok kriterli karar verme analizlerinden Analitik Hiyerarşi Yöntemi ve Bulanık Mantık yöntemleriyle belirlenmiştir (Şekil 3).



Şekil 3. Rüzgâr enerji santrali yer seçimi işleminin bulanık mantık yöntemiyle gerçekleştirilme işlem adımlarının şematik gösterimi.

Çok kriterli karar verme analizi birden fazla kritere sahip oluna durumlarda en mantıklı karar vermeyi sağlayabilen matematiksel işlemlere bağlı analiz metodudur (Roy, 1996). Rüzgâr enerji santrallerinde kurulum yerlerinin belirlenmesinde parametre ve alt gruplarının birleştirilmesinde çok kriterli karar verme analizleri yoğunlukla kullanılmaktadır. Çok kriterli karar verme analizlerinin gerçekleştirilebilmesi için öncelikle çalışma sahasında rüzgâr enerji santralleri yer seçimine ait parametre verileri (Yerleşim alanları, milli parklar ve askeri alanlar, göller ve barajlar, akarsular, karayolları, fay hatları, ormanlık alanlar, eğim, yükselti, kapasite faktörü) elde edilmiştir. Verilerin temin edilmesinden sonra yer seçimi analizi için coğrafi veri tabanı oluşturularak veriler bu ortama aktarılmıştır. Yükselti haritası yüksek çözünürlüklü (12.5x12.5m), ALOS PALSAR uydu görüntüsünden elde edilmiştir. Eğim ve bakı veri grupları ise yükselti verisinden CBS yazılımıyla üretilmiştir. Yerleşim alanlarına, milli parklara ve askeri alanlara, göllere ve barajlara, akarsulara, karayollarına, fay hatlarına, ormanlık alanlara uzaklık Öklid mesafe analizi ile elde edilmiştir.

Sınıflandırma analizi verilerin istenilen bölümlere ayrılmasını sağlayan bir yöntemdir. Her bir veri alt grubunun yer seçimi analizi üzerindeki etki düzeyi farklılaşabilir. Bu farklılık araştırma sahasının niteliklerine göre değişmektedir. Bu niteliklerin değişkenliği AHP ile veri alt gruplarına atama işlemi ile gösterilmektedir. AHP, Saaty (1994) tarafından geliştirilen bir yöntemdir. Bu yöntem özellikler setinin göreceli değerlerini açıklayan matris oluşturma işlemine dayanır (Coyle, 2004). Bu metot problemin ve aranan bilginin tespiti, üstten alta doğru karar verme hiyerarşisinin belirlenmesi, ikili karşılaştırmalar matrisinin oluşturulması, kriter tutarlılık oranlarının tespiti, kriterlerin birleştirilmesi ve sonuç haritalarının oluşturulması işlemlerine dayanır (Tombuş, 2005). Karşılaştırmanın yapılması için karşılaştırmanın yapıldığı niteliğe bağlı bir özellik veya parametrenin diğerine göre önemi veya baskınlığını gösteren bir çizelgeye ihtiyaç duyulmaktadır (Çizelge 1).

Her bir veri grubunun üyelik sınıflarının ağırlık değerleri AHP'yle belirlendikten sonra bulanık üyelik sınıflarına alınmıştır. Ağırlıklı doğrusal birleştirme analizi ile rüzgâr enerji santrali en uygun yer analizi tespit edilmiştir. En son olarak uygun değil, az uygun, uygun ve çok uygun şeklinde 4 sınıf halinde uygunluk analizi temsil edilerek görselleştirme işlemleri yapılmıştır.

Çalışmada rüzgâr enerji santrallerinin yer seçimi analizi bulanık mantık yöntemiyle de gerçekleştirilmiştir. Bulanık mantık gerçek dünyada belirsiz ya da iç içe geçmiş, kesin sınırları olmayan varlıkları ya da durumları betimlemekte kullanılan bir yöntemdir. Örneğin en uygun yer analizinde orta eğime sahip olsun, göle yakın, ama ana yola yakın olmasın gibi durumları ifade etmeye çalışırız (Kainz, 2007). Bu tür şartlar klasik küme teorisiyle ifade edilememektedir. Küme teorisinde herhangi bir varlığın veya unsurun belirli bir kümeye ait olup olmaması 1 ya da 0 gibi net ifadelerle belirtilir. Ancak az, orta veya çok gibi durumları belirtmek bu teoride mümkün değildir. Bulanık mantık teorisi Lotfi A. Zadeh tarafından geliştirilmiştir (Zadeh, 1988). Bulanık modelleme genel manada, bir sistemin matematiksel terimlerle bir tanımının oluşturulmasını ifade etmektedir (Chen & Pam, 2001). Bulanık modeller oluşturulurken değişik üyelik fonksiyonları kullanılabilmektedir (Altaş, 1999). Probleme bağlı olarak uygun değişkenler seçilerek üyelik fonksiyonları ve bulanık alt kümelere bağlı kural dizisi ve kural tabanları oluşturulur (Ross, 1995).

Çizelge 1. AHP parametre önem ölçeği (Saaty, 1994)

Önem yoğunluğu	Tanım	Açıklama
1	Eşit önem	Her iki faktör eşit öneme sahip
3	Biraz daha önemli	Birinci faktör ikinciye göre biraz daha önemli
5	Güçlü önem	Birinci faktör ikinciye göre daha çok önemli
7	Çok güçlü önem	Birinci faktör ikinciye göre çok güçlü öneme sahip
9	Son derece önemli	Birinci faktör ikinciye göre mutlak üstün bir önem sahip
2,4,6,8	Ara değerler	

2.3. Çalışmada kullanılan parametreler ve normalizasyon işlemleri

Rüzgâr enerji santrallerinin kurulumunun yer seçimi için birçok parametre gereklidir. Bu parametreler farklı çalışmalardan ele alınmıştır. Bu niteliklerden: topografya, eğim, bakı, yükselti gibi faktörler (Urfalı & Eymen, 2021; Yaman, 2024; Baban & Parry, 2001; Şahin ve ark., 2024), fay hatlarına uzaklık (Can ve ark., 2024; Yildiz, 2024), yol ağına uzaklık (Albraheem & Alawlaqi, 2023) yerleşim alanlarına uzaklık (Baban & Parry, 2001); arazi kullanımı, korunan alanlara uzaklık (Albraheem & Alawlaqi, 2023), rüzgar hızı (Yaman, 2024; Şahin ve ark., 2024; Vinhoza & Schaefer, 2021; Flora ve ark., 2021), rüzgar güç yoğunluğu (Özşahin & Kaymaz, 2013), havaalanına uzaklık (Urfalı & Eymen, 2021), akarsuya uzaklık (Özşahin & Kaymaz, 2013) gibi parametreler analiz yapılmak üzere seçilmiştir. Rüzgâr enerji santrali yer seçiminde kullanılan kriterler ve uygunluk sınıflarının elde edildiği ortamlar aşağıdaki Çizelge 2'de gösterilmiştir. Çalışmada kullanılan veriler açık veri kaynaklarından elde edilerek analiz edilmiştir. Yükselti verileri ALOS PALSAR internet sitesinden 12.5 X 12.5 metre çözünürlükte indirilerek yükselti, eğim ve bakı gibi veri altlıklarının üretilmesinde kullanılmıştır.

Rüzgâr hızı ve güç yoğunluğu Küresel Rüzgâr Atlası (Global Wind Atlas) sitesinden elde edilmiştir. Yerleşim alanları, korunan alanlar, anayollar, havaalanı gibi veri altlıkları ise Open Street Map'ten elde edilmiştir. Elde edilen verilerden yerleşim merkezleri, korunan alanlar, enerji hatları, havaalanına uzaklık ve ana yollara uzaklık parametre haritaları Öklid Mesafe Analizi yöntemiyle elde edilmiştir. Diğer parametrelerden olan eğim sayısal yükseklik verisinden elde edilmiştir.

Çizelge 2. Rüzgâr enerji santrallerinin yer seçiminde etkili olan parametrelere ait verilerin elde edildiği ortamlar

Parametre	Veri tipi	Verinin elde edildiği ortam	Url'si
Rüzgâr hızı	Raster	Global Wind Atlas	https://globalwindatlas.info/en
Rüzgâr güç yoğunluğu	Raster	Global Wind Atlas	https://globalwindatlas.info/en
Enerji nakil hatlarına uzaklık	Vektör	Overpass (OSM)	https://overpass-turbo.eu/
DEM	Raster	ALOS PALSAR	https://search.asf.alaska.edu/#/
Eğim	Raster	DEM	
Fay hatlarına uzaklık	Vektör	MTA	http://yerbilimleri.mta.gov.tr/anasayfa.aspx
Arazi kullanımı	Raster	ESRI Land Cover	https://livingatlas.arcgis.com/landcover/
Akarsuya uzaklık	Vektör	Hidroloji analizi	
Yerleşim alanlarına uzaklık	Vektör	OSM	https://www.openstreetmap.org/
Korunan alanlara uzaklık	Vektör	OSM	https://www.openstreetmap.org/
Havaalanına uzaklık	Vektör	OSM	https://www.openstreetmap.org/
Anayollara uzaklık		OSM	https://www.openstreetmap.org/

2.4. Parametrelerin ağırlıklandırılması ve normalizasyon işlemleri

2.4.1. AHP yöntemiyle kriterlerin ağırlıklandırılması

Parametrelerin ağırlıklandırılması ve normalizasyon işlemleri için AHP ve Bulanık Mantık yöntemlerinden yararlanılmıştır. AHP yöntemi (Saaty, 1990) tarafından geliştirilmiş bir metottur. Bu yöntemde sürecin matematiği ve hesaplama teknikleri özelliklere ait setin göreceli değerlerini açıklayan bir matris oluşturma işlemine dayalıdır (Coyle, 2004). Parametrelerin ağırlıklandırılmasında literatür araştırmasından yararlanılmıştır (Özşahin & Kaymaz, 2013; Arca & Keskin Çıtıroğlu, 2020; Ekiz ve ark., 2022). Her bir parametre 1-10 değer aralığında ağırlıklandırılmıştır. Parametre ikili karşılaştırma çizelgesi aşağıda verilmiştir (Çizelge 3).

Kriterlerin karşılaştırılmasının ne kadar tutarlı olduğunun ölçümü için tutarlılık oranı hesaplanmıştır (Ekiz ve ark., 2022). Tutarlılık oranı 0.10'dan büyük çıkma durumunda değerlerin birbiriyle tutarsız şekilde girildiği anlaşılır (Urfalı & Eymen, 2021).

Yapılan çalışmada ikili karşılaştırmalardan elde edilen tutarlılık oranının 0.7 olduğu tespit edilmiştir. Toplamda 13 parametre için RI değeri 1.56 alınmış, CI değeri 0.102, CR değeri $\frac{CI}{RI}$ = 0.065'tir. Bu değer 0.10'dan küçük olduğu için (Saaty, 1994) yapılan işlemlerin tutarlı olduğu ortaya çıkmıştır. Rüzgâr enerji santrallerinin en uygun yer analizi için 13 farklı veri seti kullanılmıştır (Şekil 4a ve Şekil 4b). Bunlardan rüzgâr hızı Global Wind Atlas'tan temin edilmiştir. Global Wind Atlas'tan elde edilen veriler 5 sınıfa ayrılmıştır (Çok fazla, uygun, orta, az ve uygun değil). Yapılan ikili karşılaştırmalarda AHP'de en fazla öneme sahip parametre olarak tespit edilmiştir (%21.9). Rüzgâr güç yoğunluğu rüzgâr enerji santrallerinin kurulumunda önemli bir parametredir. Birimi w/m^2'dir (Korkmaz ve ark., 2023). İkili karşılaştırmalarda AHP'de tutarlılık oranı en yüksek ikinci parametre olarak (%16.9) bulunmuştur.

Çizelge 3. Rüzgâr enerji santrali en uygu yer analizi faktörleri AHP etki değerleri ikili karşılaştırma matrisi

Faktörler	Rüzgâr hızı	Rüzgâr güç kapasitesi	Korunan alanlara uzaklık	Enerji hatlarına uzaklık	Yerleşim alanlarına uzaklık	Karayollarına uzaklık	Fay hatlarına uzaklık	Yükselti	Eğim	Arazi kullanımı	Havaalanına uzaklık	Anayollara uzaklık	Akarsuya uzaklık	AHY ağırlık %
Rüzgâr hızı	1	3	3	3	3	3	3	5	5	5	7	9	9	21.9
Rüzgâr güç kapasitesi	½	1	3	3	3	3	3	5	5	5	7	9	9	16.9
Korunan alanlara uzaklık	1/5	1/3	1	2	2	3	3	3	3	7	7	7	9	12.4
Enerji hatlarına uzaklık	1/3	1/3	½	1	1	2	3	3	5	5	5	9	9	9.7
Yerleşim alanlarına uzaklık	1/3	1/3	½	1	1	1	2	3	3	5	7	7	9	9.3
Anayollara uzaklık	1/3	1/3	1/3	½	1	1	1	2	3	3	5	7	9	7.7
Fay hatlarına uzaklık	1/3	1/3	1/3	1/3	½	1	1	1	3	3	5	7	7	6.6
Yükselti	1/5	1/5	1/3	1/3	1/3	1/2	1	1	1	2	5	7	7	5
Eğim	1/5	1/5	1/3	1/5	1/3	1/3	1/3	1	1	1	2	2	7	3.4
Arazi kullanımı	1/5	1/5	1/7	1/5	175	1/3	173	½	1	1	1	3	5	2.8
Havaalanına uzaklık	1/7	1/7	1/7	1/5	1/7	1/5	1/5	1/5	½	1	1	1	3	1.9
Litloji	1/9	1/7	1/7	1/9	1/7	1/7	1/7	1/7	½	1/3	1	1	3	1.5
Akarsuya uzaklık	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/7	1/7	1/5	1/3	1/3	1	1

Koruma altına alınan alanlar biyolojik çeşitliliğe sahip yerlerdeki kaynakların korunması ve devamlılığının sağlanması amacıyla ilgili yasal hükümlere göre yönetilen karasal, sucul ya da denizel alanlara denir (ÇŞİDB, 2024). Koruma altına alınmış alanların zarar görmemesi, yok olmaması için bu alanlara uzaklık önemli bir faktördür (Ekiz ve ark., 2022). Korunan alanlara uzaklıktaki mesafelerin belirlenmesi amacıyla Öklid mesafe analizi yapılmıştır. Sonuç haritası 6 sınıfa ayrılmıştır ve AHP'de tutarlılık oranı %12.4 olarak tespit edilmiştir. Enerji nakil hatlarına uzaklık da rüzgâr enerji santrallerinin kurulumu için önemli parametrelerden birisidir.

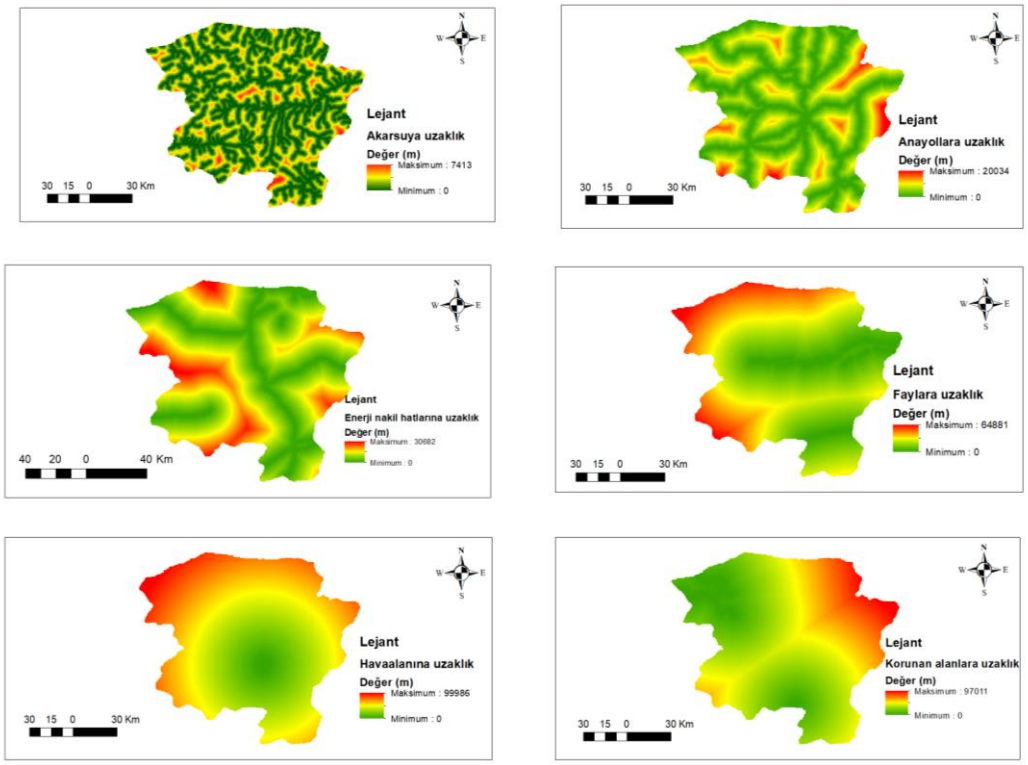
Enerji santrallerinde türbin pervane yarıçapı 101 metre olduğu için 100 metreden yakın alanlar kısıtlanmalı, enerji hatlarından uzaklaşıldıkça verilen skorda azalma meydana gelecektir (Sunak ve ark., 2015). Enerji hatlarına uzaklık Öklit mesafe analiziyle tespit edilmiştir. Bu veri katmanının yapılan analizle AHP'de tutarlılık oranının %9.4 olduğu tespit edilmiştir. Rüzgâr enerji santrallerinin sosyal kabullerden, gürültü, güvenlik estetik şartlardan dolayı yerleşim alanlarının dışında kurulması gereklidir (Sunak ve ark., 2015). Çalışma alanında 1355 yerleşim birimine uzaklıkların ortaya konması için öklid mesafe analizi gerçekleştirilerek uzaklık haritası oluşturulmuştur. Bu veri sınıfı yeniden sınıflamaya tabi tutularak ağırlıklandırılmış yerleşim alanlarına uzaklık veri katmanı üretilmiştir.

Yola uzaklık da RES kurulum yeri seçiminde etkili olan faktörlerden birisidir. Santrallere rahatça ve masrafsız şekilde ulaşım için firmalar yol açtırmaktadır (Özşahin & Kaymaz, 2013). Yola uzaklık veri sınıfını elde etmek için Öklit mesafe analizi gerçekleştirilmiştir. Deprem sırasında binalar, alt yapı unsurları zarar görmektedir. Rüzgâr enerji santralleri de deprem sırasında zarar görebilir. Aktif olan fay hatlarından uzaklaşıldıkça deprem etkisi de azalacağı için yer seçim analizinde faya yakınlık dikkate alınan bir faktördür (Arca & Keskin Çıtıroğlu, 2020).

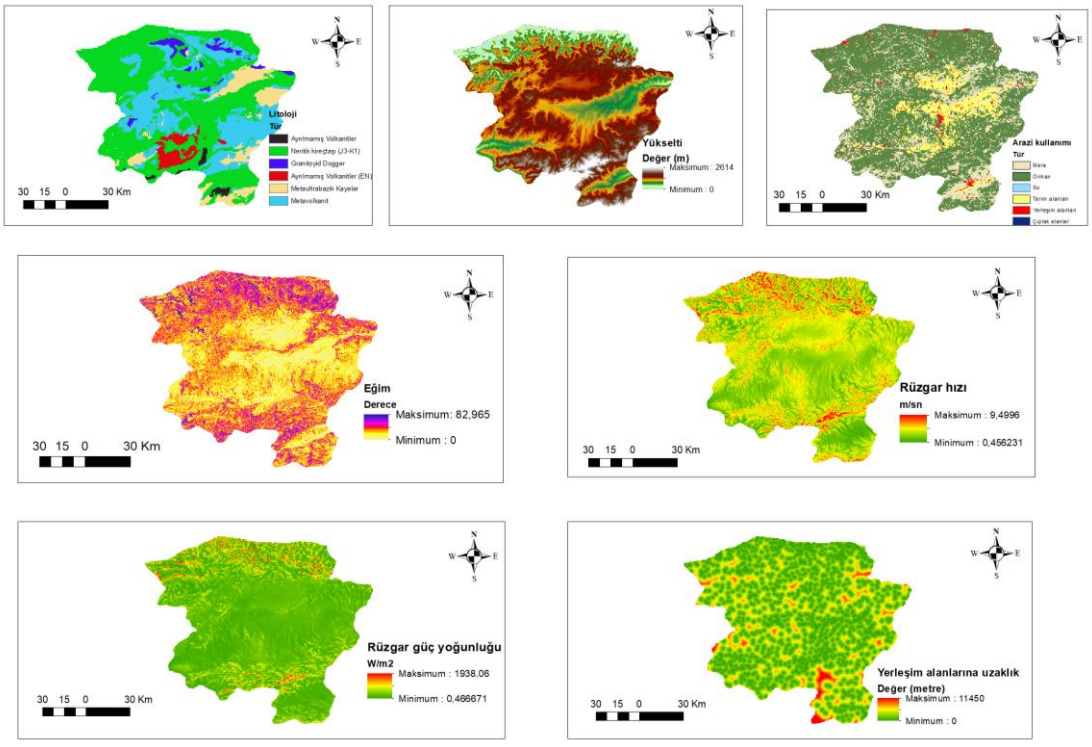
Dünya'da ve Türkiye'de en faal fay hatlarından biri olan Kuzey Anadolu Fayı Kastamonu Şehir merkezine 35 kilometre uzaklıkta ve Kastamonu'ya önemli bir tehdit kaynağıdır (Özmen, 2011). Fay zonlarına yakınlığın belirlenebilmesi için Öklid mesafe analizi gerçekleştirilmiştir. Mesafe analizinden elde edilen veri sınıfı 6 sınıfta temsil edilerek yeniden sınıflandırma işlemi gerçekleştirilmiştir. Rüzgâr hızıyla yükselti arasında korelasyon söz konusudur. Buna göre rüzgâr hızı yükseltiye bağlı olarak her yüz elli metrede bir artış göstereceği belirlenmiştir (Özşahin & Kaymaz, 2013). Yükselti haritası ALOS PALSAR uydusundan 12.5x12.5 metre çözünürlükte elde edilmiştir. 6 sınıfa ayrılan yükselti veri sınıflarına rüzgâr hızı ilişkisine bağlı olarak etki değeri atanarak yeniden sınıflandırma yapılmıştır. Çalışma alanında yükselti 0 metreden 2614 metreye kadar değişiklik göstermektedir. Yükseltisi az olan yerlerin rüzgâr enerji potansiyeli az olacağı düşünüldüğünden etki değeri az, yükseltisi fazla olan yerlerin rüzgâr enerji potansiyeli fazla olacağı düşüncesiyle yüksek etki puanı verilmiştir. Ancak yüksek yerlerde enerji santrali kurulması arazi şartlarından dolayı zor olacağı için 1500 metreden yüksek yerlerin etki değeri en az olarak değerlendirilmiştir (Ekiz ve ark., 2022). Topografik niteliklerden bakı, eğim ve yükselti arazi kullanımını etkilemektedir. Uçurumlara yakın yerler ve yüksek yerler rüzgâr türbini yapımı için uygun değildir (Bennui ve ark., 2007). Yükselti haritasından derece olarak elde edilen eğim değerleri 0-5, 5-10, 10-15, 15-20, 20-30 ve 30'dan büyük olmak üzere 6 sınıfa ayrılarak etki değerleri ataması yapılmıştır. Eğimi en az olan yerlere en büyük etki değerleri, eğimi fazla olan yerlere ise en az etki değer ataması gerçekleştirilmiştir (Ekiz ve ark., 2022).

Arazi kullanım niteliği de rüzgâr enerji santralleri yer seçiminde etkili olan faktörlerden birisidir. AHP ikili karşılaştırmalarında arazi kullanımı ağırlık değeri yüzde 2.8 olarak tespit edilmiştir. Çalışma alanındaki arazi kullanımı sınıfları şunlardır: Mera, orman, su, tarım alanları, yerleşim ve çıplak alanlardır. Bunlar içerisinde RES santrallerinin yapımı için en az uygun olduğu düşünülen arazi sınıfı olan orman, su ve yerleşim alanlarına en düşük ağırlık değeri verilirken; çıplak alanlara, tarım alanlarına en yüksek etki değeri verilmiştir (Özşahin & Kaymaz, 2013). Havaalanlarının çevresindeki ilk 3000 metre içerisinde insanların toplu biçimde bulunacağı hastane, otogar ve uçuş güvenliğini riske atacak yapılara müsaade edilmemektedir. Rüzgâr enerji santrallerinin yüksekliği fazla olduğu için havaalanından 3000 metre uzaklıkta yapımlarına izin verilmemektedir (Ekiz ve ark., 2022). Havaalanına uzaklık birimlerinin belirlenmesi için Öklit mesafe analizi yapılmış, sonrasında elde edilen uzaklık değerleri 0-3000, 3000-6000, 6000-9000, 9000-12000, 12000-15000 ve >15000 şeklinde 6 farklı sınıfta yeniden sınıflandırılmıştır. Çalışma alanında litoloji birimleri olarak granitoyid, ayrılmamış volkanitler, metavolkanit ve neritik kireçtaşı gibi birimler bulunmaktadır. Bu birimler MTA'nın sitesinden indirilerek sayısallaştırılmıştır. Zemin sertliği ve sağlamlığı nedeniyle metamorfik birimlere en yüksek etki değeri verilirken, sedimanter birimlere en düşük etki değeri verilerek yeniden sınıflandırma işlemi gerçekleştirilmiştir. Akarsulara yakın olan alanlar rüzgâr türbini kurulması için uygun değildir (Ekiz ve

ark., 2022). Çalışma alanındaki akarsulara uzaklık faktörünün elde edilmesi için Öklit mesafe analizi kullanılmıştır. Elde edilen uzaklık değerleri 6 sınıfta yeniden sınıflandırılarak alt faktör grupları oluşturulmuştur.



Şekil 4a. Çalışmada kullanılan veri setleri.



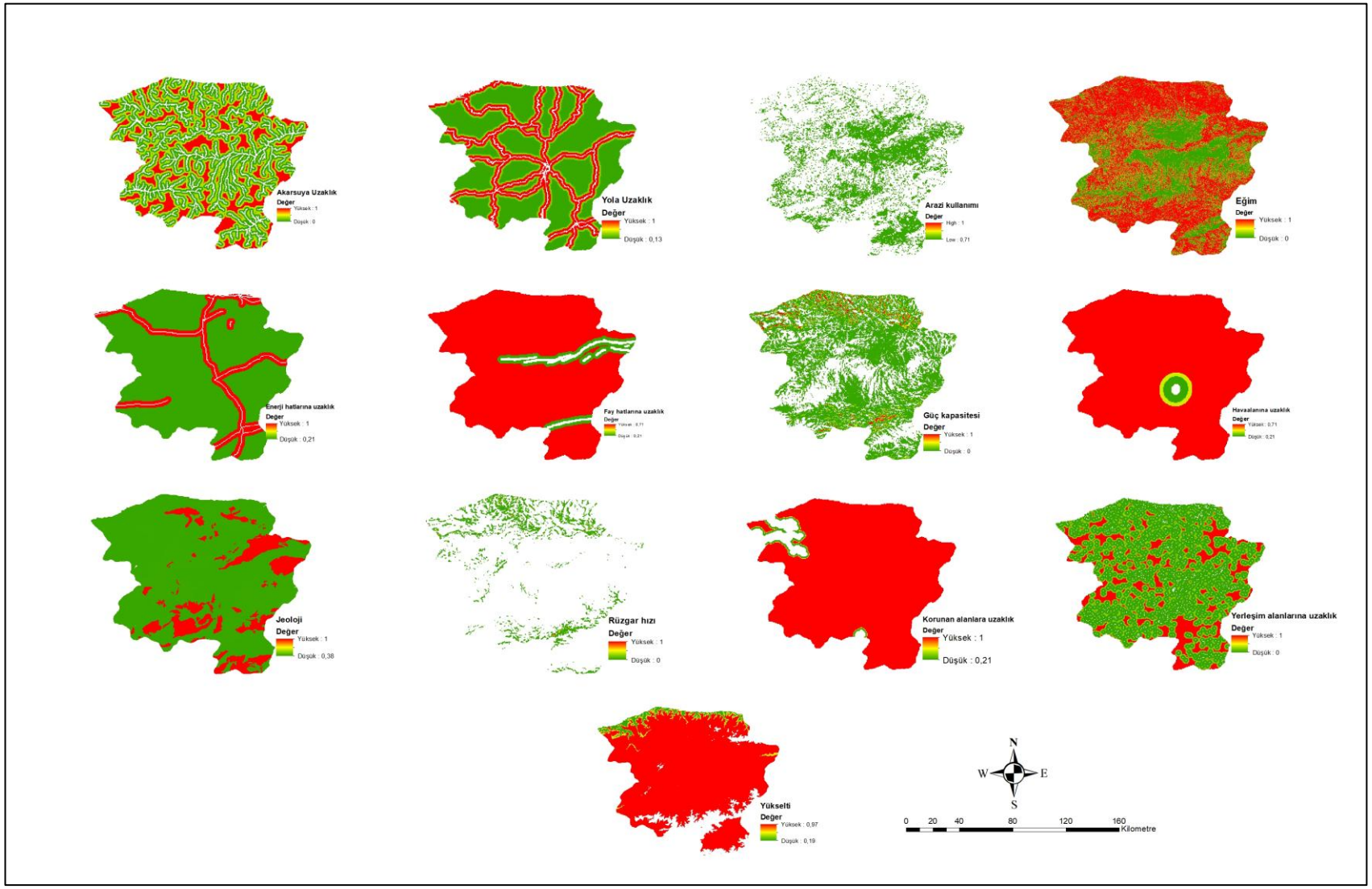
Şekil 4b. Çalışmada kullanılan veri setleri.

2.4.2. Bulanık mantık üyelik işlemleri

Çalışmada AHP'ye bağlı olarak veri gruplarının etki değerlerinin belirlenmesinin yanı sıra Bulanık Mantık yöntemiyle de normalizasyon işlemleri ve bindirme analizi gerçekleştirilmiştir. Bulanık Mantık teorisinde normalizasyon işlemlerini gerçekleştirmeden önce her bir faktörün bulanık üyeliğinin belirlenmesi gerekir. Bu işlem bulanık modellerin oluşturulması ve farklı üyelik fonksiyonlarının atanmasıyla gerçekleştirilir (Altaş, 1999). Bulanık üyelikler keskin bir setin bulanık bir sete ve bulanık bir setin bulanık kümeye dönüştürülmesi olarak tanımlanabilir. 7 farklı bulanık üyelik fonksiyonu bulunur. Bunlar: Gaussian, Lineer, MS küçük, MS büyük, Near, Large ve Small gibi fonksiyonlardır (Taştan, 2021). Çalışma alanının özelliklerine ve veri gruplarının niteliklerine göre faktör üyelik fonksiyonları belirlenmiştir. Faktör gruplarının üyeliklerinin belirlenmesinden sonra bulanık bindirme analizi gerçekleştirilir. Bulanık Mantık yöntemi katmanları birleştirmek amacıyla çeşitli matematiksel ve mantıksal operatörleri kullanır (Mitchell, 2012). 13 farklı faktörün bulanık üyelikleri her bir faktörün niteliği, arazi şartları ve rüzgâr enerji santrali kurulum niteliklerine bağlı olarak belirlenmiştir. Rüzgâr hızı, güç yoğunluğu, fay hatlarına uzaklık, eğim, havaalanına uzaklık, akarsuya uzaklık gibi faktörlerinde veri grupları nitelikleriyle enerji santrali kurulumu etki değerleri arasında doğrusal (Lineer) bir ilişki var olduğu literatür bilgilerinden ve arazi niteliklerinden yola çıkılıp belirlenmiştir. Böylelikle doğrusal üyelik fonksiyonu atanmıştır (Çizelge 4). Litoloji, yükselti, arazi kullanımı, yerleşim alanlarına uzaklık, ana yollara ve enerji güç alanlarına uzaklık gibi faktörlerde veri gruplarıyla üyelik fonksiyon ilişkisi tam olarak belirlenemediği için "Yakın-Near" üyelik fonksiyonu atanmıştır. Üyelik belirleme işlemi 13 farklı veri seti için yapılmıştır (Bakınız Şekil 5). Bulanık bindirme analizi ise her bir veri setinin üyeliklerinin belirlenmesi ve normalizasyon işlemlerinin ardından gerçekleştirilen çakıştırma analizidir. Bulanık bindirme analizleri 5 bölüm halinde incelenir. Bunlar: And, Or, Sum, Product ve Gamma tipidir. Gamma tipi bindirme analizi Product ve Sum'ın cebirsel bir ürünüdür (Taştan, 2021). 13 farklı faktör farklı etki değerlerine sahip ve farklı üyelik fonksiyonlarına sahiptir. Faktör haritalarının bindirme analizinde bulanık AHP yöntemi kullanılmıştır.

Çizelge 4. Faktör alt gruplarına atanan etki değerleri ve bulanık mantık üyelik fonksiyon biçimleri

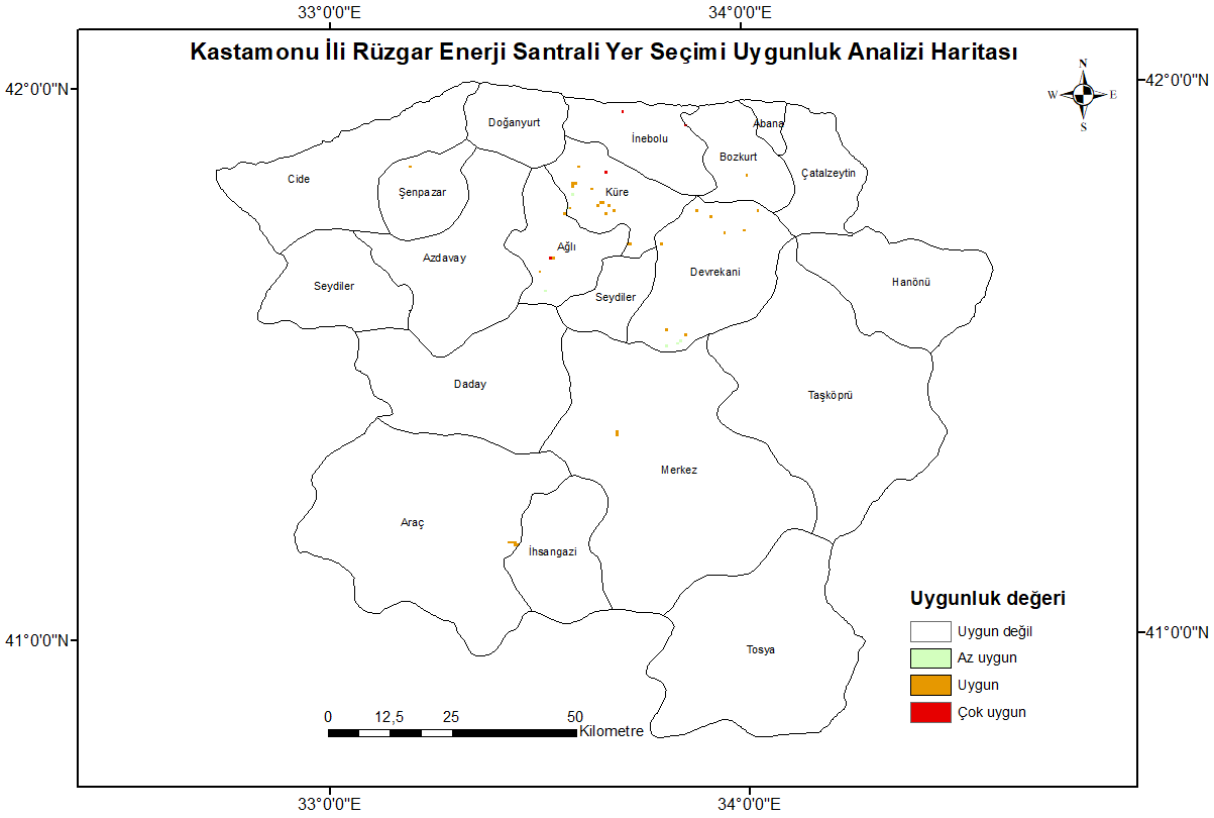
Faktörler	Birim değeri	AHP ağırlık değeri	Çok fazla uygun	Uygun	Orta uygun	Az uygun	En az uygun	Uygun değil	Kaynak	Bulanık Üyelik	Dağılım parametreleri
Rüzgâr hızı	m/sn	21.9	9-9.45	8-9	7-8	6.5-7	5-6.5	<5	Yılmaz ve ark., 2023	Lineer	Min:2 Maks: 10
Rüzgâr güç kapasitesi	W/m^2	16.9	1.938-691	691-425	425-266	266-152	152-76	76-0,46		Lineer	Min: 2 Maks: 10
Korunan alanlara uzaklık	m	12.4	>4000	3500-4000	3000-3500	2500-3000	2000-2500	<2000	Ekiz ve ark, 2022	Near	Midpoint: 8 Spread:0.1
Enerji hatlarına uzaklık	m	9.7	0-100	100-500	500-1000	1000-2500	2500-5000	5000-10000	Ekiz ve ark ., 2022	Near	Midpoint: 8 Spread:0.5
Yerleşim alanlarına uzaklık	m	9.3	>10000 >5000	5000-2500	2000-2500	1500-2000	500-1500	0-500	Urfalı & Eymen, 2021	Lineer	Min: 2 Maks: 10
Anayollara uzaklık	m	7.7	100-1000	1000-2000	2000-3000	3000-4000	4000-10000	<100 ve > 10000	Ekiz ve ark ., 2022	Near	Midpoint: 10 Spread: 0.1
Fay hatlarına uzaklık	m	6.6	>5000	4000-5000	3000-4000	2000-3000	1000-2000	<1000	Ekiz ve ark., 2022	Near	Midpoint: 8 Spread: 0.1
Yükselti	m	5	750-1500	450-750	300-450	150-300	0-150	>1500	Ekiz ve ark, 2022	Near	Midpoint: 8.5 Spread: 0.1
Eğim	Derece	3.4	0-5	5-10	10-15	15-20	20-30	>30	Ekiz ve ark., 2022	Lineer	Min: 10 Maks: 2
Arazi kullanımı		2.8	Tarım alanları, çıplak alan	Meralar				Su, Orman, Yereşim	Özşahin & Kaymaz, 2013	Near	Midpoint: 7 Spread: 0.1
Havaalanına uzaklık	m	1.9	>15000	12000-15000	9000-12000	6000-9000	3000-6000	<3000	Ekiz ve ark., 2022	Near	Midpoint:8 Spread: 0.1
Litoloji		1.5	Metamorfik	Volkanik	OfiyolitikPlütonik	(5)	Sedimenter			Near	Midpoint:7 Spread:0.1
Akarsuya uzaklık	m	1	>5000	2500-5000	1500-2500	1000-1500	500-1000	<0-500	Urfalı & Eymen, 2021	Lineer	Min:2 Maks:10



Şekil 5. Bulanık üyelik haritaları.

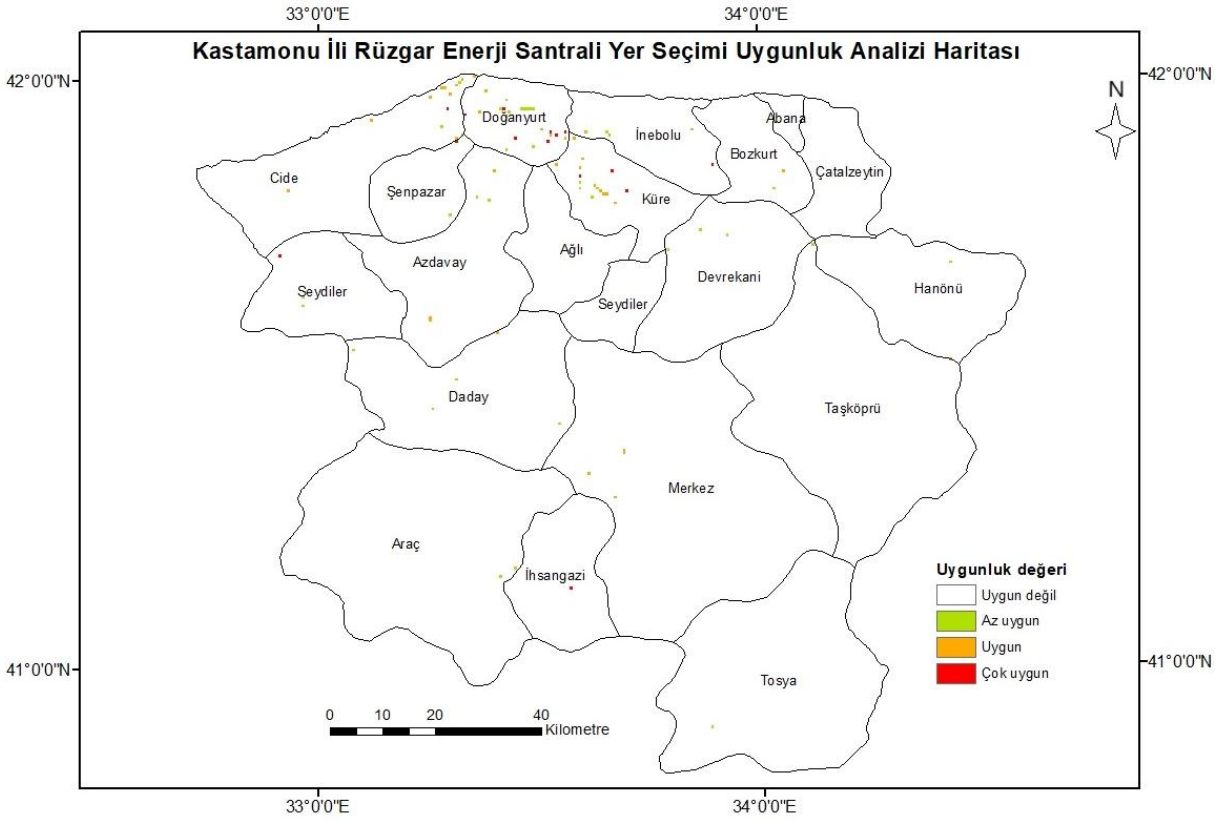
3. Bindirme analizleri ve sonuç değerlerinin elde edilmesi

13 farklı parametre alt gruplarında yukarıda bahsedilen çakıştırma analizinde etki değerinin olmaması gereken yerler sınırlandırılması gereken yerlerdir. Bu yerler yeniden sınıflandırma analizinde No Data olarak sınıflandırılmıştır. Bu alanlar harita cebiri aracıyla başka bir alanla toplandığı zaman bir sayının sıfırla çarpımı yapıldığı gibi sınırlandırılmış bir bölge ortaya çıkarmaktadır (Eroğlu, 2014). AHP'de elde edilen bindirme analizi ağırlık değerleri kullanarak CBS yazılımı ArcGIS 10.8'de "Konumsal analiz-harita cebri" işlemiyle bindirme analizine tabi tutularak sonuç haritası elde edilmiştir (Şekil 6).



Şekil 6. AHP ve ağırlıklı çakıştırma yöntemiyle elde edilen rüzgâr enerji santrali yer seçimi uygunluk analizi haritası.

Bulanık AHP yönteminde elde edilen faktör ağırlık değerleri Harita Cebri aracında her bir bulanık üyelik değer haritası değeriyle çarpılarak bindirme analizi gerçekleştirilmiştir (Eroğlu, 2014). Elde edilen sonuç haritası Şekil 7'de verilmiştir.



Şekil 7. Bulanık mantık ve ağırlıklı çakıştırma yöntemleriyle elde edilen rüzgâr enerji santrali yer seçimi uygunluk analizi haritası.

4. Sonuç

Fosil kaynakların yakın gelecekte tükenebilir olmasından dolayı insanlar yenilenebilir enerji kaynaklarına yönelimini sürdürmekte ve bundan dolayı yenilenebilir enerji kaynaklarının önemi giderek artmaktadır. Yenilenebilir enerji kaynaklarından rüzgâr enerjisi dünyada hemen hemen her yerde kullanılabilir durumdadır. Ancak arazi şartları, nüfus ve yerleşim durumları, hizmetlere uzaklık, rüzgâr hızı ve kapasitesi gibi birçok faktöre bağlı olarak rüzgâr enerji santralinin kurulum yeri sınırlanmaktadır. Bu enerji kaynağının verimli bir şekilde kullanılabilmesi için rüzgâr enerji santral kurulum yerinin ihtiyaçlar ve gereksinimler doğrultusunda belirlenmesi gerekmektedir.

Çalışmada çok kriterli karar verme analizlerinden AHP ve Bulanık Mantık yöntemiyle rüzgâr enerji santrali en uygun yer analizi gerçekleştirilmiştir. Analizde birbirinden farklı niteliğe sahip 13 faktörün rüzgâr enerji santrali yer seçimindeki etki değeri incelenmiştir. Hem AHP hem de Bulanık Mantık ve ağırlıklı çakıştırma analizleriyle elde edilen enerji santrali uygunluk değerleri uygun olmayan (Sınırlandırılmış), az uygun, uygun ve çok uygun olmak üzere dört farklı sınıfta gösterimi yapılmıştır. Rüzgâr enerji santrali yer seçiminin yapılabilmesi için birçok farklı kriter gerekmektedir. Yer seçiminin sağlanması için RES'lerin kurulamayacağı alanların belirlenerek, uygun olan yerlerin de birbirine göre önem değerlerinin tespiti gereklidir. Bu kapsamda hem AHP hem de Bulanık Mantık yöntemiyle elde edilen RES dağılım haritaları incelendiğinde Kastamonu ilinin çok büyük bir bölümünün RES kurulumu için yeterli olmadığı sonucu ortaya çıkmıştır. Bu sonucun ortaya çıkmasında RES santralinin kurulamayacağı alanların sonuç üzerindeki etkisinin olmaması için yeniden sınıflandırmada No Data verilerek çakıştırma analizlerinin gerçekleştirilmesi, arazi şartları ve farklı detay sınıflarına uzaklık şartları etkili olmuştur.

Analizden belde edilen bulgulara göre RES santrali kurulabilecek alanlar ilin kuzeyinde bulunan Doğanyurt, Küre, Bozkurt, Devrekani gibi yerleşim merkezlerine yakın alanlarda yoğunlaşmaktadır. AHP yönteminde elde edilen bulgulara göre RES santrali kurulabilecek yerleşmelerin Küre, Devrekani ve İnebolu gibi ilçelerde olduğu görülür. Bulanık mantıkla elde edilen değerlere göre Küre, Doğanyurt ve Cide çevresinde RES santrali kurulabilecek alanlar yoğunlaşmaktadır. Her iki yöntemde de çok

uygun sınıfların Küre ve Devrekani'de bulunduğu belirlenmiştir. Elde edilen uygunluk değerleri No Data olarak sınıflandırılan alanlarla karşılaştırılmış ve sonuç değerlerinin No Data olarak verilen (Sınırlandırılan) alanlarla örtüşmediği belirlenmiştir. Böylelikle işlemlerin doğru yapıldığı sonucuna ulaşılmıştır. Aynı zamanda elde edilen uygunluk sonuç değerleri Rüzgâr Enerji Potansiyel Atlası'yla karşılaştırıldığında sonuçların birbirine benzer olduğu ve modellerin uygunluk sınıflarını doğru tespit edebildiğini göstermektedir.

Kastamonu çevresinin engebeli ve yüksek olması, alanda iki tane milli park bulunması, ormanlık alanların fazla oluşu gibi nedenler rüzgâr enerji santralinin kurulumunu sınırlandırmaktadır. Bu alanların analize dahil edilmemesi çevresel faktörlerin uygunluk değerini artırmaktadır. RES kurulum yeri faktör ve uygunluk sınıfları için yer seçimi analizlerinde her bir yerleşim biriminin niteliğinin birbirinden farklı olması bu durumun ortaya çıkmasına neden olmaktadır. Araştırmadan elde edilen bulgular göstermiştir ki, AHP yönteminin yanı sıra Bulanık Mantık yönteminin de kullanılması optimum yer seçimi analizinde alternatif sayısını artırmaktadır. Böylelikle yer seçimi analizlerinde daha farklı ve uygun seçeneklere ulaşmak mümkündür. Ancak araştırmadan elde edilen bulgular saha çalışmalarıyla desteklenerek sonuçlar daha ayrıntılı olarak değerlendirilmelidir.

Teşekkür

Bu çalışmada "CBS ve çok kriterli karar verme analiz yöntemleriyle rüzgâr enerji santralleri yer seçimi analizi; Kastamonu ili örneği" isimli TÜBİTAK 2209-A Üniversite öğrencileri araştırma projesi verilerinden yararlanılmıştır.

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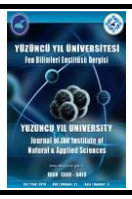
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Araştırma Makalesi

2002-2024 Yılları Arasında Gıda ve Nanoteknoloji Üzerine Yapılan Çalışmaların Bibliyometrik Analizi

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Öz: Nanoteknoloji gıda endüstrisinde gıdaların üretimi, işlenmesi, ambalajlanması gibi konularda önemli uygulama alanına sahip bir disiplindir ve gıda endüstrisinin çeşitli alanlarında nanoteknoloji uygulamaları gün geçtikçe artmaktadır. Bu çalışmanın amacı, bibliyometrik analiz yöntemini kullanarak literatürde yer alan gıda ve nanoteknoloji ile ilgili çalışmaları incelemektir. Web of Science (WoS) veri tabanında, "food" ve "nanotechnology" kavramlarının geçtiği makale ve derleme makale türünde çalışmalar taratılmış ve toplam 1950 çalışmaya ulaşılmıştır. Çalışmada elde edilen bazı veriler, VOSviewer haritalama tekniği ile görselleştirilmiştir. Elde edilen veriler incelendiğinde, gıda ve nanoteknoloji ile ilgili makale türünde ilk çalışmanın 2002 yılında yayımlandığı, konuya dair en fazla çalışmanın ise 2021 yılında (197 makale) yapıldığı belirlenmiştir. En fazla çalışma yapan ülkelerin sırasıyla Amerika Birleşik Devletleri (ABD) (354 makale), Çin Halk Cumhuriyeti (311 makale) ve Hindistan (255 makale) olduğu görülmüştür. Türkiye'de yapılan çalışma sayısı 56 olmuştur. Çalışmaların tarandığı indeksler arasında ilk sırada 1503 makale ile Science Citation Index Expanded (SCI-EXPANDED) yer alırken, çalışmaların en fazla yayımlandığı dergi Elsevier (842 makale) olmuştur. Çalışmalarda en çok kullanılan yayım başlığı "tarım ve gıda kimyası yayını" olurken, en fazla kullanılan anahtar kelimelerin "nanoteknoloji" ve "nanopartiküller" olduğu tespit edilmiştir. Dünyada nanoteknoloji konusunda yapılan çalışma sayıları dikkate alındığında, geleceğin teknolojisi olarak kabul edilen ve gıda sektöründe çok önemli uygulamalara sahip nanoteknoloji alanında Türkiye'nin diğer ülkelerle rekabet edebilir bir konuma ulaşması için gerekli yatırımların yapılması ve insan kaynaklarının yetiştirilmesinin önemi ortaya çıkmaktadır.

Anahtar Kelimeler: Bibliyometrik analiz, Gıda, Nanomateryal, Nanoteknoloji

Bibliometric Analysis of Studies on Food and Nanotechnology from 2002 to 2024

Abstract: Nanotechnology is a discipline with essential application areas in the food industry, such as the production, processing, and packaging of foods. Nanotechnology applications are increasing daily in various areas of the food industry. This study aims to examine the studies on food and nanotechnology in the literature using the bibliometric analysis method. In the Web of Science (WoS) database, studies in the type of articles and review articles in which the concepts of "food" and "nanotechnology" were mentioned were scanned, and a total of 1950 studies were reached. Some data obtained in the study were visualized with the VOSviewer mapping technique. When the data obtained was examined, it was determined that the first study in the type of article on food and nanotechnology was published in 2002, and most studies on the subject were published in 2021 (197 articles). It was observed that the countries with the most studies were United States of America (USA) (354 articles), People's Republic of China (311 articles) and India (255 articles). The number of studies conducted in Turkey was 56. Among the indexes where studies were scanned, Science Citation Index Expanded (SCI-EXPANDED) ranked first with 1503 articles, while the journal in which the most studies were published was Elsevier (842 articles). While the most used publication title in the studies was "journal of agricultural and food chemistry", it was determined that the most used keywords were "nanotechnology" and "nanoparticles". Considering the number of studies conducted on nanotechnology in the world, the importance of making the necessary investments and training human resources in order for Turkey to reach a competitive position with other countries in the field of nanotechnology, which is considered the technology of the future and has very important applications in the food sector, becomes evident.

Keywords: Bibliometric analysis, Food, Nanomaterial, Nanotechnology

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1. Giriş

Nanoteknoloji, nano ölçekte yeni malzemelerin üretimi için bilim ve teknolojideki geniş uygulamasıyla hızla büyüyen bir alan olarak ortaya çıkmaktadır (Berekaa, 2015). Nanoteknoloji, boyutları 1 ile 100 nm arasında değişen nanomateryallerin uygulanması olarak tanımlanmaktadır. Çok sayıda malzeme nanoölçek boyutuna küçültüldüğünde eşsiz özellikler sergilemektedir (Jagtiani, 2022). Nanomalzemeler, yüksek yüzey/hacim oranı ve renk, çözünürlük ve termodinamik gibi yeni fizikokimyasal özellikleri nedeniyle makro ölçekli benzerleriyle karşılaştırıldığında benzersiz özelliklere sahiptir. Bu yeni özellikler, gıdanın tat, doku ve renk gibi duyusal niteliklerini geliştirme fırsatları sağlamaktadır. Nanosensörlerin ve nanoambalaj malzemelerinin kullanılması mikrobiyal kontaminasyonun, zararlı kimyasalların ve pestisitlerin hızlı, hassas ve güvenilir bir şekilde tespit edilmesini sağlamaktadır. Nanokapsülleme sistemleri, gıdalardaki biyoyararlanımı arttırmak için biyoaktif bileşiklerin dağıtımını sağlayarak gıda işlemeyi geliştirme potansiyeline sahiptir (Chaudry ve ark., 2008; Yu ve ark., 2018). Nanoteknoloji, bariyer malzemeleri sağlayarak veya gıda kaynaklı patojenleri tespit ederek ürünlerin güvenliğini ve raf ömrünü artırabilen yenilikçi ambalaj malzemelerinin geliştirilmesine katkıda bulunmaktadır. Bazı gıda maddelerinin ambalajları, tedarik zinciri boyunca gıda ürünlerinin, tabletlerinin ve kaplarının iç ve dış koşullarını izlemek üzere tasarlanmış nano sensörlerle donatılmıştır. Bu tür ambalajlar zaman içinde sıcaklığı veya nemi izleyebilmekte ve ardından bu koşullarla ilgili bilgileri sağlayabilmektedir (Samal, 2017).

Nanoteknoloji çok disiplinli bir bilimdir ve biyoloji, kimya, fizik ve diğer disiplinlerden gelen bilgileri içermektedir (Manjunatha ve ark., 2016). Gıda ve tarımsal üretim alanındaki kullanımları, ilaç taşıma sistemleri ve eczacılıkla karşılaştırıldığında neredeyse yenidir. Nanoteknoloji, küresel gıda üretimini ve ayrıca gıdanın besin değerini, kalitesini ve güvenliğini artırma potansiyeli ile tüm tarımsal gıda alanını büyütüp dönüştürecek bilimsel bir ilerleme olarak gelişmiştir. Gıda biliminde nanoteknoloji kullanımı, gıdanın korunmasından yeni gıda ürünleri ve bileşenlerinin moleküler sentezine kadar gıda üretiminin en önemli yönlerini etkilemektedir (Thiruvengadam ve ark., 2018).

Geçtiğimiz birkaç on yılda nanoteknolojinin gıda sektöründe devrim yaratan cazip bir teknoloji olduğu giderek daha fazla kabul görmeye başlamıştır (Rai ve ark., 2009; Singh ve ark., 2017). Gıda endüstrisinde araştırılan nanomalzemeler arasında inorganik (metal ve metal oksit nanopartiküller), organik (esas olarak doğal ürün nanopartiküller) ve kombine edilmiş (ör. kil) maddeler yer almaktadır. Tüm metal nanopartiküller arasında, antimikrobiyal aktivitesi nedeniyle gümüş nanopartiküller ticari olarak en çok üretilen ve uygulanan nanopartikül iken, altın nanopartiküller bir sensör/dedektör olarak geniş çapta incelenmektedir. Titanyum dioksit nanopartiküller aynı zamanda dezenfekte edici ajan olarak ve bunun yanı sıra gıda katkı maddesi (beyaz renk pigmenti) ve lezzet arttırıcı olarak da iyi bir şekilde incelenmiştir. Doğal ürün olan nanopartiküller genellikle bir dağıtım sistemi olarak tasarlanmaktadır ve aynı zamanda gıda endüstrisinde gıda bileşenleri veya takviyeler olarak da yer almaktadır (He ve ark., 2019).

Gıda işlemede nanoteknoloji uygulamaları, kapsülleme (tat veya koku), ürünün dokusunun, viskozitesinin veya kalitesinin iyileştirilmesi ve daha iyi stabilite ve biyoyararlılığa sahip takviyeler gibi işlemleri içermektedir. Dolayısıyla nanobilim, gıdanın besin değerini ve biyoyararlılığını temel anlamıyla değiştirebilmektedir (Cruz-Lopes ve ark., 2021). Nanoteknoloji gıda ambalajlamada önemli bir kullanım alanına sahiptir. Arzu edilen bir ambalaj malzemesinin, mukavemet ve biyolojik olarak parçalanabilirlik ile birlikte gaz ve nem geçirgenliğine sahip olması gerekmektedir (Couch ve ark., 2016). Nano bazlı “akıllı” ve “aktif” gıda ambalajları, geleneksel ambalajlama yöntemlerine göre, gelişmiş mekanik mukavemet, bariyer özellikleri, antimikrobiyal filmler içeren daha iyi ambalaj malzemesi sağlamaktan, patojen tespiti için nano algılamaya ve tüketicileri gıdanın güvenlik durumu konusunda uyarmaya kadar birçok avantaj sağlamaktadır (Mihindukulasuriya & Lim, 2014; Singh ve ark., 2017). Gıdayla, çevreyle ve her ikisiyle etkileşime giren ambalaj bileşenlerini kullanan aktif ambalaj, ürünün raf ömrünü etkin bir şekilde uzatmaktadır (Singh ve ark., 2023). Nanoyapılandırılmış metaller, ametaller ve bunların oksitlerinin işlevselliklerinin geliştirilmesi ile birlikte nanoteknolojinin gıda ambalajlama sektöründeki uygulamaları sürekli olarak artmaktadır (Sahoo ve ark., 2021).

Nanomateryaller gıda sektöründe çeşitli potansiyel faydalar sunarken, potansiyel tehlikeleri sadece uzmanların değil aynı zamanda genel kamuoyunun, özellikle de tüketicilerin ilgisini çekmiştir (Jagtiani, 2022). Nanomalzemeler, geleneksel formlarıyla karşılaştırıldığında oldukça farklı fizikokimyasal ve biyolojik özellikler sergileyebilmekte ve bu bilinmeyen özellikler, öngörülemeyen

tehlikeler yaratabilmektedir (Yu ve ark., 2018). Gıda işinde, tüketimin her aşamasıyla ilişkili sağlık tehlikeleri ve artan maruz kalmanın yanı sıra vücutta birikme olasılığı ve etkisi ile ilgili endişeler dile getirilmiştir. Endişelerden biri, tüketicilerin ürünün tüketimi yoluyla "ağır" maddeler olarak da bilinen bazı biyolojik olarak kalıcı ve çözünmeyen nanopartiküllere maruz kalabilmeleridir. Buradaki zorluk, nanopartiküllerin vücuda girdiğinde biyolojik engelleri aşabilmesi (Chaudry & Castle, 2011) ve vücudun partikül madde istilasına karşı bağışık olması gereken bölgelerine ulaşabilmesidir (Simon ve ark., 2008) İnsan kullanımı için de güvenli olan, uygun maliyetli işleme yöntemleri ve formülasyonların geliştirilmesi nanoteknolojiler için kritik bir konudur. Artan bu endişeleri gidermek için uzmanlar, gıda saflığında malzemelerden yapılmış güvenli, toksik olmayan ve biyouyumlu nanoyapıların kolay, uygun maliyetli ve çevre dostu teknikler kullanılarak üretilebileceğine inanmaktadır (Jagtiani, 2022). Gıda sektöründe nanoteknoloji ile ilgili yapılmış çalışmalara geniş bir çerçeveden bakmanın alan açısından yararlı olacağı düşünülmektedir. Bunu yapabilmenin en güncel yöntemlerinden biri de bibliyometrik analizdir.

Bibliyometrik analiz, büyük hacimli bilimsel verileri araştırmak ve analiz etmek için popüler ve titiz bir yöntemdir (Donthu ve ark., 2021). Belirli bir araştırma alanındaki yayınların, yazarların, kurumların ve ülkelerin karşılıklı ilişkilerini ve etkilerini değerlendirmek için matematiksel ve istatistiksel araçları uygulayan nicel bir yöntemdir (Fu ve ark., 2023). Literatürde gıda alanında bibliyometrik analiz yöntemi kullanılarak yapılan çalışmalar incelendiğinde, bu çalışmaların daha çok gıda güvenliği (Bouzembrak ve ark., 2019; Wahyuni ve ark., 2019; Abdallah ve ark., 2021; Shen ve ark., 2021; Xie ve ark., 2021; Bellia ve ark., 2022; Liu ve ark., 2023) ve tarım-gıda tedarik zinciri (Luo ve ark., 2018; Monteiro ve Barata, 2021; Niknejad ve ark., 2021; Rejeb ve ark., 2021; Avşar ve ark., 2022; Pandey ve ark., 2022) konuları üzerinde yoğunlaştığı görülmektedir. Bununla birlikte gıda israfı eğilimleri (Zhang ve ark., 2018), gıda endüstrisi alanındaki teknolojik yenilikler (Castillo-Vergara ve ark., 2021), yenilebilir mantar (Öztürk, 2022), genetiği değiştirilmiş gıdalara yönelik tüketici algısı ve tercihi (Sendhil ve ark., 2022) gibi konuların incelenmesinde bibliyometrik analiz yönteminin kullanıldığı tespit edilmiştir. Çok disiplinli bir bilim olan nanoteknoloji, gıdaların işlenmesi, ambalajlanması ve muhafazası gibi konularda kullanılabilmesi nedeniyle gıda sektöründe oldukça önemli uygulamalara sahiptir. Bu araştırmada, gıda ve nanoteknoloji üzerine yapılan çalışmaların bibliyometrik analizi yapılmış ve elde edilen bazı veriler VOSviewer programı kullanılarak görselleştirilmiştir. Bu kapsamda, çalışmanın gıda ve nanoteknoloji ile ilgili çalışmalar hakkında araştırmacılara fikir vermesi ve bu konudaki bilgi boşluklarını ortaya koyarak yapılacak yeni çalışmalara dair faydalı olması hedeflenmektedir.

2. Materyal ve Yöntem

Web of Science (WoS) veri tabanında "food" and "nanotechnology" anahtar kelimelerini içeren 2002-2024 yılları arasında yapılan "article" (makale) ve "review article" (derleme) türünde çalışmalar 13.11.2024 tarihinde taratılmıştır. İlk olarak kavramların geçtiği toplam 10264 çalışma tespit edilmiştir. Ardından WoS kategorilerinden "food science technology" (gıda bilimi teknolojisi) alanına ilişkin filtreleme yapılarak 2052 çalışma elde edilmiştir. Son olarak "document types" (belge türü) kriterine göre ikinci bir filtreleme yapılarak "article" (makale) ve "review article" (derleme) türünde toplamda 200 yazara ait 1950 çalışmaya erişim sağlanmıştır. Çalışma kapsamında, WoS veri tabanında gıda ve nanoteknoloji ile ilgili yayımlanan makalelerin yıllara, indeksine, ülkelere, yayımlandığı dergiye, kullanılan yayım başlıklarına, atıf durumuna göre dağılımları ve makalelerde kullanılan anahtar kelimelerin dağılımı gibi verilere ulaşılmıştır. Çalışmada elde edilen bazı veriler, VOSviewer (1.6.19 sürümü) haritalama tekniği kullanılarak görselleştirilmiştir.

3. Bulgular ve Tartışma

WoS veri tabanında, "gıda" (food) ve "nanoteknoloji" (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türünde 1950 çalışma olduğu belirlenmiş ve bu çalışmaların yayım yılı, yer aldığı indeksler, en fazla çalışma yapılan ülkeler, en fazla çalışmanın yayımlandığı dergiler, çalışmalarda en fazla kullanılan yayım başlıkları, en fazla kullanılan anahtar kelimeler ve en fazla atıf alan ilk on makaleye yer verilmiştir.

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türündeki çalışmaların yıllara göre dağılımı Çizelge 1'de sunulmuştur. Buna göre, gıda ve nanoteknoloji kavramlarının yer aldığı makale türündeki ilk çalışmanın 2002 yılında yayımlandığı görülmektedir. 2008 yılına kadar gıda ve nanoteknoloji ile ilgili az sayıda çalışma yapılırken 2008 yılından itibaren bu konuda yapılan çalışmalar önemli düzeyde artış göstermiştir. Konuyla ilgili en fazla çalışma 2021 yılında (197 makale) yapılmış, bunu sırasıyla 2023 (176 makale) ve 2024 yılları (176 makale) izlemiştir.

Çizelge 1. Çalışmaların yıllara göre dağılımı

Yayım Yılı	Yayım Sayısı	Yayım Yılı	Yayım Sayısı	Yayım Yılı	Yayım Sayısı
2024	176	2016	145	2008	24
2023	176	2015	87	2007	9
2022	170	2014	86	2006	8
2021	197	2013	89	2005	1
2020	137	2012	61	2004	2
2019	139	2011	33	2003	1
2018	172	2010	46	2002	1
2017	159	2009	31		
					Toplam: 1950

Kaynak: WoS veri tabanı

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türünde çalışmaların yer aldığı indeksler Çizelge 2'de görülmektedir. Çalışmaların tarandığı indeksler arasında ilk sırada 1503 makale ile Science Citation Index Expanded (SCI-EXPANDED) yer almaktadır. Bu konuda yayımlanmış çalışmaların tarandığı diğer indeksler ise sırasıyla Book Citation Index – Science (BKCI-S) (343 makale), Emerging Sources Citation Index (ESCI) (110 makale), Conference Proceedings Citation Index – Science (CPCI-S) (43 makale), Social Sciences Citation Index (SSCI) (40 makale) ve Index Chemicus (IC) (2 makale) olmuştur.

Çizelge 2. Çalışmaların yer aldığı indeksler

İndeksler	Yayım Sayısı
Science Citation Index Expanded (SCI-EXPANDED)	1503
Book Citation Index – Science (BKCI-S)	343
Emerging Sources Citation Index (ESCI)	110
Conference Proceedings Citation Index – Science (CPCI-S)	43
Social Sciences Citation Index (SSCI)	40
Index Chemicus (IC)	2

Kaynak: WoS veri tabanı

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türünde en fazla çalışma yapan ülkeler Çizelge 3'te sunulmuştur. Buna göre, gıda ve nanoteknoloji ile ilgili makale (article) ve derleme (review article) türünde en fazla çalışma yapan ülkenin ABD (354 makale) olduğu görülmektedir. Çin Halk Cumhuriyeti 311 makale, Hindistan 255 makale ile en fazla çalışma yapan ülkeler arasında yer almakta, bu ülkeleri 151 makale sayısı ile Brezilya ve 144 makale sayısı ile İran takip etmektedir. Türkiye, gıda ve nanoteknoloji ile ilgili 56 makale yayımlamıştır. 2000'li yıllarda başta ABD olmak üzere dünyadaki

birçok ülkenin nanoteknolojiyi öncelikli alan ilan ederek bu alana yatırım yapmaya başladığı belirtilmiştir (Barış Eren, 2022). 1999 yılında ABD'de yayınlanan ulusal nanoteknoloji bildirgesi ile ülkenin nanoteknoloji alanındaki önceliklerinin belirlendiği ve bu konuda yapılan AR-GE çalışmaları için bütçeler ayrıldığı görülmektedir (2000 yılında bu çalışmalar için sağlanan destek 420 milyon dolar civarında iken 2003 yılı için yaklaşık 700 milyon dolar olduğu ifade edilmiştir). Bununla birlikte, gelişen nanoteknoloji alanlarında akademik programlar oluşturulduğu belirtilmiştir. Çin Halk Cumhuriyeti de nanoteknolojiye yatırım yapan ülkelerin başında gelmektedir. Nanoteknoloji alanında çalışmaların yürütülmesine yönelik faaliyet gösteren birçok araştırma merkezine ek olarak nanoteknoloji kullanılarak üretilen ürünlerin ticarileşmesine imkân sağlamak amacıyla çalışan birçok kuruluşun da bulunduğu bildirilmiştir (Anonim, 2024). Dünyada nanoteknolojiye yatırım yapan ülkelerin toplam nanoteknoloji AR-GE harcamalarının gayri safi yurtiçi hasılaya (GSYİH) oranları değerlendirildiğinde, 2020 yılı için bu oran ABD'de 0.81 iken Türkiye'de 0.28 olmuştur (Barış Eren, 2022). Bu durum, ABD ve Türkiye'ye ait çalışma sayıları arasındaki fark ile ilişkilendirilebilir.

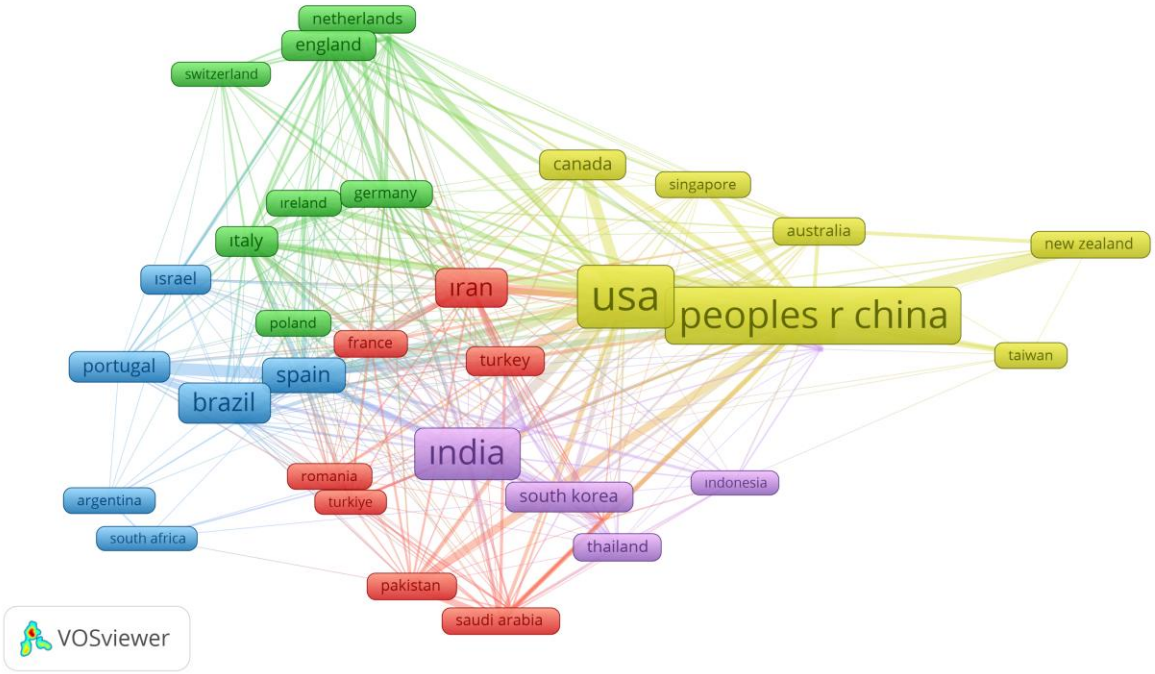
Çizelge 3. En fazla çalışma yapılan ülkeler (2002-2024)

Ülkeler	Çalışma Sayısı	Ülkeler	Çalışma Sayısı
ABD	354	Kanada	62
Çin Halk Cumhuriyeti	311	İtalya	62
Hindistan	255	Japonya	61
Brezilya	151	Güney Kore	61
İran	144	İsrail	56
İspanya	112	Türkiye	56
Portekiz	76	Avustralya	47
Meksika	75	Tayland	47
İngiltere	67	Hollanda	41

Kaynak: WoS veri tabanı

VOSviewer programında gıda (food) ve nanoteknoloji (nanotechnology) ile ilgili çalışmalarda en çok iş birliği yapan ülkelerin ağ haritası oluşturulurken, ülkelerin en az doküman sayısı 15 ve atıf sayısı 15 olarak seçilmiştir. Bunun sonucunda 100 ülkeden 37'si eşik değeri karşılamıştır. Şekil 1'de en fazla iş birliği yapan ülkelerin 5 küme oluşturdukları görülmektedir. Kırmızı renkli birinci kümede yer alan "İran" (144 makale); yeşil renkli ikinci kümede yer alan "İngiltere" (67 makale); mavi renkli üçüncü kümede yer alan "Brezilya" (150); sarı renkli dördüncü kümede yer alan "ABD" (353 makale) ve mor renkli beşinci kümede yer alan "Hindistan" (255 makale) "nanotechnology" ve "food" konulu çalışmalarda en fazla iş birliği yapan ülkeler olarak tespit edilmiştir. Ağ haritasında ABD ve Çin Halk Cumhuriyeti'nin en büyük kutucuk ile gösterilmesi ve aralarındaki çizgilerin kalın olması ise en çok iş birliği yapan ülkeler olduklarını ifade etmektedir. Dünyada en fazla bilimsel araştırma yapan ülkenin Çin ve en fazla AR-GE harcaması yapan ülkenin ABD olması (Euronews, 2024) bu ülkelerin gıda biliminde de oldukça önemli uygulamalara sahip nanoteknoloji konusunda iş birliği yapmalarını teşvik etmiş olabilir.

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türünde çalışmaların en fazla yayımlandığı dergiler Çizelge 4'te görülmektedir. Bu dergiler arasında 842 makale ile Elsevier ilk sırada yer almaktadır. Wiley (281 makale), Springer Nature (179 makale) ve American Chemical Society (144 makale) ise gıda ve nanoteknoloji ile ilgili en fazla çalışmanın yayımlandığı diğer dergiler olmuştur. Bu çalışmaların büyük bir kısmının (%43), küresel araştırma çıktısının %17'sinden fazlasını oluşturan, yaklaşık %28 ile oldukça yüksek bir atıf payına sahip olan ve yüksek kaliteli içerik yayımlamayı önemseyen Elsevier (2024) dergisinde yayımlanması, konu ile ilgili çok sayıda nitelikli çalışmanın yapıldığını göstermektedir.



Şekil 1. En fazla iş birliği yapan ülkelerin ağ haritası.

Çizelge 4. En fazla çalışmanın yayımlandığı dergiler

Dergi Adı	**Yayım Sayısı**
Elsevier	842
Wiley	281
Springer Nature	179
American Chemical Society	144
Taylor & Francis	111
Mdpi	68
Royal Society of Chemistry	57
Woodhead Publishing Limited	33

Kaynak: WoS veri tabanı

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türündeki çalışmalarda en çok kullanılan yayım başlıkları Çizelge 5'te görülmektedir. Buna göre en çok kullanılan yayım başlığı "tarım ve gıda kimyası yayını" olmuş ve 134 çalışma ile ilk sırada yer almıştır. Bunu sırasıyla "tarımsal gıda sektöründe nanoteknoloji", "gıda kimyası", "gıda bilimi ve teknolojisinde trendler", "uluslararası gıda araştırmaları", "gıda hidrokolloidleri", "gıda bilimi ve beslenmede eleştirel incelemeler", "gıdalar", "gıda kontrolü", "gıda ve kimyasal toksikoloji", "biyonanoteknoloji", "fonksiyonel gıda bilimi ve teknolojisi", "gıda bilimi yayını" başlıklı yayımlar takip etmiştir. Bu sonuçlar, gıda (food) ve nanoteknoloji (nanotechnology) anahtar kelimelerini içeren makale (article) ve derleme (review article) türündeki çalışmalarda, tarım ve gıda kimyası alanlarında daha fazla yayım yapıldığını göstermektedir. Dünyada beslenme durumu göz önüne alındığında özellikle gelişmekte olan ülkelerde yaşayan insanların büyük bir kısmının günlük gıda sıkıntısıyla karşı karşıya kaldığı görülmektedir. Tarımsal üretimde temel amaç, verimi en üst düzeye çıkarmak için kuraklığa ve zararlılara dayanıklı ürünler geliştirmektir. Nanoteknoloji, kontrollü veya gecikmiş salınım yeteneğine sahip, daha etkili ve çevre dostu nanoparçacıklar ve nanokapsüller kullanarak pestisit ve kimyasal gübre üretmek ve pestisitlerin

daha düşük dozda uygulanmasını sağlamak amacıyla etkinliklerini arttırmaya yönelik nanokristaller üretmek suretiyle tarım bilimlerine ve çevre kirliliğinin azaltılmasına yardımcı olmaktadır. Nano gübrelerin kullanımının besin kullanım verimliliğini artırdığı, toprak toksisitesini azalttığı, aşırı dozajla ilişkili olası olumsuz etkileri en aza indirdiği ve uygulama sıklığını azalttığı belirtilmiştir. Bu nedenle, nanoteknolojinin özellikle gelişmekte olan ülkelerde sürdürülebilir tarıma ulaşmada yüksek bir potansiyeli olduğu ifade edilmiştir (Manjunatha ve ark., 2019). Bu durum, tarım alanında nanoteknoloji çalışmalarının önemini ortaya koymaktadır. Ayrıca, nanobilim ve mühendislik, nanoteknolojinin farklı ve yeni özellikler yaratabilmesi nedeniyle, gıda güvenliği, paketleme ve nihayetinde yeni gıda bileşenleri konusunda önemli iyileştirmeler sunabilmektedir. Nanobilim yaklaşımları, gıda bileşenleri olan protein, lipit veya polisakkarit arasındaki etkileşimleri ve moleküler ölçekte kendi kendine birleşme davranışlarını kontrol etmek ve yönlendirmek için kullanılabilmekte ve böylece gıdanın istenen reolojik ve yapısal özellikleri elde edilebilmektedir (Otles & Yalcin, 2013). Dolayısıyla, gıda alanında nanoteknoloji uygulamalarına yönelik çalışmalarda en fazla yayım yapılan konulardan birinin gıda kimyası olması kaçınılmazdır.

Çizelge 5. Çalışmalarda en çok kullanılan yayım başlıkları

Yayım Başlığı	**Yayım Sayısı**
Tarım ve Gıda Kimyası Yayını (Journal of Agricultural and Food Chemistry)	134
Tarımsal Gıda Sektöründe Nanoteknoloji (Nanotechnology in the Agri Food Industry)	120
Gıda Kimyası (Food Chemistry)	104
Gıda Bilimi ve Teknolojisinde Trendler (Trends in Food Science and Technology)	94
Uluslararası Gıda Araştırmaları (Food Research International)	74
Gıda Hidrokolloidleri (Food Hydrocolloids)	70
Gıda Bilimi ve Beslenmede Eleştirel İncelemeler (Critical Reviews in Food Science and Nutrition)	63
Gıdalar (Foods)	51
Gıda Kontrolü (Food Control)	49
Gıda ve Kimyasal Toksikoloji (Food and Chemical Toxicology)	45
Biyo Nanoteknoloji (Bio Nanotechnology)	43
Fonksiyonel Gıda Bilimi ve Teknolojisi (Functional Foods Science and Technology)	43
Gıda Bilimi Yayını (Journal of Food Science)	42

Kaynak: WoS veri tabanı

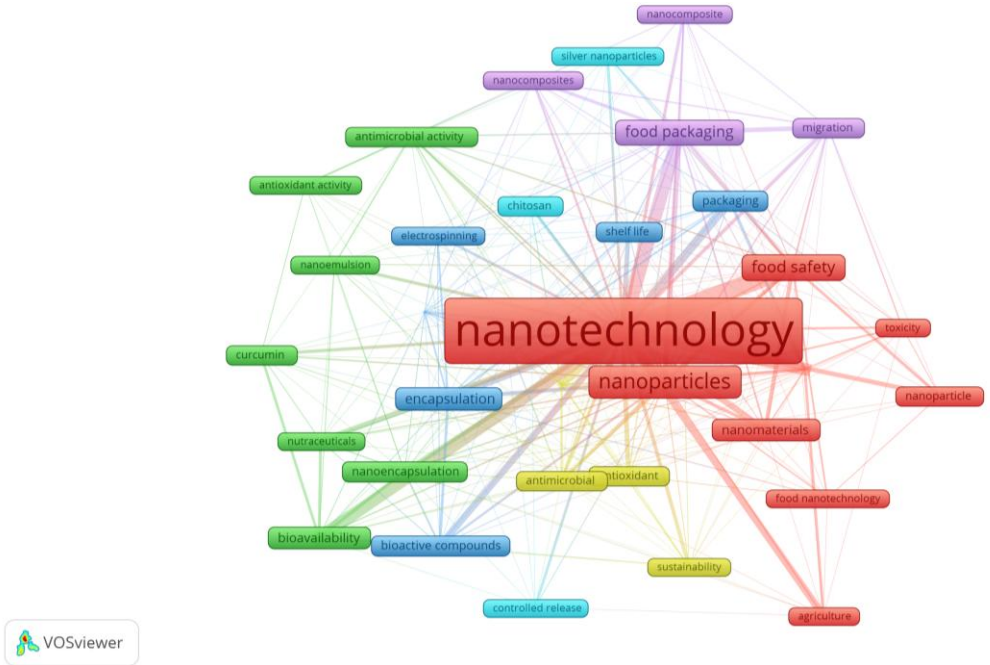
WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) konusunda makale (article) ve derleme (review article) türünde çalışmalarda en fazla kullanılan anahtar kelimeler Çizelge 6'da görülmektedir. Çalışmalarda toplam 4338 anahtar kelimenin kullanıldığı tespit edilmiştir. VOSviewer programı kapsamında bu anahtar kelimeler arasından en az 20 kere tekrar eden 34 kavram bulunmuştur. Buna göre en fazla kullanılan anahtar kelimenin "nanoteknoloji" (nanotechnology) olduğu görülmektedir. Bu anahtar kelimenin kullanım sıklığının 443 olduğu belirlenmiştir. "Nanopartiküller" (nanoparticles) kelimesi 148 kez kullanılarak ikinci sırada, "gıda güvenliği" (food safety) ise 89 kez kullanılarak üçüncü sırada yer almıştır. Buna göre, gıda alanında yapılan nanoteknoloji çalışmalarında daha çok gıda güvenliği konusunun ön plana çıktığı görülmektedir. Nanoteknolojinin, gıda güvenliği uygulamalarında devrim yaratmak ve tarımsal verimliliği sürdürülebilir bir şekilde yükseltmek için önemli fırsatlar sunan umut verici bir yol olarak ortaya çıktığı ifade edilmektedir. Nanomalzemelerden ve gelişmiş tekniklerden yararlanarak gıda tedarik zincirindeki kirleticilerin tespit edilmesinde ve azaltılmasında hassasiyet sağlaması, ayrıca çabuk bozulabilen ürünlerin raf ömrünü uzatma potansiyeline sahip olup, gıda israfının azaltılmasına ve kaynakların daha sürdürülebilir bir şekilde kullanılmasına katkıda bulunması (Kiran ve ark., 2024) nedeniyle nanoteknolojinin gıda güvenliği açısından önemi ortaya çıkmaktadır.

Çizelge 6. En fazla kullanılan anahtar kelimeler

Anahtar kelime	Kullanım sıklığı	Anahtar kelime	Kullanım sıklığı
Nanoteknoloji (Nanotechnology)	443	Raf Ömrü (Shelf Life)	26
Nanopartiküller (Nanoparticles)	148	Zerdeçal (Curcumin	26
Gıda Güvenliği (Food Safety)	89	Nanopartikül (Nanoparticle)	26
Gıda Ambajlama (Food Packaging)	77	Esansiyel Yağlar (Essential Oils)	25
Enkapsülasyon (Encapsulation)	57	Nanoemülsiyon (Nanoemulsion)	25
Biyoyararlılık (Bioavailability)	54	Tarım (Agriculture))	24
Gıda (Food)	53	Elektro Lif Çekimi (Electrospinning)	24
Nanomateryaller (Nanomaterials)	50	Nutrasötikler (Nutraceuticals)	23
Aktif Ambalajlama (Active Packaging)	44	Biyopolimerler (Biopolymers)	23
Ambalajlama (Packaging)	37	Nanokompozit (Nanocomposite)	23
Nanoenkapsülasyon (Nanoencapsulation)	37	Gümüş Nanopartiküller (Silver Nanoparticles)	23
Biyoaktif Bileşikler (Bioactive Compounds)	36	Gıda Nanoteknolojisi (Food Nanotechnology)	23
Antimikrobiyal (Antimicrobial)	32	Kontrollü Salınım (Controlled Release)	22
Antioksidan (Antioxidant)	32	Antioksidan Aktivite (Antioxidant Activity)	22
Göç (Migration)	29	Toksiklik (Toxicity)	21
Antimikrobiyal Aktivite (Antimicrobial Activity)	29	Sürdürülebilirlik (Sustainability)	20
Kitosan (Chitosan)	28	Nanokompozitler (Nanocomposites)	20

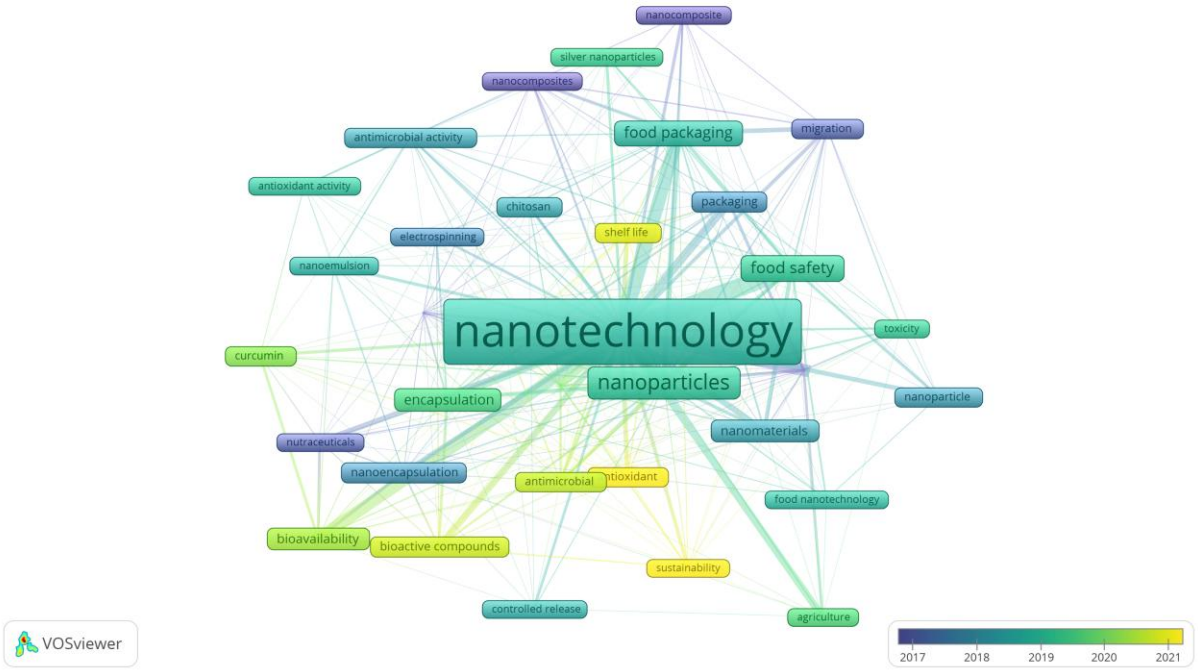
Kaynak: WoS veri tabanı

VOSviewer programı kullanılarak gıda (food) ve nanoteknoloji (nanotechnology) ile ilgili WoS veri tabanında taranan makale (article) ve derleme (review article) türündeki çalışmalarda en fazla kullanılan anahtar kelimelerin ağ haritası oluşturulmuş ve Şekil 2'de gösterilmiştir. Çalışmalarda en fazla kullanılan anahtar kelimelerin 6 küme oluşturduğu görülmektedir. Anahtar kelimeler arasındaki çizgiler iki anahtar kelime arasındaki bağlantı kuvvetini göstermektedir. Anahtar kelimeler arasındaki korelasyona bağlı olarak kalınlığı çizilmektedir. Çizginin kalın olması, iki anahtar kelime arasındaki bağlantının güçlü olduğunu ifade etmektedir (Chen ve ark., 2016). Buna göre nanoteknoloji (nanotechnology) kavramı ile gıda (food), nanopartiküller (nanoparticles), tarım (agriculture), gıda güvenliği (food safety), gıda ambalajlama (food packaging), biyoyararlılık (bioavailability) kavramları arasında güçlü bir ilişki olduğu görülmektedir.



Şekil 2. En fazla kullanılan anahtar kelimelerin ağ haritası.

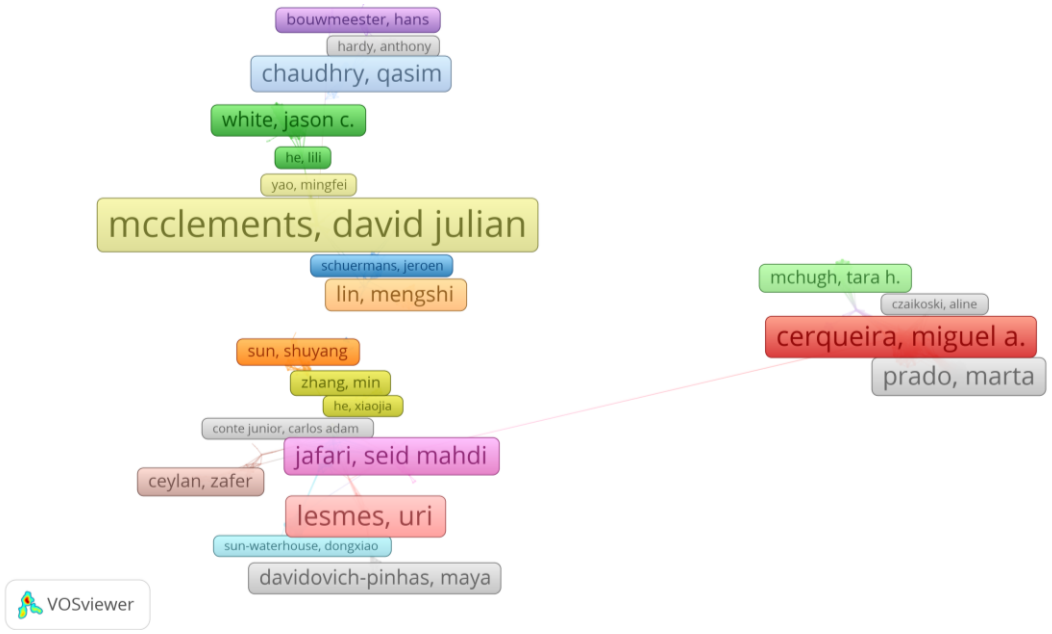
VOSviewer programı kullanılarak, gıda (food) ve nanoteknoloji (nanotechnology) ile ilgili WoS veri tabanında taranan makale (article) ve derleme (review article) türündeki çalışmalarda en fazla kullanılan anahtar kelimelerin yoğunluk haritası oluşturulmuştur. Şekil 3'te gıda ve nanoteknoloji ile ilgili en fazla kullanılan anahtar kelimelerin 2017 ve 2021 yılları arasındaki yoğunluk haritası görülmektedir. Buna göre, haritada sarı renk ile gösterilen antioxidant (antioksidan), sürdürülebilirlik (sustainability), shelf life (raf ömrü), antimicrobial (antimikrobiyal) ve bioactive compounds (biyoaktif bileşikler) kavramları konu ile ilgili kullanılan güncel kelimeler olmuştur**.**



Şekil 3. En fazla kullanılan anahtar kelimelerin yıllara göre yoğunluk haritası.

VOSviewer programı kullanılarak gıda (food) ve nanoteknoloji (nanotechnology) ile ilgili çalışmalarda en fazla iş birliği yapan araştırmacıların ağ haritası oluşturulmuş ve Şekil 4'te sunulmuştur. Şeklin görsel açıdan daha net bir biçimde sunulması amacıyla ağ haritası oluşturulurken yazarların en az doküman sayısı 2 ve atıf sayısı 2 olarak belirlenmiş ve 7255 araştırmacıdan 1020 tanesi seçilmiştir. Bazı araştırmacılar birbiriyle bağlantılı olmadığından 368 araştırmacı konuya dâhil edilmiştir. Şekil 4 incelendiğinde, en fazla iş birliği yapan araştırmacıların 25 küme oluşturduğu görülmektedir. En fazla çalışma yapan araştırmacıların 37 çalışmayla David J. McClements ve 23 çalışmayla Zuobing Xiao olduğu anlaşılmaktadır. Bu araştırmacıları sırasıyla 22 çalışmayla Miguel Ângelo Cerqueira ve Uri Lesmes takip etmektedir.

WoS veri tabanında taranan, gıda (food) ve nanoteknoloji (nanotechnology) ile ilgili makale (article) ve derleme (review article) türündeki çalışmaların en fazla atıf alma durumuna göre dağılımı Çizelge 7'de görülmektedir. Gıda ve nanoteknoloji ile ilgili en fazla atıf alan makale türündeki çalışma, Jamshidian ve ark. (2010) tarafından yayımlanmış olan "Poly-lactic acid: Production, applications, nanocomposites, and release studies" isimli çalışma olmuştur. "Comprehensive Reviews in Food Science and Food Safety" dergisinde yayımlanmış olan bu çalışma, yıllık ortalama 66 atıf sayısı ve toplamda 991 atıf sayısı ile birinci sırada yer almaktadır.



Şekil 4. En fazla iş birliği yapan araştırmacıların ağ haritası.

Çizelge 7. Çalışmaların en fazla atıf alma durumuna göre dağılımı

Makalenin adı	Dergi	Yazarlar ve yayım yılı	Yıllık ortalama atıf	Atıf
Poly-lactic acid: Production, applications, nanocomposites, and release studies	Comprehensive Reviews in Food Science and Food Safety	Jamshidian ve ark. (2010)	66	991
Mechanisms of nanotoxicity: Generation of reactive oxygen species	Journal of Food and Drug Analysis	Fu ve ark. (2014)	84	924
Zinc oxide nanoparticles: Synthesis, antimicrobial activity and food packaging applications	Food and Bioprocess Technology	Espitia ve ark. (2012)	71	920
Applications and implications of nanotechnologies for the food sector	Food Additives & Contaminants: Part A	Chaudhry ve ark. (2008)	47	799
Bio-nanocomposites for food packaging applications	Progress in Polymer Science	Rhim ve ark. (2013)	50	793
A review of the dietary flavonoid, kaempferol on human health and cancer chemoprevention	Food Chemistry	Chen & Chen (2013)	58	699
Potential perspectives of bio-nanocomposites for food packaging applications	Trends in Food Science & Technology	Sorrentino ve ark. (2007)	39	696
Functional materials in food nanotechnology	Journal of Food Science	Weiss ve ark. (2006)	34	639
Nanoencapsulation techniques for food bioactive components: A review	Food and Bioprocess Technology	Ezhilarasi ve ark. (2012)	46	551
Emerging chitosan-based films for food packaging applications	Journal of Agricultural and Food Chemistry	Wang ve ark. (2018)	73	511

Kaynak: WoS veri tabanı

4. Sonuç

Nanoteknoloji; tıp, tarım, gıda, enerji, elektronik vb. dâhil olmak üzere yaşamın tüm alanlarında devrim yaratmış bir teknolojidir ve bu teknolojinin temelini 1-100 nm aralığındaki nanomateryaller oluşturmaktadır. Nanoteknoloji gıdaların işlenmesinde ve ambalajlanmasında önemli bir potansiyele sahiptir. Bu çalışmada, gıda sektöründe geniş bir uygulama alanı bulan nanoteknoloji konusunda yapılmış çalışmalar bibliyometrik analiz yöntemi kullanılarak incelenmiştir. WoS veri tabanında "gıda" ve "nanoteknoloji" kavramlarını içeren makalelerin ve derleme makalelerinin taranması sonucunda toplam 1950 çalışma tespit edilmiştir. Gıda ve nanoteknoloji üzerine yapılan ilk makalenin 2002 yılında yayımlandığı, bu alandaki en yoğun çalışmanın ise 2021 yılında gerçekleştirildiği görülmüştür. En fazla çalışmaya imza atan ülke Amerika Birleşik Devletleri (ABD) iken, onu sırasıyla Çin Halk Cumhuriyeti, Hindistan, Brezilya ve İran takip etmiştir. Gıda ve nanoteknoloji kavramlarını içeren makale türündeki çalışmaların en fazla tarandığı indeks Science Citation Index Expanded (SCI-EXPANDED) olurken, en fazla çalışmanın yayımlandığı dergi Elsevier (842 makale) olmuştur. Çalışmalarda en çok kullanılan yayım başlıklarının "tarım ve gıda kimyası yayını" ve "tarımsal gıda sektöründe nanoteknoloji" olduğu tespit edilmiştir. Çalışmalarda en fazla kullanılan anahtar kelime "nanoteknoloji" olurken bunu "nanopartiküller", "gıda güvenliği", "gıda ambalajlama", "enkapsülasyon" ve "biyoyararlılık" kavramları izlemiştir.

Dünyada gıda ve nanoteknoloji konusunda yapılan çalışma sayısı bakımından ABD ve Çin Halk Cumhuriyeti'nin öne çıktığı görülmektedir. Bu durum, bahsedilen ülkelerin nanoteknoloji alanında önemli düzeyde yatırım yapmaları ile ilişkilendirilebilir. Ülkelerin, nanoteknoloji konusundaki ulusal çalışmaları yönlendirmek üzere çeşitli kurumsal yapılanmalara gittiği ve kalkınma planlarında nanoteknolojiye önemli bir yer ayırdığı ifade edilmiştir. Nanoteknoloji araştırmaları alanında başı çeken ABD'nin, 2000 yılında Ulusal Nanoteknoloji Girişimini (NNI) kurarak örgütlenme alanında öncü olduğu belirtilmiştir. Günümüze kadar toplam nanoteknoloji AR-GE harcamaları dikkate alındığında, ABD'nin bu konuda da öncü bir rol oynadığı, 2014 yılında sadece NNI için ayırdığı bütçenin 1,7 milyar ABD Doları olduğu bildirilmiştir. ABD'yi takip eden diğer ülkelerin ise Güney Kore, Almanya, Japonya, Fransa ve Rusya Federasyonu olduğu görülmektedir. Rusya'nın, kurduğu Rusya Nanoteknoloji Birliği (RUSNANO) sayesinde nanoteknoloji konusunda yükselen bir değer olduğu, RUSNANO tarafından nanoteknolojiye ayrılan bütçenin 2015 yılında 1,5 milyar ABD Doları'na ulaştığı belirtilmiştir. Avrupa Birliği'ne üye ülkeler arasında Almanya ve Fransa'nın Ar-Ge harcamaları bakımından diğer AB ülkelerinden ayrıldığı görülmektedir. Uzakdoğu'da ise Güney Kore, Çin ve Japonya'nın ön plana çıktığı, Çin'de bu alandaki Ar-Ge çalışmalarının savunma sanayii alanında yoğunlaştığı belirtilmiştir (T.C. Bilim, Sanayi ve Teknoloji Bakanlığı, 2017). Türkiye'nin ise diğer ülkelere nazaran nanoteknoloji çalışmaları konusunda geride kaldığı, ancak 2000'li yılların başından itibaren çeşitli adımlar atılmaya başlandığı ifade edilmiştir. Başta Bilkent Üniversitesi'nde faaliyet gösteren UNAM (Ulusal Nanoteknoloji Araştırma Merkezi) olmak üzere nanoteknoloji ile ilgili farklı alanlarda çalışmalar yürüten birçok üniversite bulunduğu belirtilmiştir (TÜSİAD, 2008). Türkiye'de nanoteknoloji konusunda nitelikli insan kaynağı oluşturmak ve uluslararası düzeyde yeterlilik kazanmak amacıyla çeşitli üniversitelerde lisans ve lisansüstü nanoteknoloji programları açılmaya başlandığı görülmektedir. Nanoteknolojiye yönelik AR-GE faaliyetlerinin; üniversiteler bünyesinde kurulan araştırma merkezlerinde, kamu kurumları desteğiyle kurulan merkezlerde ve birçok disiplinden araştırmacıların yer aldığı lisans, yüksek lisans ve doktora programları kapsamındaki çalışmalarda yürütüldüğü ifade edilmiştir (T.C. Bilim, Sanayi ve Teknoloji Bakanlığı, 2017). TÜBİTAK tarafından hazırlanan Vizyon 2023 Programı'nda belirlenen stratejik teknolojiler arasında nanoteknolojinin öncelikli alanlardan biri olarak yer aldığı bildirilmiştir. Başta TÜBİTAK olmak üzere, Bilim, Sanayi ve Teknoloji Bakanlığı ile Sağlık Bakanlığı tarafından bilimsel araştırmaların desteklendiği ifade edilmiştir. Desteklenen bu projelerden birinin, Türkiye'nin 2023 stratejik hedeflerinden birisi olan nanoteknoloji konusunda farkındalığı arttırmayı hedefleyen UNINANO isimli proje olduğu belirtilmiştir (Barış Eren, 2022). Türkiye'nin, 2003-2011 yılları arasında nanoteknoloji araştırma merkezlerine 244 milyon ABD Doları tutarında yatırım yaptığı, bu miktarın yıllık yaklaşık olarak 30 milyon ABD Dolarına denk geldiği bildirilmiştir. Bunun yanı sıra, nanoteknoloji projeleri ve firmalarının kamu tarafından desteklendiği ancak toplam destek tutarlarının OECD ortalamasının altında olduğu belirtilmiştir. Türkiye'de nanoteknoloji alanında üretilen bilimsel yayım sayısının 2016 yılı itibariyle toplam 2366 olduğu ifade edilmiştir (T.C. Bilim, Sanayi ve Teknoloji Bakanlığı, 2017).

Bu çalışmada, gıda alanında yapılan nanoteknoloji çalışmalarının hangi konularda yoğunlaştığı ve Türkiye'nin gıda alanında gerçekleştirilen nanoteknoloji çalışmaları konusunda dünyadaki yeri gibi hususların araştırılması hedeflenmiştir. Elde edilen veriler doğrultusunda, nanoteknoloji uygulamaları ile ilgili gıda işleme ve gıda ambalajlama konularında önemli düzeyde çalışma yapıldığı görülmüştür. Nanoteknoloji gıda sektöründe oldukça geniş bir kullanım alanına sahip olmakla birlikte, gıda işleme ve ambalajlamada kullanılan ve geleneksel formlarıyla karşılaştırıldığında oldukça farklı fizikokimyasal ve biyolojik özelliklere sahip olan nanomateryallerin kullanımının, gıda güvenliği ve çevreye olan etkileri açısından değerlendirilmesine yönelik daha fazla çalışmaya yer verilmesi gerektiği söylenebilir. Bununla birlikte, gıda alanında yapılan nanoteknoloji çalışmalarının toplam nanoteknoloji çalışmaları içindeki payının oldukça düşük düzeyde olduğu görülmektedir. Türkiye'deki nanoteknoloji araştırma ve uygulamaları temel alanlarının öncelikle malzeme bilimi, kimya, fizik, klinik tıp ve biyomedikal bilimler olduğu bildirilmiştir (Darvish & Tonta, 2015). Türkiye'de gıda bilimi ve teknolojisi alanında nanoteknoloji uygulamalarına dair yeterli çalışma yapılabilmesi için bu alanda gelişmek isteyen üniversitelerin desteklenmesi gerekmektedir. Bu kapsamda, alana özgü araştırma çalışmalarını gerçekleştirecek bilim insanlarının yetiştirilmesi, gerekli altyapının oluşturulması ve yeterli bütçe desteği sağlanması, ulusal ve uluslararası iş birliklerinin arttırılmasına yönelik düzenlemeler yapılması gerektiği düşünülmektedir.

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Research Article

Fractal Geometries in Wireless Communication: A Focus on Sierpinski Carpet Fractal Antennas

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Abstract: This article explores the design and performance of a Sierpinski carpet fractal antenna aimed at achieving a resonant frequency of approximately 2.4 GHz, a critical band for wireless applications like Wi-Fi. The study emphasizes the advantages of fractal geometries in enhancing antenna miniaturization, bandwidth, and gain, making them suitable for modern communication systems. Using COMSOL Multiphysics, the antenna's electromagnetic characteristics were simulated and experimentally validated, focusing on reflection coefficients, radiation patterns, and impedance matching. The simulation revealed strong impedance matching at 2.432 GHz with an S11 reflection coefficient of about -30 dB, indicating minimal power loss. Experimental results closely align with simulations, confirming the design's narrowband operation and nearly spherical radiation pattern, which are suitable for applications such as RFID, Wi-Fi, and certain medical devices.

Keywords: 2.4 GHz, Antenna design, Sierpinski carpet fractal antenna, Wireless communication

Kablosuz İletişimde Fraktal Geometriler: Sierpinski Halı Fraktal Antenlerine Odaklanma

Öz: Bu makale, Wi-Fi gibi kablosuz uygulamalar için kritik bir bant olan yaklaşık 2,4 GHz'lik bir rezonans frekansına ulaşmayı amaçlayan bir Sierpinski halı fraktal anteninin tasarımını ve performansını araştırmaktadır. Çalışma, fraktal geometrilerin anten minyatürizasyonunu, bant genişliğini ve kazancını artırmadaki avantajlarını vurgulayarak onları modern iletişim sistemleri için uygun hale getiriyor. COMSOL Multiphysics kullanılarak antenin elektromanyetik özellikleri simüle edilmiş ve yansıma katsayıları, ışıma örüntüleri ve empedans eşleşmesine odaklanılarak deneysel olarak doğrulanmıştır. Simülasyon, 2,432 GHz'de yaklaşık -30 dB'lik bir S11 yansıma katsayısı ile güçlü empedans eşleşmesi ortaya çıkardı ve bu da minimum güç kaybına işaret ediyor. Deneysel sonuçlar, RFID, Wi-Fi ve bazı tıbbi cihazlar gibi uygulamalar için uygun olan tasarımın dar bant çalışmasını ve neredeyse küresel radyasyon modelini doğrulayan simülasyonlarla yakından uyumludur.

Anahtar Kelimeler: 2.4 GHz, Anten tasarımı, Kablosuz iletişim, Sierpinski halısı fraktal anten

1. Introduction

Fractal geometries have become a crucial design approach across various applications, such as antenna design, frequency selective surfaces (FSS), and electromagnetic interference shielding. Among the notable fractal designs, the Sierpinski carpet fractal has demonstrated significant potential in achieving miniaturization, improved bandwidth, and enhanced gain, making it particularly useful in antenna technology. Various studies have examined the use of fractal structures to meet the increasing demand for compact and efficient devices in modern communication systems.

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For example, nano-carbon-based materials have been widely researched for applications in electromagnetic interference (EMI) shielding and sensing, offering properties similar to traditional materials like copper (Ugale et al., 2016). Moreover, fractal-based unit cells, including those utilizing split ring resonators (SRRs), have demonstrated distinctive electromagnetic properties, producing cloaking effects within specific frequency ranges (Jagtap et al., 2018). These properties make fractal designs ideal for high-performance, compact antennas.

Microstrip patch antennas, commonly used in wireless communication devices, have been simulated using COMSOL Multiphysics, demonstrating improvements in resonant frequency, bandwidth, and reflection coefficients (Gawade & Dahotre, 2021). Furthermore, fractal designs, such as the square fractal metasurface combined with a PIN diode, have been optimized for dual-band operations in both C- and X-bands, enhancing radiation efficiency and phase distribution (Kim et al., 2022). Reflectarray antennas with fractal structures have also been shown to significantly improve gain, with one study reporting an increase from 21.6 dBi to 23.1 dBi through fractal unit cell modifications (Urul, 2022).

Furthermore, artificial neural networks (ANN) have been used to model and predict the resonant frequency of microstrip antennas, delivering precise results over various input parameters (Bayram et al., 2021). Fractal geometries such as the Minkowski shape have been particularly successful in reflectarray designs, offering compactness and improved phase agility without altering the patch size (Costanzo et al., 2016). These features make fractals a valuable tool for optimizing the performance of antennas in various applications.

In acoustic metamaterials, fractal structures like the Hilbert fractal have been found to influence transmission loss behavior, further illustrating the versatility of fractal designs across different domains (Comandini et al., 2023). Additionally, fractals have been explored for use in strain sensors, where geometries like the Sierpinski carpet and Koch curve have proven effective in miniaturizing sensor dimensions and improving sensitivity (Herbko et al., 2022). Other applications of fractal designs include their use in mechanical resonators, where fractal shapes enhance the frequency response and functionalization area, making them suitable for nanoscale devices (Tzanov et al., 2020).

Recent advances in solar absorber technology also leverage fractal tree-shaped metasurfaces to achieve high absorption efficiencies across a broad spectral range, further highlighting the adaptability of fractal designs in optimizing electromagnetic properties (Das et al., 2024). Similarly, fractal-based designs have been shown to enhance the performance of energy storage devices like supercapacitors, increasing the effective electrode area and overall capacitance (Ramesh et al., 2023).

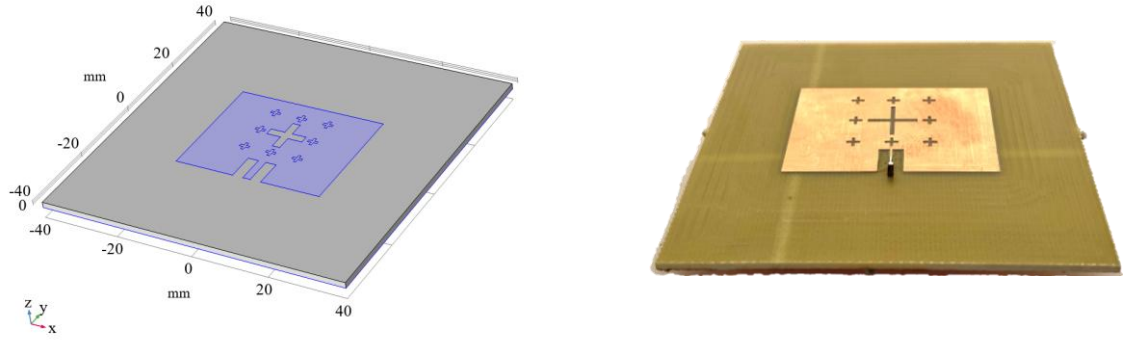
In wireless communication, fractal antennas are integral to next-generation technologies like massive multiple-input multiple-output (MIMO) systems, where their compactness and multi-band capabilities are essential for 5G networks (Palanisamy et al., 2021). Moreover, fractal geometries have been applied in terahertz (THz) antenna designs, where they influence the bandwidth and radiation properties, offering potential for advanced communication systems (Uttley et al., 2023).

This study focuses on designing and analyzing a Sierpinski carpet fractal antenna targeting a resonant frequency of 2.4 GHz, commonly used for Wi-Fi and other wireless applications. COMSOL Multiphysics software was employed for the simulation, emphasizing reflection coefficients, radiation patterns, and impedance matching. Experimental results further validate the design, providing a comprehensive assessment of its performance. By leveraging COMSOL Multiphysics software for simulation, the antenna's performance will be evaluated in terms of reflection coefficients, radiation patterns, and bandwidth (Gawade & Dahotre, 2021).

The results seek to add to the expanding body of research on fractal-based antennas, which have shown great potential in reducing size and enhancing the performance of modern communication systems (Costanzo et al., 2016, Herbko et al., 2022, Das et al., 2024).

2. Material and Methods

The Sierpinski carpet fractal antenna was designed and simulated using COMSOL Multiphysics. The methodology involved modeling the antenna with specific parameters for the patch, substrate, and surrounding air domain. The simulation targeted a frequency of 2.432 GHz, which is within the 2.4 GHz ISM band commonly utilized for wireless communication (Figure 1).



a) b)

Figure 1. Structure of the Sierpinski carpet fractal patch microstrip antenna: a) Simulation model b) Fabricated sample.

To simulate electromagnetic wave propagation and analyze antenna radiation patterns, a three-dimensional model was selected from the Model Wizard using the Electromagnetic Waves, Frequency Domain (emw) physics interface in COMSOL Multiphysics. The simulation was set up to operate in the frequency domain, targeting a frequency of 2.432 GHz, which is standard for the Wi-Fi band and falls within the 2.4 GHz ISM (Industrial, Scientific, and Medical) band, commonly used for various wireless communications.

A set of parameters was defined globally to facilitate the configuration of geometry and material dimensions (Figure 2) efficiently. The parametric sizes of the antenna are listed in Table 1.

Table 1. Antenna size parameters

Parameter	Length (mm)
w	70
l	70
w1	38.37
w2	16.935
w3	2
w4	0.5
l1	28
t1	0.75
t2	0.5
d	1.6

An extra block was created for the patch, positioned on the surface of the substrate. The dimensions of the patch were specified as width (w1), length (l1), and thickness (d).

Subsequently, additional blocks were introduced to represent the impedance matching stub and the 50Ω feed line. The stub was defined with the following parameters: width (w4) and length (l2). Its position was determined relative to the patch.

To model the antenna's electromagnetic behavior, a Perfect Electric Conductor (PEC) boundary condition was applied to the conductive surfaces, and a lumped port simulated the feed point. PML (Perfectly Matched Layer) was used to eliminate boundary reflections, ensuring accurate far-field radiation pattern analysis (Figure 3). This ensures that the antenna’s S-parameter and radiation pattern results reflect its true performance, free from distortions caused by boundary effects.

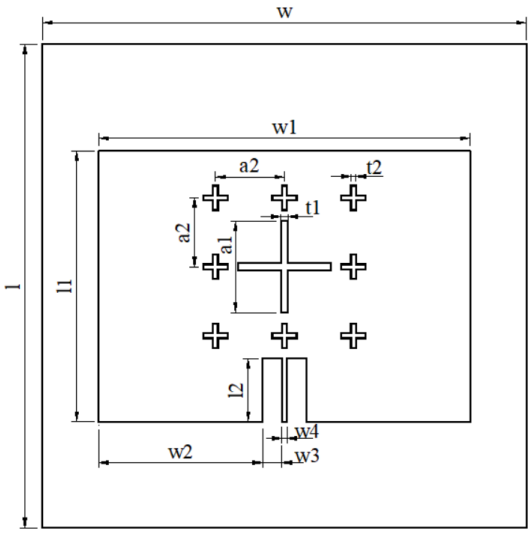


Figure 2. Dimensions of the proposed Sierpinski carpet fractal antenna.

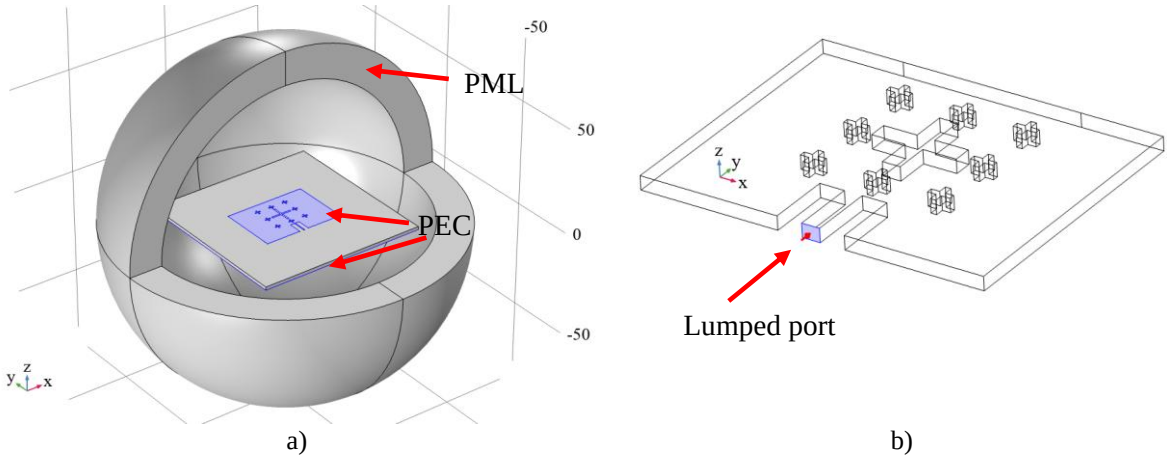


Figure 3. a) 3D view of the finite element model; b) lumped port boundary condition.

The built-in Air material was selected from the material library provided by COMSOL and applied to the spherical domain surrounding the antenna structure, with the objective of simulating the propagation of electromagnetic waves in free space. The substrate material was identified as FR4. A Perfect Electric Conductor (PEC) is defined as a material that allows the unrestricted movement of electric charge without any resistance. The conducting components, including the patch and feed line, were modeled using the PEC condition to represent ideal conductor behavior, thus simplifying the simulation process.

The Electromagnetic Waves, Frequency Domain (emw) physics interface was set up to simulate the antenna's performance, using the following parameters. A lumped port was used to simulate the feed point of the antenna. The wave excitation feature was activated by default, and this port was used for calculating the input impedance and S-parameters during the simulation. A far-field domain condition was applied to calculate the far-field radiation patterns.

A mesh was automatically generated for the entire model using COMSOL's meshing tools. The study configuration was based on a frequency domain analysis, which allowed for the examination of electromagnetic behavior at a specific frequency. The frequency of interest was set at 2.432 GHz.

In the experimental setup, FR4 (Flame Retardant 4) was used as the substrate material, with a relative permittivity (εr) of 4.4 and a thickness of 1.6 mm. FR4 was selected due to its widespread availability, cost-effectiveness, and suitability for high-frequency applications. In the fabricated sample,

these components were implemented using copper to replicate the designed structure and validate the simulation results.

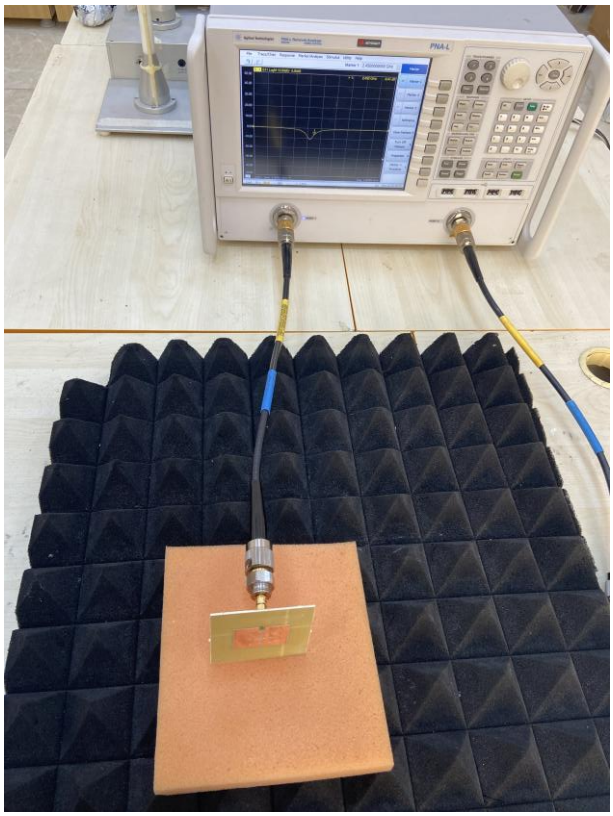


Figure 4. Measurement setup of fabricated sample.

The reflection coefficient S11 of the Sierpinski fractal patch antenna was measured using an Agilent Technologies PNA-L Network Analyzer. The antenna was designed to operate within the 2–3 GHz frequency range. The measurement setup involved placing the antenna on a foam block to minimize unwanted reflections and interference. The device was calibrated prior to the measurement to ensure accuracy, and the S11 parameter was recorded over the designated frequency range to assess the antenna's impedance matching performance (Figure 4).

3. Results

The simulated S-parameter (S11) response of the antenna, as shown in Figure 5, demonstrates a clear resonance at 2.432 GHz, with a minimum reflection coefficient of approximately -30 dB. This indicates strong impedance matching at the target frequency, minimizing reflected power and maximizing power transfer to the antenna. The S11 curve shows a bandwidth (defined by S11 ≤ -10 dB) covering a narrow frequency range centered around 2.432 GHz, suggesting that the antenna is well-suited for narrowband applications operating at this frequency. The distinct dip in S11 at the resonant frequency confirms the design's effectiveness and validates the antenna's expected operating characteristics.

Although the experimental results in the graphs are consistent, they may not exactly match the simulated results due to inherent differences between real-world measurements and idealized simulations. While the experimental data shows internal consistency, it could still be influenced by factors such as measurement system limitations, calibration errors, or environmental influences like temperature or humidity, which aren't fully captured in the simulation. Additionally, the physical device may have slight variations from the model due to manufacturing tolerances, misalignments, or material properties that differ from the idealized assumptions used in the simulation. These differences can lead

to variations in S11 values between the experimental and simulated data, even though both sets of results are internally consistent.

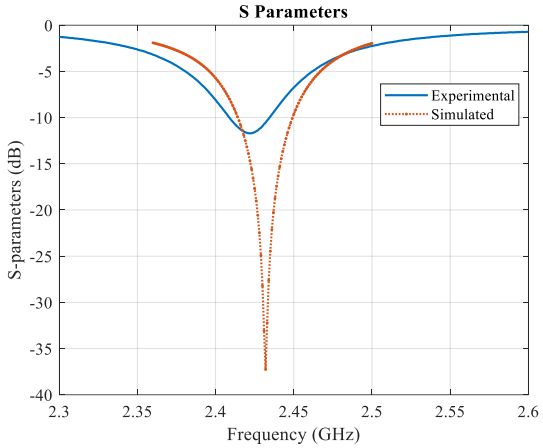


Figure 5. The simulated and experimental S-parameter (S11) response of the Sierpinski carpet fractal antenna.

The simulated far-field gain pattern in dBi, shown in Figure 6, illustrates the antenna's performance across the E-plane and H-plane at 2.432 GHz. The E-plane pattern (solid blue line) displays a bidirectional main lobe structure with a peak gain of approximately -10 dBi at around ±70°, achieving compactness compared to conventional microstrip patch antennas, which typically have higher directivity but larger dimensions. The fractal geometry also offers multi-band capabilities and size reduction benefits, as supported by prior studies, making it suitable for narrowband applications. Optimized for operation at 2.4 GHz, the antenna achieves a nearly spherical radiation pattern, ideal for omnidirectional coverage in applications such as IoT devices, RFID systems, and Wi-Fi access points.

Compared to other fractal designs, such as Minkowski or Koch, the Sierpinski Carpet geometry provides a unique balance of compactness and performance, contributing to advancements in fractal-based antenna design. Its uniform power distribution supports reliable connectivity regardless of the receiver's orientation or placement.

In contrast, the H-plane pattern (dashed green line) shows a more consistent gain distribution, with a broader lobe and peak values near -12 dBi. These patterns indicate that the antenna radiates more effectively in certain directions within the E-plane, while the H-plane exhibits a relatively uniform gain distribution. This result suggests that the antenna's design could be optimized for applications that benefit from bidirectional coverage in the E-plane. Further design adjustments could enhance the gain and directivity to improve performance for specific directional requirements.

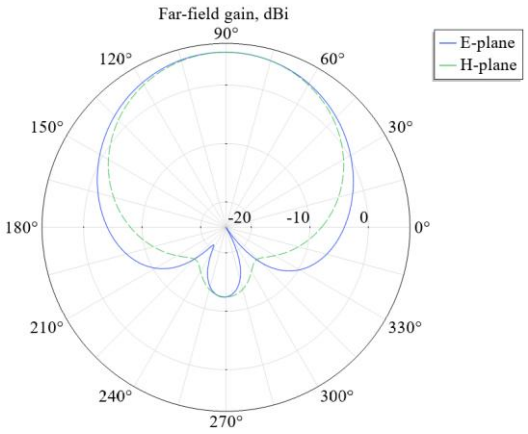


Figure 6. Simulated far-field gain pattern in dBi of the Sierpinski carpet fractal antenna.

The simulated far-field radiation pattern of the antenna at 2.432 GHz, shown in Figure 7, exhibits a nearly spherical distribution with a peak electric field intensity of approximately 1.48 V/m. The pattern indicates an omnidirectional radiation characteristic, with a gradual decrease in intensity

from the top (red) to the bottom (blue) regions. This suggests a relatively uniform power distribution across the upper hemisphere, which is desirable for applications requiring broad coverage in multiple directions. However, the results also suggest potential for further design adjustments to improve directivity, depending on specific application requirements. The uniformity in the radiation pattern confirms that the antenna achieves its intended frequency response, validating both the design and simulation approach.

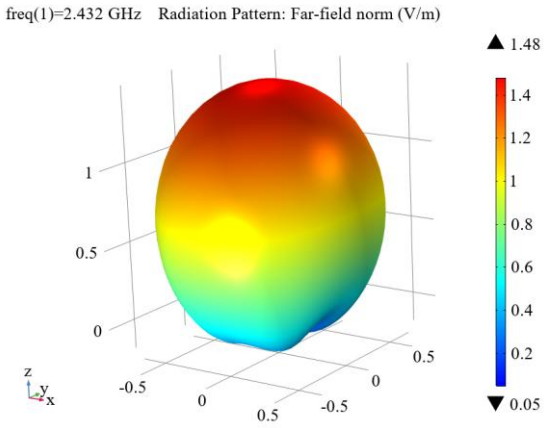


Figure 7. Simulated far-field radiation pattern of the Sierpinski carpet fractal antenna.

Figure 8 illustrates the current density distribution on the Sierpinski fractal antenna at the operating frequency of 2.432 GHz. The results reveal a significant concentration of surface currents in the central regions of the patch and feedline, confirming the effective resonance of the fractal structure. This distribution demonstrates how the fractal design optimally guides the current flow, facilitating efficient electromagnetic radiation and ensuring proper impedance matching. The analysis further supports the hypothesis that the fractal geometry contributes to the antenna's broadband characteristics and enhanced performance at high frequencies.

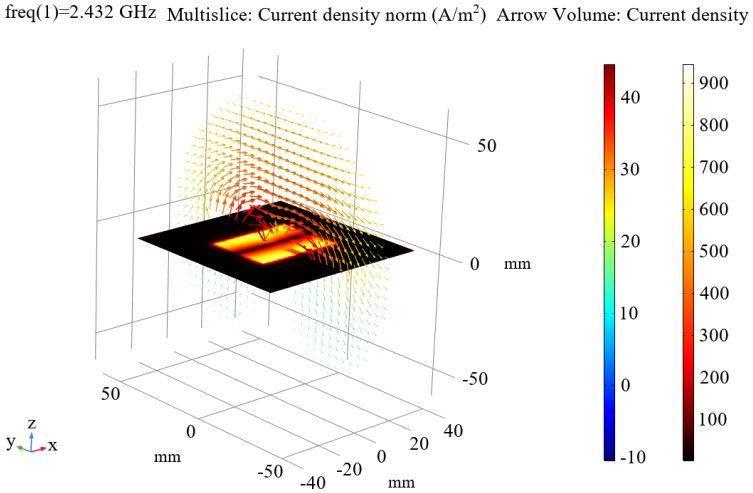


Figure 8. Current density distribution on the Sierpinski fractal antenna at the operating frequency of 2.432 GHz.

4. Conclusion

The principal objective of this study is to fabricate a high-gain directional antenna comprising square and rectangular patches at a frequency of 2.45 GHz. Theoretical studies and practical applications indicate that the antenna is optimized at 2.45 GHz, with a gain of -15 dBm achieved in both cases. Furthermore, a high-gain region of use was identified at angles greater than 180° with respect to the

antenna surface. In future studies, the number of rectangular patches can be increased to enable operation at different frequencies.

In conclusion, the simulated results indicate that the designed antenna performs efficiently at 2.432 GHz, exhibiting a well-matched impedance with an S11 value of -30 dB, a nearly spherical radiation pattern, and a gain pattern ideal for applications that demand broad coverage in the E-plane. The narrowband characteristic, as indicated by the S11 response, makes this antenna ideal for applications that require minimal interference and operate within a restricted frequency range, such as IoT devices, RFID systems, Wi-Fi communication, and certain medical devices. These findings validate the design's suitability for targeted narrowband applications, confirming its potential for efficient and reliable performance in these domains.

Future work could explore higher iteration levels of the fractal geometry to further enhance gain and bandwidth. Introducing multilayer configurations or tuning the substrate material and patch dimensions could support multiband operation, making the design adaptable for emerging technologies like 5G or advanced IoT applications.

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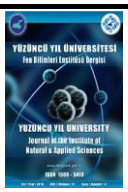
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Research Article

The Impact of Weapon Systems on Structural Damage and Progressive Collapse: A Case Study of Belgorod Oblast

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Abstract: Structures are exposed to unexpected loads throughout their service life nowadays. This phenomenon, referred to as progressive collapse in the literature, has attracted the attention of researchers in recent years. This study examines the effects of firearms on buildings during wartime and their relationship with progressive collapse. Conducted using the example of Belgorod Oblast, a border city in Russia, the research evaluates the destructive impacts of various types of firearms and ammunition on residential buildings, commercial buildings, and historical structures. During the data collection phase, the data obtained daily was converted into weekly data. The research provides detailed data on the frequency of structures exposed in various villages and cities in the Belgorod region to different types of attacks and the types of damage caused by these attacks. In the analysis method, damages were classified from superficial damage to complete destruction, and the cause-effect relationship between firearm types and building damage was evaluated. The findings indicate that buildings suffer significant structural deterioration due to the types of damage sustained during wartime, and progressive collapse is rarely triggered. It is suggested that future studies focus on developing new design and construction techniques to enhance the durability of buildings, especially in the façade and roof, in light of these findings. The results of the study provide valuable information that will help us better understand the effects of firearms and modern warfare technologies on progressive collapse and the impacts of firearms on buildings.

Keywords: Blast loads, Progressive collapse, Russia-Ukraine war, UAV, Weapon systems

Silah Sistemlerinin Yapılar Üzerinde Yarattığı Tahribat ve Aşamalı Göçme Bağlantısı: Belgorod Oblastı Örneği

Öz: Günümüzde yapılar hizmet ömürleri süresince beklenmedik yüklere maruz kalmaktadırlar. Literatürde aşamalı göçme olarak adlandırılan bu durum son yıllarda araştırmacıların ilgisini çekmektedir. Bu çalışmada, savaş sırasında ateşli silahların yapı üzerindeki etkileri ve bu etkilerin aşamalı göçme ile ilişkisi incelenmiştir. Rusya'nın sınır kenti olan Belgorod Oblastı örneği üzerinden yürütülen araştırmada, farklı türde ateşli silahlar ve mühimmatların konutlar, ticari binalar ve tarihi yapılar üzerindeki yıkıcı etkileri değerlendirildi. Veri toplama aşamasında, günlük olarak elde edilen veriler haftalığa çevrilmiştir. Araştırma, Belgorod bölgesindeki çeşitli köy ve şehirlerdeki yapıların, farklı türde saldırılara maruz kalma sıklığı ve bu saldırıların neden olduğu hasar türleri üzerine ayrıntılı veri sağlamaktadır. Analiz yönteminde, hasarlar yüzeysel hasardan tamamen yıkılmaya kadar sınıflandırılmış ve ateşli silah türleri ile yapı hasarı arasındaki sebep-sonuç ilişkisi değerlendirilmiştir. Bulgular, yapıların savaş sırasında maruz kaldıkları hasar türlerine göre ciddi yapısal bozulmalara uğradığını ve aşamalı göçmenin nadiren de olsa tetiklendiğini göstermektedir. Gelecekteki çalışmaların, bu bulgular ışığında, yapıların özellikle cephe ve çatıda dayanıklılığını artıracak yeni tasarım ve inşaat tekniklerinin geliştirilmesine odaklanması önerilmektedir. Çalışmanın sonuçları, ateşli silahların ve modern savaş teknolojilerinin yapı üzerindeki aşamalı göçme etkilerini daha iyi anlamamıza ve ateşli silahların yapılar üzerindeki etkilerini anlamaya yardımcı olacak değerli bilgiler sunmaktadır.

Anahtar Kelimeler: Aşamalı göçme, İHA, Patlama yükleri, Rusya-Ukrayna savaşı, Silah sistemleri

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1. Introduction

Progressive collapse can be defined as a chain-reaction failure mechanism that can occur when structures are subjected to unexpected loads. These unexpected loads, which are not considered during the design phase, can arise for various reasons. The most significant of these is the impact of explosives or firearms. This situation typically occurs during terrorist attacks or on the battlefield. In war and conflict environments, the damage inflicted on structures and damage impact on structural integrity are of critical importance. It is known that this damage, which begins with the loss of a column, imposes additional loads on the rest of the system.

The first known example of progressive collapse occurred in 1968 at the 22-story Ronan Point apartment building. This structure was built using the large panel system (LPS) method with prefabricated concrete panels. A gas explosion on the 18th floor dislodged the exterior walls of the building, causing the upper floors to collapse sequentially in a domino effect. The collapse revealed significant deficiencies in the assembly of the prefabricated concrete panels and the safety of the gas installation, leading to major changes in building safety regulations in the United Kingdom. As a result of this incident, developed countries began to include explanations and criteria related to progressive collapse in their regulations, the 2001 terrorist attacks on the World Trade Center (WTC) (Kilicer, 2024).

Today, the United States Department of Defense's UFC 4-023-03 '*Design of Buildings to Resist Progressive Collapse*' is actively used in relation to progressive collapse. Design engineers can determine a structure's resistance to progressive collapse by using the analysis methods outlined in this guide. Although countries such as the United Kingdom, Canada, Russia, and others have included definitions and descriptions related to progressive collapse in their regulations, they have not provided clarity on the analysis methods. Therefore, the UFC 4-023-03 guide is used worldwide as a reference for progressive collapse analyses. While the UFC 4-023-03 guide does not generally address the specific events leading to progressive collapse, it examines the structural effects of potential column losses and offers various analysis methods. Events that could cause column loss include firearms and modern technological weapons.

This study examines the effects of firearms on structures and current research on progressive collapse. Studies such as those by Tahmilci (2007) and Francioli et al. (2021) address the behavior of structures under blast effects and the relationship between these effects and progressive collapse. Ozgan et al. (2023) examined the effect of ground influence on progressive collapse, while Abdelwahed (2019) aimed to provide design engineers with a broader perspective on minimizing the consequences of building progressive collapse following a column removal scenario. Byfield et al. (2014) addressed the challenges of frame modelling with steel connections and highlighted the advantages and disadvantages of some modelling procedures related to the treatment of connections. Stephen et al. (2019) proposed different alternative numerical approaches to simulate the sudden column removal in frame buildings and to investigate the effect of rise time on the structural response. Marjanishvili (2004) compared different modelling techniques used in progressive collapse analysis. He discussed the advantages and disadvantages of each method and concluded that the most effective analysis procedure for progressive collapse evaluation is a method that incorporates the advantageous parts of all four procedures. Kim & Kim (2009) investigated the progressive collapse-resisting capacity of steel moment-resisting frames using alternate path methods recommended in the GSA (2003) and DoD (2015) guidelines. They considered linear static and nonlinear dynamic analysis procedures for comparison. Compared to the linear analysis results, the nonlinear dynamic analysis provided larger structural responses, and the results varied more significantly depending on variables such as applied load, location of column removal, or number of building stories. Weng et al. (2016) examined nonlinear analysis methods for column removal scenarios in reinforced concrete buildings. Yuzbasi & Arslan (2019) conducted a comprehensive investigation into various methods used to model the progressive collapse mechanism of structures, as well as their application in simulating demolition processes. Building on this, Yuzbasi (2024) carried out experimental verification on the progressive collapse of a full-scale silo structure, specifically focusing on the effects of successive column removal. This study utilized the finite element method and incorporated blast load simulations to replicate the collapse sequence, offering valuable insights into the practical application of these methods. Fan et al. (2023) studied the Gurson-Tvergaard-Needleman (GTN) constitutive model, which describes the aggregate failure of metal voids, is selected

as the constitutive relation to investigating the damage evolution and fracture of semi-rigid joints in steel structures during a progressive collapse.

Today, the rapid advancement of warfare technologies and the proliferation of firearms increase the risks structures face during war. Particularly, modern warfare techniques, such as UAV and FPV kamikaze drone attacks, raise questions about whether they cause significant structural damage and trigger progressive collapse. This situation raises curiosity about how the resilience of both civilian and military structures changes during warfare. Specifically, using the ongoing Russia-Ukraine war and the example of Belgorod, the destructive effects of different types of firearms and ammunition on residential buildings, commercial buildings, and historical structures will be evaluated. The primary objective of the research is to classify the types of damage structures encounter during war and examine the impact of this damage on structural integrity and progressive collapse. In this context, the cause-effect relationship between types of firearms and structural damage will be analyzed, and the potential for progressive collapse will be assessed. This research aims to contribute to the development of strategies for protecting structures under wartime conditions

This research examines in detail the frequency and types of damage caused by various attacks on structures across different villages and towns in the Belgorod region. The methodology of the study consists of three main stages: data collection, analysis, and presentation of results. Data were systematically collected from the Governor of Belgorod, official accounts, and the Russian Ministry of Emergency Situations. These data were supplemented with additional information such as photos and locations of the structures. The collected data were classified according to the types of damage, and the cause-effect relationship between types of firearms and structural damage was evaluated. Analysis results and key findings were reported, and recommendations were made to enhance the resilience of structures based on the types of damage they endure during wartime. The findings of the research indicate that structures undergo different structural deteriorations based on the types of damage they sustained during the war.

2. Material and Methods

The concept of progressive collapse has been increasingly observed in the literature since the 2000s, although it has always been present on battlefields and in structures exposed to unexpected loads. This study aims to explain the damage caused by firearms and modern weapon technologies on structures through real and contemporary examples. In this context, the Belgorod Oblast of Russia, which has been frequently subjected to attacks, has been considered. The types of modern and conventional attacks experienced by the oblast and its structures, including kamikaze drones, unmanned aerial vehicles, and classifications of structural damage, are explained under the following headings.

2.1. The Belgorod Oblast of Russia

Belgorod Oblast is a region in the southwestern part of Russia, bordering Ukraine. It has a total area of approximately 27.100 km² and a population of about 1.5 million people. Belgorod Oblast shares a border with Ukraine that is approximately 540 km long (Figure 1). This border holds significant importance, particularly in terms of military, security, and trade. Due to its strategic location, it is a region of great military importance for Russia. The region hosts various military structures, including air defense systems, logistics and support services, facilities, and bases. These bases play a strategic role in both protecting Russia's western borders and in its relations with Ukraine. The area is also equipped with air defense systems, which play a crucial role in protecting the oblast from threats posed by various firearms and aerial dangers. Given Belgorod Oblast's political significance and the ongoing Russia-Ukraine war, the locations of attacks by Ukrainian armed forces on Russia's Belgorod Oblast are provided using the map from Google Earth (2003) (Figure 1).

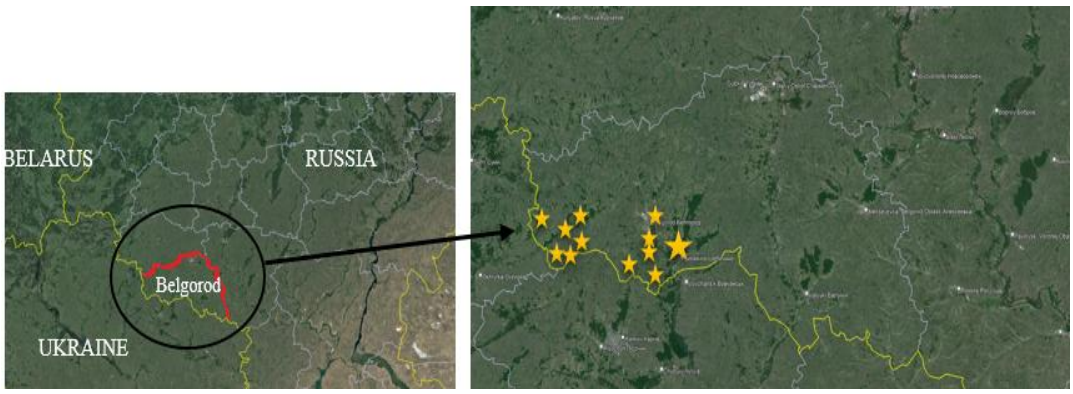


Figure 1. The location of Belgorod Oblast and the areas where the attacks.

Between May 6, 2024, and June 16, 2024, the structures most affected by attacks conducted by the Ukrainian Armed Forces on Russia's Belgorod Oblast were located in Shebekino (27 attacks), Murom (16 attacks), Belgorod city center (13 attacks), Novaya Tavolzhanka (10 attacks), Dubovoye (10 attacks), and Bezymeno (6 attacks).

Belgorod Oblast stands out as a border region due to its location. The buildings constructed in these areas are similar to those in the rest of Russia. It would be more accurate to evaluate the buildings in Russia based on the pre-1970 and post-1970 periods in terms of construction technology and material quality.

Ateş Can & Bakır (2021) discussed how residential architecture in the Soviet Union in the 1920s was approached to support the ideology, laying the foundations for communal housing in an ideological sense. These foundations were developed through studies conducted under Stroikom with state support, and the resulting housing designs were improved through analysis and optimizations in various categories, similar to the works in the West. Various competition proposals for new buildings that emerged during these years are presented in Figure 2 (Movilla Vega, 2020).

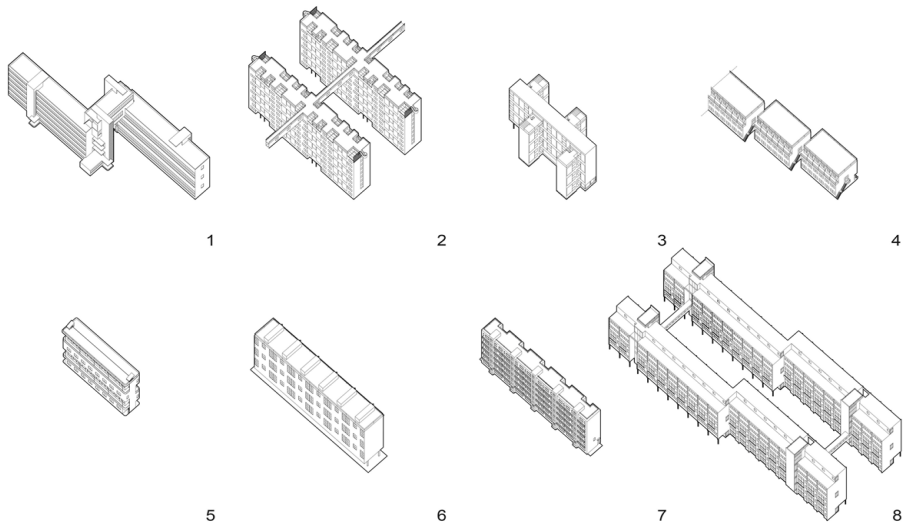


Figure 2. Axonometric views of the eight proposals submitted to the 1926 Comradely Competition: Ginzburg (1), Vegman (2), Vladimirov (3), Ol' (4), Vorotyntseva and Polyak (5), Nikol'skiy (6), Pasternak (7) and Sobolev (8). Graphics by Daniel Movilla Vega (Movilla Vega, 2020).

Buildings constructed before 1970 bear the marks of the impacts of World War II and the political, economic, and socio-cultural differences that followed. The first of these is wooden architecture, the oldest type of architecture in Russia. The most importan t areas where wood was used as a construction material were Russian national houses and various facilities (Anlatilaninotesi, 2016).

Another example is Brutalism, which refers to the appearance resulting from the use of concrete in its raw, massive, imposing, and stark form on the building's exterior. This type of architecture typically featured materials like steel and glass over time, becoming essential elements of Brutalist architecture, which offers economical, simple, and ergonomic structures (Venni, 2024). In residential buildings, wooden structures and a series of five-story prefabricated buildings were constructed to quickly address the need for housing. Although many different types of buildings were constructed, especially in housing, the exterior walls consisted of large-sized expanded clay concrete blocks (40 cm), the interior walls were made of concrete blocks (39 cm), the inner walls were made of gypsum slag concrete panels (8 cm), and the floors were made of prefabricated hollow reinforced concrete slabs (22 cm) (Novostroev, 2019). Despite having thick exterior and interior walls, these structures cannot be said to be resistant to firearms and explosions that release greater energy.

After 1970, the way was paved for Russia to attract tourists and for local architecture to change by using modern, diversified, and different types of buildings and construction materials. At the same time, restoration work was carried out on buildings constructed in previous years (Sayer, 2020). Various building types were identified, and construction began, distributed across all regions of Russia. These buildings were constructed using different materials. The construction year, building materials, and purpose of some Russian buildings after 1970 are presented in Table 1.

Table 1. Characteristics of some types of Russian buildings after 1970 (Prawdom, 2024)

Building Type	Construction Year	Building Material	Purpose
111-96	1975-1996	Large Panel	Housing
111-97	1970	Large Panel	Housing
111-101 (P-101)	The Late 1970s	Panel	Military Housing
111-108	1970	Panel	Housing
111-121	1970	Panel	Housing
111-134	1975-1990	Large Panel	Housing
114-85	1974-2000	Brick	Housing
114-86	1975	Brick	Housing
1605	1958-1985	Panel	Industrial
90	1971	Large Panel	Housing
E-93	1970-2000	Brick	Housing
II-18/12	1967-1970	Panel	Housing
II-49	1965-1985	Multi-Unit Panel	Housing

The types of structures listed in Table 1, built throughout the Soviet Union, are mostly constructed of panel and brick. Some of these types of structures were built in the Belgorod region. The progressive collapse resistance of the structures subject to the study is particularly low in panel-type buildings. In structures built before 1970, the initiation of progressive collapse is simpler due to both poor material quality and technological deficiencies compared to the present day. Although buildings constructed throughout the Soviet Union after 1970 are seen as somewhat more resistant to progressive collapse, they were built with this deficiency as the structural analyses and designs did not take progressive collapse into account. In rural areas outside the city center, the quality and workmanship of the buildings are separate issues that need to be discussed. In the following sections, real-time examples and locations are provided to illustrate how munitions targeted at buildings can cause progressive collapse.

2.2. Kamikaze drones

FPV (First-Person View) kamikaze drones are remotely controlled unmanned aerial vehicles equipped with explosives. These drones are primarily used for military and security purposes and are usually designed for one-way missions. They are typically equipped with explosive payloads and complete their missions by crashing into targets or detonating at specific locations. High-resolution cameras and low-latency video transmission systems are used to allow the operator to control the drone with precision. These drones are generally equipped with some explosives and aim to cause damage by

crashing into targets or detonating at predetermined locations. Drone operators can control them with high precision using special control devices or FPV goggles. Their applications include military operations, counter-terrorism, and security. They offer advantages such as high precision, flexibility, and low cost, while disadvantages include being single-use, the risk of signal interruption, and legal and ethical issues. Although there may not be a direct destructive effect on the structures, the fires initiated after the explosion can cause maximum damage to the building as they spread. Otherwise, localized explosions will only cause superficial damage.

Borsari & Davis (2023) describe various types of drones, including military-class medium-altitude long-endurance drones like the Turkish TB2, loitering munitions like the U.S. Switchblade, commercial DJI quadcopters, and homemade first-person view drones. Axe (2023) noted that in the later stages of the war, the use of FPV-piloted kamikaze drones to target both infantry and armored vehicles became widespread. This provided Ukraine with an incredibly cheap and effective attack alternative as well as a tool for psychological warfare. Rickli & Mantellassi (2024) noted that the quality of personnel is also reflected in the use of drones and is one of the most important factors in their effective utilization. Depending on the quality of the pilot, the success rate of an FPV drone flight can vary from 10% to 80%. An example of an FPV drone and its payload frequently used by the Ukrainian Army is shown in Figure 3.



(a) (b)

Figure 3. FPV Drones (Militarnyi, 2023) a) FPV Drone appearance b) FPV Drone with payload.

FPV drones play a significant role in modern battlefields and security operations. With technological advancements, the usage and effectiveness of these drones have also increased. However, in the context of progressive collapse, FPV drones do not seem to be successful. Although the impact at the target depends on many parameters, their effects on structures are quite limited. Even though drones can carry different amounts of TNT, Their carrying capacity is generally in the range of 1–5 kg (SavunmaTR, 2024). If these types of drones cause a fire after exploding, they can inflict maximum damage. Otherwise, they do not have the maneuverability and power to initiate a chain collapse mechanism in structures. They can cause regional damage at the point of explosion. Farcaş (2023) revealed that aside from structural damages, the most effective weapon in the Black Sea conflict was the drone. Many experts claim it is an artillery war, but they argue that they do not acknowledge. Also, the Chinese army, which has seen the intensive use of FPV drones in the Russia-Ukraine war, aims to expand the use of these drones; it conducts training and exercises for this purpose. For example, in a drill held in March 2024, Chinese army personnel used tanks and checkpoints (structural and non-structural elements) (Alpusam, 2024).

2.3. UAV (Unmanned Aerial Vehicle)

Unmanned Aerial Vehicles (UAVs) are aircraft that can be remotely controlled or autonomously programmed to perform various flight missions and tasks. UAVs, also defined as aircraft without human pilots onboard, can come in various sizes and shapes suitable for different types of missions. Nowadays,

these vehicles are widely used across nearly every sector, primarily in military, civil, and commercial applications.

The history of UAVs began with the development of the Kettering Bug during World War I. However, the widespread adoption and advancement of this technology gained momentum with the use of radio-controlled target drones before and during World War II. Throughout the Cold War, the United States and the Soviet Union developed UAVs for espionage and intelligence-gathering purposes. In the 1970s, Israel laid the foundations of modern UAV technology by developing the Scout UAV. Throughout the 1990s and 2000s, the United States became a pioneer in this field by utilizing advanced UAVs such as the Global Hawk and Predator in military operations. Today, UAVs have a wide range of applications in both military and civilian fields, becoming more autonomous and versatile with technological advancements (Army Technology, 2021; Anderson, 2023; Wikipedia, 2024). Over the years, the evolution and transformation of technology, along with developments in military and political arenas, have influenced the current uses and development of UAVs. In recent years, UAVs have clearly demonstrated their ability to change the course of many conflicts. However, the impact of such new technological products on structures has not been fully explained. The damage that different types of UAVs can cause to structures and whether they can lead to structural collapse remains a subject of curiosity.

Many UAVs today are capable of carrying munitions and are actively used in wars for intelligence, surveillance, reconnaissance, assault, and special operations. Table 2 provides information on some UAVs in the inventory of the Ukrainian army and their missions during operations on Russian territory.

Table 2. Some UAVs in the inventory of the Ukrainian Army (Ukrspecexpor, 2024)

Name	Role	Country
Bayraktar TB2	Intelligence, Surveillance, Reconnaissance (ISR), Attack (Karar, 2023)	Türkiye
Leleka-100	ISR (Savunmasanayist, 2021a)	Ukraine
Punisher	ISR and operations (Crumley, 2022)	Ukraine
Spectator-M1	Surveillance and reconnaissance (Interfax, 2019)	Ukraine
PD-2	ISR, Attack (Savunmasanayist, 2021b)	Türkiye

From the table above, it can be assessed that the Leleka-100, Punisher, RQ-20 Puma, and Spectator-M1 UAVs, which are solely for ISR missions, are not capable of causing damage to structures. In contrast, the Bayraktar TB2 and PD-2 UAVs, which have attack roles, are capable of causing damage to structures. These UAVs, which carry munitions, sometimes target buildings and other elements. The Leleka-100, Punisher, and Spectator-M1 are manufactured by Ukraine, the RQ-20 Puma by the USA, and the Bayraktar TB-2 and PD-2 by Türkiye. The Bayraktar TB-2 is shown in Figure 4, and the PD-2 UAVs are shown in Figure 5.



Figure 4. Bayraktar TB-2 (Baykartech, 2024).



Figure 5. PD-2 (Ball, 2024).

The type and amount of munitions they carry are directly proportional to the damage they can inflict on structures. It is generally considered that these UAVs aim to target more practical and hard-to-reach areas rather than to demolish a building. In the following sections, the effects of the attacks carried out by the Ukrainian army using UAVs over Russia's Belgorod Oblast on structures are examined. Detailed information about traditional bombardment vehicles, rocket launchers, mortars, shrapnel, or MLRS used by the Ukrainian army is deemed unnecessary. These types of attack vehicles have been used worldwide for years and currently have no different designs or features. Particularly military unmanned aerial vehicles can damage structures due to the munitions they carry. Yiğit et al. (2018) stated that strategic and tactical UAVs are used for bombing, damage infliction, and assessment missions, while Erdil (2021) noted that UAVs are equipped with munitions and perform similar tasks to air force aircraft in many countries

2.4. Classification of structural damages

This study evaluates structural damages under six categories: no damage, minor damage, moderate damage, severe damage, total collapse and progressive collapse (Figure 6).



Figure 6. Classification of structural damages.

No damage: It is the condition where no structural or non-structural damage occurs in the building. In this case, the building maintains its full functionality without any compromise in safety or performance. Both the primary structural elements and secondary systems remain unaffected by external forces.

Minor damage includes superficial damages that do not affect the structure's overall integrity. It encompasses superficial damages such as small cracks, peeling plaster, flaking paint, removal of a facade or cladding material, and broken windows. The crack width should be less than 0.5 mm. It does not affect the load-bearing system of the structure and generally does not require repair or can be addressed with simple repairs. Minor cracks in interior and exterior walls, deterioration of roof covering materials, or small damages to floor coverings are also considered in this scope.

Moderate damage refers to noticeable damages in some parts of the structure that partially affect its usability. Examples include large cracks in the walls (limit 0.5 mm < w < 3.0 mm), cracks in columns or beams, jamming of doors and windows, and deformations in some parts of the structure. It can partially damage the load-bearing system, requiring repair, but does not cause the structure to completely collapse. Large cracks, issues with door and window closures, cracks in concrete elements, holes in the roof, and deteriorations in the ridge and rafters of the roof are evaluated within this category.

Severe damage involves significant damage to the load-bearing system of the structure, greatly endangering the safety and usability of the structure. Examples include serious cracks or breaks in columns and beams, large collapses in the walls, and complete collapse of some parts of the structure. The load-bearing system is severely damaged, potentially rendering the structure unusable. It requires either irreparable or very costly repairs. Breaking of columns, collapse of beams, falling of walls, and total collapse of some parts of the structure are included. These damage types are crucial criteria for evaluating structures after unexpected loads. Appropriate repair and strengthening works should be carried out for each type of damage.

Progressive collapse is a structural chain reaction in which damage that starts in any part of the structure spreads over time to other sections, causing a partial or total collapse of the structure. This type of collapse is triggered when initially small, localized damage (caused by various factors such as abnormal loads, terrorist attacks, construction errors, etc.) spreads to other parts of the structure. Typically, the building does not collapse suddenly but loses its stability over a period of time, eventually collapsing. The differences in this collapse process distinguish progressive collapse from total collapse. Figure 7 shows an image from SAP2000, where Kilicer (2024) determines the progressive collapse resistance of a reinforced concrete structure after the loss of a column. As can be seen, plastic hinges form in the beams, and the structure may start to collapse from a specific area due to the loss of load-bearing capacity in one or more elements. In this study, the difference between total collapse and progressive collapse were identified by the fact that the structure does not collapse all at once but experiences a chain reaction mechanism triggered by the loss of elements.

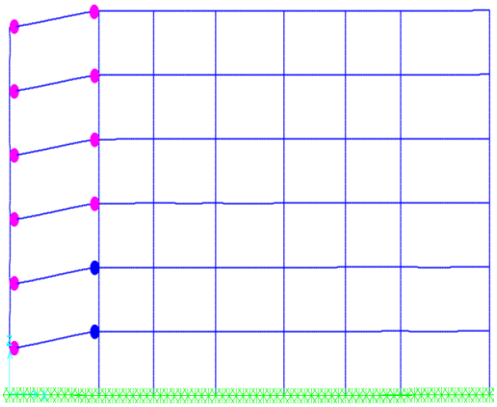


Figure 7. A view of a progressive collapse analysis in the SAP2000 program (Kilicer, 2024).

Total collapse is a failure in buildings where the entire structure or a significant portion suddenly and completely collapses. It typically occurs due to severe weaknesses in the load-bearing elements, sudden overloading, material fatigue, or external factors such as earthquakes, explosions, or high winds (Figure 8). The difference from progressive collapse is that total collapse happens suddenly, rendering a large portion of the structure unusable at once, whereas progressive collapse starts in one section of the structure and spreads to other areas over time. Total collapse events occur when the supporting and load-bearing components fail to perform their functions, leading to the structure becoming entirely unusable. Such a collapse can result in both significant financial loss and serious casualties.



(a) (b)

Figure 8. A view of a total collapse a) before collapse b) Total collapse (Kim et al., 2019).

3. Results

The research and investigations conducted in the Belgorod Oblast of Russia include a comprehensive weekly and regional examination of the damage structures sustained during the war, with a specific focus on progressive collapse. In these investigations, the destructive effects of different types of firearms and ammunition on residential, commercial, and historical buildings have been analyzed in detail, taking into account the data officially presented by the Governor of Belgorod Region, Mr Vyacheslav Vladimirovich Gladkov, and the Belgorod Region Operational Headquarters. During the data collection phase of the research, photographs of damaged structures, damage assessment reports, and other supplementary information obtained weekly have been systematically gathered. This data has been sourced from the Belgorod Regional Government and official accounts, as well as the Russian Ministry of Emergency Situations**.**

A comprehensive review of the existing literature on progressive collapse and war damage has been conducted and supported by data obtained from Russia. The analysis methods are based on classifying the various levels of damage to structures, ranging from superficial damage to progressive collapse. This classification covers a wide spectrum, from minor cracks to the complete collapse of buildings. Additionally, the cause-and-effect relationship between types of firearms, ammunition, and structural damage has been thoroughly evaluated. The primary aim is to determine how much of the damage caused to structures within a specific timeframe during the war can lead to progressive collapse or identify which type of attack triggers the chain-collapse mechanism.

In some cases, attacks occur near structures without causing any damage. Many such attacks have been recorded. Explosions around infrastructure facilities, auxiliary buildings (barns, outbuildings), wildfires, various equipment, motor vehicles, and military vehicles have been disregarded unless they caused damage to structures. Two images of such incidents are provided in Figure 9.



Figure 9. An example of attacks that did not cause structural damage (Governor of Belgorod, 2024).

In light of the information provided above, Table 3 has been prepared considering the attacks by Ukrainian armed forces on Russia's Belgorod Oblast between May 6, 2024, and June 16, 2024. Only cases of window breakage have been excluded; all other attacks that have been officially recorded are considered under the headings No Damage, Minor Damage, Moderate Damage, Severe Damage, Total Collapse, and Progressive Collapse**.**

Table 3. Types and distribution of structural damage sustained

Date	No Damage	Minor Damage	Moderate Damage	Severe Damage	Total Collapse	Progressive Collapse
06.05/12.05		16	10			1
13.05/19.05		19	13	4	3	
20.05/26.05		17	10	6	1	
27.05/02.06	1	23	6	2	1	
03.06/09.06		18	6	2		
10.06/16.06	1	7	1	1		1

The table shows the types of damage sustained by structures and their numerical distribution according to damage levels as a result of attacks in the Belgorod region during specific dates. Between May 6 and May 12, a significant number of superficial and moderate damage cases were observed, with one case of progressive collapse. During the period from May 13 to May 19, in addition to superficial and moderate damage, the presence of severe damage and total collapse incidents is noteworthy. In the week of May 20 to May 26, there are high amounts of superficial and moderate damage, along with severe damage and total collapse cases. The week of May 27 to June 2 saw the highest number of superficial damage cases. In the week of June 3 to June 9, the severe damage cases relatively decreased, while superficial and moderate damages continued. In the week of June 10 to June 16, there was a general decrease in the types of damage, but still, one case of progressive collapse was recorded. It is thought that the increase in attacks at the end of May and the beginning of June is due to improved weather conditions. Overall, the data shows that structures in the Belgorod region have sustained various levels of damage as a result of the attacks. Progressive collapse cases have been recorded on specific dates, indicating serious structural failures. According to the given data, the percentage of progressive collapse cases in total damage incidents is approximately 1.18%, while total collapse cases account for about 2.92 %. These percentages show that progressive collapse is rare among all damages, whereas total collapse represents a more serious condition. This situation highlights the severity of risks faced by structures in the region during the war and the need to enhance their resilience.

Structures in the Belgorod region suffer various damages during the war. The intensity of attacks and the targeted areas affect the degree of damage to the structures. Examples of superficial damage, the lowest degree of damage, which can sometimes be repaired with low budgets or may not require any repair at all, are shown in Figure 10.



Figure 10. Examples of Minor Damage: a) exterior wall damage, b) roof puncture, c) facade damage, d) roof damage, e) porch damage, and f) facade damage (Governor of Belgorod, 2024).

The images show superficial damages such as small damages and deformations on the exterior walls of residential buildings, punctures and deteriorations on roofs, window damages, facade cladding damages, peeling paint, and falling plaster. Additionally, cladding damage on commercial buildings, cracks, and peeling on the exterior walls of apartment buildings are noticeable. These superficial

damages are cosmetic in nature, do not affect structural integrity, and usually require simple repairs. These damages, caused directly by the war, can negatively impact the usability limits of the structures.

Previously, it was explained that moderate damage refers to a situation where a structure or object has suffered a certain degree of damage but has not become completely unusable. This type of damage is typically characterized by the preservation of structural integrity to a large extent but with significant damage to some non-load-bearing walls, roofs, or other components. The structure or object may partially lose its function; for example, some rooms in a building may become unusable while other parts remain functional. Visible cracks, fractures, or deformations may be present, but severe situations like the collapse of the structure are not in question. Moderate damage, although requiring significant repairs, can be restored to a usable condition through these repairs.

Structures in the Belgorod region do not always sustain the same level of damage during the war. The intensity of the attacks and the targeted areas affect the degree of damage to the structures. Moderate damage represents the middle level of damage, with noticeable damages in some parts of the structure, partially affecting its usability. Examples of Moderate Damage are shown in Figure 11.



(a) (b)

Figure 11. Examples of Moderate Damage are a) Collapse of non-load-bearing wall and roof damage and b) Damage to facade, windows, and doors along with porch and mechanical systems damage (Governor of Belgorod, 2024).

The figure shows two buildings from the Belgorod region in Russia, both moderately damaged due to the attacks. The image on the left (a) depicts a house that has sustained significant structural damage. Part of the roof has collapsed, and there are visible cracks in the walls caused by external forces or a catastrophic event. The image on the right (b) shows a commercial building with a damaged ground floor. The storefront is severely damaged, with debris scattered around. This damage likely resulted from an explosion or a similar impact.

Structures in the Belgorod region sometimes sustained severe damage during the war. One of the most adverse levels of damage is severe damage, where some parts of the structure have damage to the load-bearing system and the building is rendered unusable without repairs. Examples of Severe Damage are shown in Figure 12.



(a) (b)

Figure 12. Examples of Severe Damage are a) Severe exterior damage to the structure and b) Severe interior damage to the structure (Governor of Belgorod, 2024).

Figure 12 shows examples of two different structures that have sustained severe damage. The heavily damaged buildings are presented as a result of the attacks in the Belgorod oblast. The image on the left (a) depicts a building that has suffered significant structural damage, with most of the roof completely collapsed and the walls of the building largely destroyed; such damage renders the structure unusable and requires extensive repairs. The image on the right (b) shows severe interior damage, with the ceiling and walls of the room largely collapsed and the interior completely ruined; windows and other structural elements are significantly damaged. Such damage typically renders the structure completely unusable and requires extensive repairs or rebuilding.

Another type of structural damage is the concept of progressive collapse, which differs from total collapse and initial damage. Progressive collapse starts with the loss of a column and can lead to the collapse of a portion of the structure or even the entire structure. Examples of progressive collapse encountered during incidents investigated in the Belgorod region of Russia over specific dates are shown in Figure 13.



Figure 13. Examples of Progressive Collapse (Governor of Belgorod, 2024).

Figure 13 shows examples of progressive collapse in buildings located in the Belgorod region of Russia. The top two photos and the bottom two photos depict the same structure. Such collapses can occur due to structural failures and may be exacerbated by external factors or internal weaknesses. These incidents highlight the importance of engineering and regular maintenance. The visible damage and smoke indicate significant structural weaknesses and emergency response efforts. The initial damage during the dates examined was caused by bombardment and MLRS (Multiple Launch Rocket System). Damage to one or several load-bearing elements disrupts the balance of the structural system, resulting in the collapse of a portion. This type of collapse, compared to other structural failures, is characterized by casualties, injuries, and socio-cultural and political consequences.

While the types of damage can vary, they are caused by various firearms and modern equipment. Two such examples are FVP drones and Unmanned Aerial Vehicles (UAVs). Traditional means include bombardment, rocket launchers, mortars, multiple launch rocket systems (MLRS), and fragments of attack munitions shattered in the air by air defense systems (shrapnel). The frequency of these types of attacks occurring in the Belgorod oblast of Russia over a specific time period is provided in Table 4.

Table 4. Weekly distribution of attacks on structures during the war in the Belgorod region

Date	FVP	Bombardment	UAV	Rocket Launcher	Mortar	MLRS	Shrapnel Fragments	Unknown
06.05/12.05	1	8	2	6		1	7	2
13.05/19.05	8	4	3	7		1	13	4
20.05/26.05	10	5	3	4	1	1	7	3
27.05/02.06	13	6	7		2		5	
03.06/09.06	8	2	7				6	2
10.06/16.06	6	3	1			1		1

According to the data in the table, FVP drones are the most frequently used weapon type, accounting for 26.90% of attacks, with a total of 46 instances. Shrapnel fragments come in second at 22.22%, used 38 attacks. Rocket launchers were used 17 attacks, making up 9.94%, while bombardments were recorded 28 attacks, accounting for 16.37%. UAVs were used 23 attacks, constituting 13.45% of the attacks. Mortars were used three attacks, making up 1.75%, and multiple launch rocket systems (MLRS) were used four attacks, accounting for 2.35%. The "unknown" category was recorded 12 attacks, making up 7.02%. These data indicate that FVP drones and shrapnel fragments are particularly prominent in the conflicts.

On a weekly basis, FVP drones and shrapnel fragments have been the most frequently used weapons. During the period from 06.05 to 12.05, bombardments and shrapnel fragments were heavily used, while from 13.05 to 19.05, the use of FVP drones and rocket launchers increased. In the period from 20.05 to 26.05, FVP drones were the most used weapon. From 27.05 to 02.06, the use of FVP drones and rocket launchers peaked. From 03.06 to 09.06, there was an increase in the use of UAVs and rocket launchers, while other categories saw a decrease. In the period from 10.06 to 16.06, there was a general decrease in all categories.

FVP drones are reflected in the statistics as one of the most frequently used types of attacks. Although their direct damage capability to structures is limited, they can significantly increase damage by causing fires in the areas where they crash and explode. Figure 14 shows the increase in damage and fire on the roof of a commercial building in the Belgorod region as a result of an FVP drone attack.



Figure 14. Damage to the structure caused by FVP (Governor of Belgorod, 2024).

Such attacks are frequently encountered in modern warfare; however, there are no recorded instances of FPV drones causing progressive collapse in structures. While they can cause significant damage, this can only happen indirectly. Drones cannot cause severe damage to structures built with non-combustible roof and facade materials. This type of attack can only be useful in specific and sensitive locations and does not have an impact strong enough to initiate a progressive collapse mechanism in buildings. Another type of modern attack is the use of UAVs. Although various UAVs are manufactured, Table 5 provides details on the types of UAVs used, their missions, and whether they can cause progressive collapse in the attacks conducted in the Belgorod region.

Table 5. UAV missions and progressive collapse risk in Belgorod Region

Name	Mission	Progressive Collapse Risk
Bayraktar TB2	Intelligence, surveillance, reconnaissance (ISR), attack (Karar, 2023)	Yes
Leleka-100	ISR (Savunmasanayist, 2021a)	No
Punisher	ISR and precision operations (Wikipedia, 2024)	No
Spectator-M1	Surveillance and reconnaissance (Crumley, 2022)	No
PD-2	ISR, attack (Savunmasanayist, 2021b)	Yes

The table shows the missions and progressive collapse risk of unmanned aerial vehicles (UAVs) used in the Belgorod region. The Turkish-made Bayraktar TB2 and PD-2 models undertake intelligence, surveillance, reconnaissance (ISR), and attack missions, and both carry a progressive collapse risk. The Leleka-100 is solely involved in ISR missions and does not carry this risk. The Punisher is used for ISR

and precision operations, while the Spectator-M1 is only used for surveillance and reconnaissance; neither model has a migration risk. This information is important for assessing the operational capacities and potential structural impacts of UAVs. An example of the damage UAVs have caused to structures in the Belgorod region is shown in Figure 15.



Figure 15. Example of damage caused by UAV to structures (Governor of Belgorod, 2024).

Figure 15 shows an example of damage caused by unmanned aerial vehicles (UAVs) to a structure. The impact of UAVs has resulted in noticeable damage to the structure. Such attacks can create structural weaknesses and collapse risks in the upper parts of the structure. Particularly, historical and architecturally valuable buildings become more vulnerable to such damage, increasing the need for repairs. The visual clearly demonstrates the potential destructive effects of military and strategic UAV uses on civilian structures. Additionally, the destructive impact of UAVs can vary depending on the type of attack and the amount of ammunition carried. UAVs generally have more destructive effects than compared to drones; however, in terms of progressive collapse, they currently have limited capability to initiate a chain collapse mechanism like drones. On the other hand, shrapnel fragments, which may not be a direct attack type but an indirect effect of an attack, have been observed to cause unexpected damage to structures. Figure 16 shows the damage caused to a structure by elements neutralized by air defense systems.



Figure 16. Example of the effects caused by attack elements neutralized by the air defense system (Governor of Belgorod, 2024).

Air defense systems are critical military elements designed to detect and intercept enemy aircraft or missiles. These systems play a vital role in protecting strategic facilities and defending civilian settlements. However, as shown in Figure 16, the debris from neutralized elements can fall onto structures, sometimes destroying parts of residential buildings. This is a rare occurrence even with drones and UAVs. The damage to a structure, despite the prevention of an air attack, indicates that some physical impacts are inevitable. Additionally, the intervention of emergency teams and the containment

of damage are crucial in such situations. These incidents highlight the capacity of air defense systems to protect civilian areas. They also lead to confusion between the concepts of regional collapses and complete collapses through progressive collapse in structures.

In previous sections, the damage caused by different types of attacks was discussed. The study examined these types of damage and evaluated the impacts of various forms of attacks. Table 6 below details the distribution of damage according to these attack types, providing a comparative view of the damage levels caused by factors such as bombardment, drone attacks, and shrapnel.

Table 6. Damage distribution according to different types of attacks

	No Damage	Roof Damage	Facade Damage	Fire	Total Collapse	Progressive Collapse
Bombardment		17	15	5	3	1
FVP Drone	1	24	19	6		
UAV	1	14	11	3		
Rocket Launcher		12	9	2	1	
Mortar		1	2			
MLRS		3	4			1
Shrapnel		30	20	4	2	
Unknown Attack	1	7	8	1		

Table 6 summarizes the types of damage caused by various attack methods. Different types of damage such as no damage, roof damage, facade damage, fire, total collapse, and progressive collapse are listed according to bombardment, FPV drone, UAV, rocket launcher, mortar, multiple launch rocket system (MLRS), shrapnel, and unknown attack types. For instance, bombardment resulted in roof damage 7.45% of the time (17 instances), while causing facade damage 6.58% of the time (15 instances). FPV drones caused roof damage 10.53% of the time (24 instances) and facade damage 8.33% of the time (19 instances). UAVs caused facade damage 4.82% of the time (11 instances), whereas rocket launchers left roof damage 5.26% of the time (12 instances). Mortars caused facade damage 0.89% of the time (2 instances). MLRS caused roof damage 1.32% of the time (3 instances) and facade damage 1.75% of the time (4 instances). Shrapnel left roof damage 13.16% of the time (30 instances) and caused facade damage 38.77% of the time (20 instances). Unknown attack types caused roof damage 3.07% of the time (7 instances), facade damage 3.51% of the time (8 instances), and progressive collapse was most commonly observed (1 instance) in both bombardment and multiple launch rocket systems. This indicates that structures subjected to these types of attacks experienced progressive collapse. The least frequent attack was by mortars, occurring only twice, causing facade damage. The most frequent attack was by FPV drones, causing roof damage 24 times and facade damage 19 times.

The analysis of different levels of damage caused by various types of attacks on structures examines the impacts of different attack forms. The varying levels of damage to structures based on these attack types are presented comparatively in Table 7. This table helps us understand the varying impacts of attacks of different intensities and the resistance levels of structures.

Table 7. Damage levels according to different types of attacks

	No Damage	Minor Damage	Moderate Damage	Severe Damage	Total Collapse	Progressive Collapse
Bombardment		13	5	2	3	1
FVP Drone	1	31	9	5		
UAV	1	14	6	2		
Rocket Launcher		3	9	3	1	
Mortar		2	1			
MLRS		1	1	1		1
Shrapnel		21	15	2	1	
Unknown Attack	1	9	2			

Table 7 details the damage levels caused by different types of attacks. FVP drone attacks result in 18.56% superficial damage overall, while shrapnel effects cause 8.98% moderate damage and 1.20%

severe damage. Bombardment is associated with severe impacts such as 1.80% complete destruction and 0.60% total collapse. MLRS systems can also lead to 0.60% moderate damage and complete destruction. Rocket launcher attacks have caused 5.40% moderate damage, 1.80% severe damage, and 0.60% complete destruction. The least frequent types of attacks are mortar and MLRS systems, each causing only a few instances of damage. The most frequent type of attack is by FVP drones, which cause 18.56% superficial damage, making them more impactful compared to other attack types. The least common type of damage is progressive collapse, occurring at a rate of 1.20%, while the most common type of damage is superficial damage at 56.29%. Progressive collapse indicates a reduction in the structure's durability and poses a risk of complete collapse over time. This situation is a threat to the long-term safety of the structures. Overall, the table shows the effects of different types of attacks on structures at various damage levels.

4. Discussion and Conclusion

This study conducted in the Belgorod Oblast of Russia provides a comprehensive assessment of the types of damage structures faced during the war and the concept of progressive collapse. The research shows that bombardment and MLRS attacks seriously threaten the structural integrity of buildings and can trigger progressive collapse. In this context, it is evident that measures to enhance structural resilience must be taken. The study reveals that the war has caused significant structural degradation and occasional progressive collapse in buildings. In particular, bombardment and FPV drones, although indirect, have a high potential for damage, posing a direct threat to structures. Buildings are at great risk from such attacks, highlighting the need to improve their resilience, particularly in roofs and facades. Additionally, different types of attacks (rocket launcher, mortar, MLRS) have varying impacts on the damage levels of buildings. The frequency and intensity of the attacks increase the risks faced by structures, underscoring the importance of structural resilience.

Supported by concrete data, this study offers crucial insights into the need to strengthen structural resilience. From May 6 to June 16, 2024, damage types in Belgorod Oblast were meticulously classified. Minor damage was observed in 16 to 31 structures, while moderate damage affected between 1 to 6 structures. Moreover, severe damage and total collapse were rare but recorded in 1 to 3 cases. Progressive collapse, while accounting for only 1.18% of total damage, presents a serious long-term risk to structural integrity. These findings highlight the significant risks buildings face during war and the critical, though infrequent, nature of progressive collapse as a structural failure. Abdelwahed (2019) provides a comprehensive review of studies on progressive collapse and, similar to this study, discusses methods to enhance buildings' resistance to progressive collapse. Studies such as Byfield et al. (2014) and Marjanishvili (2004) also discuss the significance of progressive collapse in civil engineering, while similarly addressing the weaknesses in structures, as highlighted in this study.

The study emphasizes the importance of enhancing the resistance of buildings to modern warfare technologies. Current building materials and design methods are inadequate to prevent progressive collapse. Therefore, developing new materials and construction techniques will play a critical role in improving building safety. Future research should focus particularly on this area. The effective intervention of emergency teams is crucial for protecting structures and preventing loss of life after a war. Enhancing the training and equipment of these teams will facilitate quick response and repair of buildings. Additionally, such interventions will boost the sense of security in the community.

Informing the community about threats to buildings during wartime, increasing awareness, and ensuring individuals are prepared is of great importance. This will not only enhance personal safety but also contribute to preventing structural damage. Structural reinforcement efforts should be prioritized. Buildings should be constructed to withstand bombardment and drone attacks more effectively. This includes encouraging the strengthening of existing buildings and the construction of new ones using new materials and technologies. Building designs should consider features that prevent progressive collapse and develop solutions to increase load-bearing capacity.

The integration of modern defense systems is critically important. Developing effective defense mechanisms against unmanned aerial vehicles and drones will play a significant role in minimizing structural damage. These systems should be enhanced to protect both civilian and military structures. Extensive research and development should be conducted. Scientific studies should be increased to better understand the effects of firearms and modern warfare technologies and to develop strategies to

minimize these effects. Such research can provide innovative solutions to minimize the risks structures face during war.

Collaborations should be encouraged at both local and international levels to enhance the protectability of buildings. Joint strategies should be developed to protect structures in war zones. These efforts are crucial for ensuring the safety of both the buildings and their occupants. In summary, this research outlines the impacts of war on structures and the measures needed to minimize these effects in detail. Structural reinforcement, integration of defense systems, and advanced research and development activities are critical to improving building safety. Future studies should follow these recommendations and develop innovative solutions to enhance the durability of structures under war conditions. These steps provide a strategic approach to minimizing the risks buildings face during war. While military structures require more protection measures, similar resilience standards must be established for civilian structures. This is essential for the protection of both the buildings and the people within them

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Research Article

A Research on the Proportion, Balance, and Modulation Relationship of the Caravanserais Built Under the Patronage of Kayqubad I †

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Abstract: This study aims to examine the caravanserais (khans) built during the patronage of Kayqubad I in terms of proportion, balance, and modulation. These structures reflect the architectural understanding and technical skills of that period in both aesthetic and functional terms. The study addresses the importance of the culture of patronage within the social structure by examining the period of a ruler rather than focusing on a specific region or city. Caravanserais, particularly those from the Anatolian Seljuks, are discussed in detail concerning their structural properties, plan typologies, facade features, supporting structures, materials used, and decorations. The research also explores the role of proportion, balance, and modulation across different cultures and their interactions with Anatolian Seljuk architecture. Additionally, the presence of these concepts within Anatolian Seljuk architecture is questioned. Observational methods adopted from Orhan Cezmi Tuncer's analysis and measurements of the Sivas Gök Medrese serve as the basis for this study. Specific khans built during the era of Kayqubad I, such as Aksaray Sultan Hanı, Tuzhisarı Sultan Hanı and Alara Han, are examined. These structures have been analyzed with regard to proportion, balance, and modulation in their plans, facades, and crown gates. The structural properties of the khans have been investigated using drawings, photographs, and digital tools. To this end, this study provides a comprehensive architectural analysis of Anatolian Seljuk period caravanserais, examining their aesthetic and structural features through the concepts of proportion, balance, and modulation.

Keywords: Anatolian Seljuk, Balance, Caravanserais, Modulation, Proportion

I. Alaeddin Keykubat'ın Baniliğinde Yapılan Hanların Orantı, Denge ve Modülasyon İlişkisi Üzerine Bir İnceleme

Öz: Bu çalışmada, I. Alaeddin Keykubat döneminde yapılan kervansarayların (hanların) orantı, denge ve modülasyon açısından incelenmesi amaçlanmıştır. Bu yapılar, estetik ve işlevsel anlamda o dönemin mimari anlayışını ve teknik becerilerini yansıtmaktadır. Çalışma, bölge veya şehir yerine bir hükümdar dönemini ele alarak, banilik kültürünün sosyal yapı içindeki önemine değinmiştir. Kervansarayların, Anadolu Selçuklu kervansaraylarının yapısal özellikleriyle, plan tipolojileri, cephe özellikleri, taşıyıcı yapılar, malzeme kullanımı ve süslemeler gibi başlıklar altında detaylı bir şekilde ele alınmıştır. Araştırma, orantı, denge ve modülasyonun farklı kültürlerdeki yerini ve Anadolu Selçuklu mimarisiyle olan etkileşimini incelemiştir. Ayrıca, Anadolu Selçuklu mimarisinde bu kavramların varlığı da sorgulanmıştır. Gözlem yöntemi olarak Orhan Cezmi Tuncer'in Sivas Gök Medrese örneğinde yaptığı analiz ve ölçümler esas alınmıştır. I. Alaeddin Keykubat döneminde yapılan özel hanlar arasında Aksaray Sultan Hanı, Tuzhisarı Sultan Hanı ve Alara Han incelenmiştir. Bu yapıların plan, cephe ve taçkapısında orantı, denge ve modülasyon incelemesi yapılmıştır. Hanların yapısal özellikleri, çizimler, fotoğraflar

† This study is derived from the master's thesis titled "I. Alaeddin Keykubat'ın Baniliğinde Yapılan Hanların Orantı, Denge ve Modülasyon İlişkisi Üzerine Bir İnceleme" written by Melek Ersoy under the supervision of Tuğba Erdil Dinçel at Haliç University in 2021.

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ve dijital araçlar kullanılarak incelenmiştir. Özet olarak, bu çalışma, Anadolu Selçuklu dönemi kervansaraylarının mimari analizini, orantı, denge ve modülasyon kavramları üzerinden ele alarak, bu yapıların estetik ve yapısal özelliklerini kapsamlı bir şekilde değerlendirmiştir.

Anahtar Kelimeler: Anadolu Selçuklu, Denge, Kervansaray, Modülasyon, Orantı

1. Introduction

Throughout history, Anatolia has hosted many civilizations and has been a crossroads for various cultural interactions due to its strategic location. The Seljuk period, in particular, was a time when Anatolian architecture and urban development were significantly shaped. The reign of Kayqubad I stands out as a particularly productive period in terms of architecture and urban planning among the Anatolian Seljuks. The caravanserais built during this period played an important role not only as safe havens on trade routes but also as centers of social and cultural activities. Many of the Seljuk khans were constructed under the patronage of Kayqubad I, and these structures are among the most impressive examples of Seljuk architecture that have survived to the present day. This research aims to provide a detailed analysis of the architectural features of these khans, as well as the geometric and aesthetic principles of proportion, balance, and modulation. These structures reflect the architectural understanding and technical skills of that period in both aesthetic and functional terms. The study of Seljuk caravanserais reveals how these structures were planned, their aesthetic and functional characteristics, and their impact on social and economic life. Additionally, the research will examine the relationship between the architectural analysis of the khans and the overall economic and sociological structure of the Seljuk period. The study will scrutinize the place of the concepts of proportion, balance, and modulation in Seljuk architecture and their interactions with various cultures. In this context, this study aims to offer new perspectives on understanding and evaluating Seljuk architecture. Furthermore, information on the current preservation status and restoration works of these khans will be provided to raise awareness for the protection of cultural heritage. This introduction sets the general framework and outline of the thesis, and the following sections will present detailed architectural analyses of the Khans and their cultural interactions. These analyses will help us better understand the place and importance of these significant structures, built under the patronage of Kayqubad I, within Anatolian Seljuk architecture.

2. Material and Methods

This study aims to examine the caravanserais built during the reign of Kayqubad I of the Anatolian Seljuks in terms of proportion, balance, and modulation. The structures selected for analysis, such as Aksaray Sultan Han, Tuzhisarı Sultan Han, and Alara Han, are significant examples that reflect the aesthetic and functional characteristics of Seljuk architecture. These buildings were analyzed with a focus on their plan typologies, facade characteristics, and crown gates.

The research includes a literature review focusing on the socio-economic and architectural context of the Seljuk period. Key sources such as Kuban (1981), Tuncer (1981; 2015), and Turan & Kırpık (2016) provided the theoretical framework. Kuban (1981) examines Anatolian Seljuk architecture within a historical, sociocultural, and artistic context, highlighting the functional and symbolic aspects of Seljuk structures, with a focus on concepts like proportion and symmetry. Tuncer (1981; 2015)'s studies focus on the use of proportion and modulation in Anatolian Seljuk architecture, underscoring the importance of mathematical relationships and providing detailed analyses, such as his work on the Sivas Gök Medrese, to demonstrate the geometric schemes contributing to the aesthetic and structural unity of Seljuk architecture. Meanwhile, Turan & Kırpık (2016) emphasize the social and economic impact of architecture during the Seljuk period, discussing how caravanserais served as vital centers for trade, security, and cultural interactions. The literature review highlighted that these caravanserais were not only architectural monuments but also played an integral role in the social and economic structure of the period. As such, this study examined the caravanserais not only through the lens of architectural analysis but also in terms of their socio-economic significance. These structures functioned as social and commercial hubs, offering insights into the cultural and economic dynamics of the Seljuk period. Building on this theoretical foundation, the present study specifically investigates the

role of proportion, balance, and modulation in caravanserais constructed during the reign of Alaeddin Keykubat I, thus providing unique insights and filling specific gaps in the existing literature on Seljuk architecture.

Methodologically, this research is based on the analyses of Orhan Cezmi Tuncer, who has extensively studied proportion and modulation in Anatolian Seljuk architecture. Tuncer's work, particularly his geometric and proportional studies on the Sivas Gök Medrese, forms the foundation of this analysis. In this study, the selected caravanserais were analyzed using Tuncer's methods, with a particular emphasis on the repetition of modular units and their role in establishing aesthetic and structural harmony. Each structure's plan was divided into grid units, and these modules were used to evaluate the balance and symmetry within the overall composition.

Digital tools were employed to conduct detailed analyses of the proportion and modulation characteristics of these structures, allowing for a more precise understanding of their geometric properties. Due to the limitations on fieldwork imposed by the pandemic, digital modeling techniques were used to assess the facade layouts, plan features, and proportional systems of the caravanserais. For example, in the analysis of Aksaray Sultan Hanı, the 2/3 Seljuk ratio was identified as a key element of its aesthetic balance. Similar proportional and modular analyses were conducted for the other caravanserais, revealing that each structure adhered to its unique system of proportions.

Both quantitative and qualitative analyses were employed in this study. Quantitative analysis involved measuring and comparing the geometric dimensions of the structures, while qualitative analysis focused on the historical and cultural significance of their decorative elements, materials, and spatial organization. This combined approach allowed for a comprehensive understanding of the caravanserais as architectural works that not only demonstrated aesthetic coherence but also played a vital role in shaping the socio-economic landscape of their time.

2.1. Anatolian Seljuk architecture and the cross-cultural examination of proportion, balance, and modulation

A whole is made up of parts. The mathematical relationship between these parts is called proportion. Structures raise the question of how existing proportions have influenced architects. Throughout history, humanity has adopted certain ratios and gained experience using them. The Egyptians applied ratios such as the 3x4x5 triangle as well as ratios like 1/2, 5/8, and 4/3. The golden ratio was also used in Greek architecture. There is also a proportion in nature, and this creates balance (Tuncer, 1981). According to Plato, beauty lies in simple geometric shapes. He says that what creates the beauty of form is the mathematical order created by numbers and their ratios. This order creates harmony. In nature or art, what makes them beautiful is not their content but their forms. These shapes are simple circles and rectangles. Therefore, the real reason that creates all beauty is the numbers and the ratio between numbers (Kalaycı, 1994). Even the juxtaposition of opposite shapes can be perceived as beautiful with a good balance. A triangle and a vertical line, a semicircle, and a vertical line can be seen in the silhouette of our classical mosques. This represents the balance of a pyramid and a cylinder. It is seen that when these two geometric shapes are placed side by side with a good ratio in volume, they do not overpower each other but instead strengthen each other (Tuncer, 1981). Modulation is the repetition of a measure or a geometric shape determined as a unit (Tuncer, 2015). Modulation is related to proportion. The repetition of a unit by multiplying it creates the concept of modulation. It can be seen sometimes in details and sometimes in the entire section, plan, and view. According to Vitruvius, when designing a structure, a unit should be determined as a standard, and the exact proportions of the structure should be determined according to this unit. The dimensions and sizes that will form the symmetry should be adjusted in this way. Fixed measurements that will form symmetry should be decided. Changes can be made based on this basic measure. After determining the dimensions, proportions should be made to ensure that the appearance of the structure is proper (Vitruvius, 2019).

The points in the section The Role of Proportion, Balance, and Modulation in Anatolian Seljuk Architecture, it is observed that the architectural style diverges from classical Anatolian Seljuk architecture. In the section Interpretation of Universal Geometric Proportions, the concept of proportion in architecture is discussed as a universal principle and is related to various civilizations such as Egypt, Greece, and Rome were examined. However, in classical Anatolian Seljuk architecture, proportions are primarily based on local traditions and practical applications. While global geometric influences play a

secondary role in Seljuk structures, the primary focus is on achieving functionality and aesthetic balance (Erzen, 1976). In the Mathematical Basis of Modulation section, modulation is presented as a mathematical structure based on the repetition of measurement units, grounded in Vitruvius' understanding of classical architecture. However, in Seljuk architecture, modulation is used to achieve functional and aesthetic balance, and the proportions of structures are more shaped by local and practical needs (Goodwin, 1997). Finally in the section Relationship Between Nature and Architecture, it's seen that the natural proportions and balance in architecture are linked to the ideas of philosophers like Plato. However, in Seljuk architecture, the understanding of beauty is more closely associated with faith and functionality. In Seljuk structures, aesthetics are integrated with the functional and religious significance of the building, rather than being based purely on mathematical beauty (Scruton, 1979).

Since ancient Egypt, Byzantium, and Rome, the relationship of balance and proportion between the parts and the whole has been known (Lubicz, 1981). In these civilizations, the relationship of balance and proportion is defined mathematically. They created beautiful appearances with the golden ratio (Tuncer, 2010).

Since the first civilizations, proportions have been applied to plans, sections, and views to achieve balance. Architects have used compasses for this. Greek temples, peripteral and dipteral, and their derivatives are the peak of this development, starting from the megaron (Figure 1).

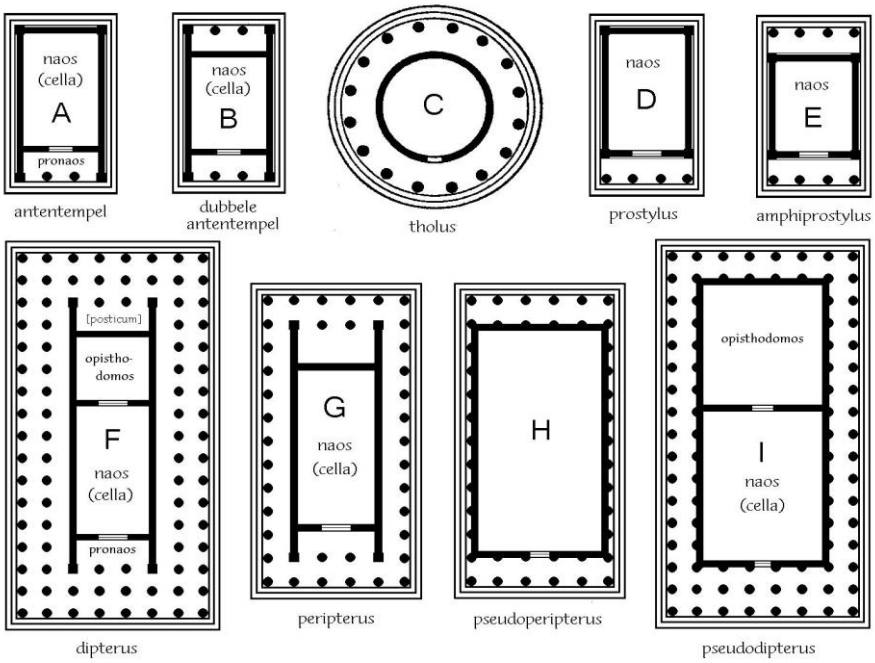


Figure 1. Balance from megaron to Greek temples (Vitruvius, 2019).

Balance and proportion are also seen in the Abu Simbel Temple in Egypt. As seen in the plan of the Abu Simbel Temple, a grid system was used. On the facade, proportion was achieved with two circles (Figure 2). The Poseidoma (Paestum) Temple also uses a grid plan. In the section, as seen, the fullness and void ratio of the interior volume is balanced using a circle (Figure 3).

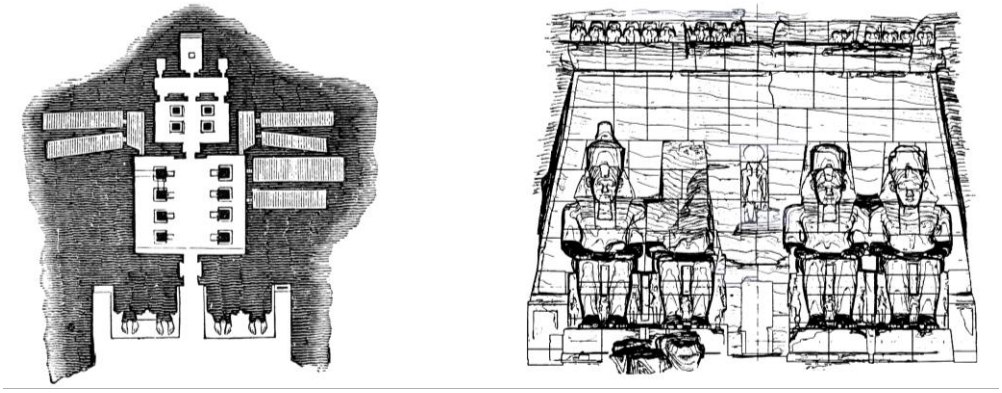


Figure 2. Plan and facade of the Abu Simbel Temple (Schliephacke, 1968).

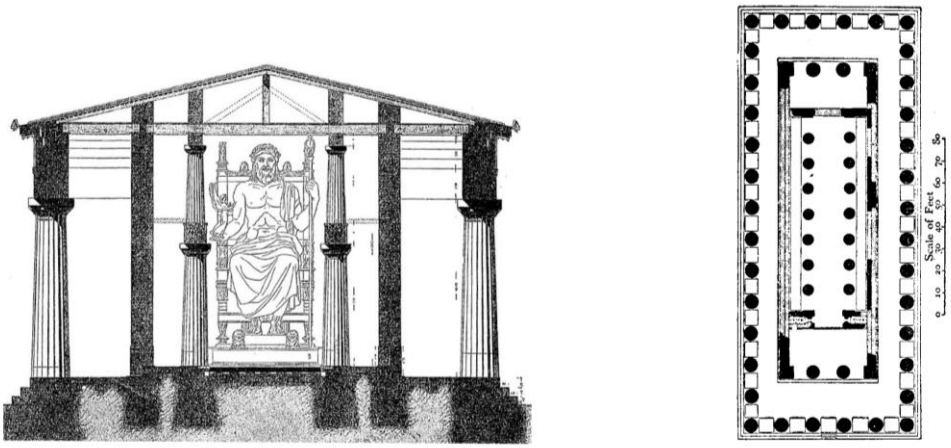


Figure 3. Section and plan of the Poseidoma (Paestum) Temple (Yalouris & Yalouris, 1995).

The proportion of the Khafre Pyramid in Egypt is approximately 2x6.5. In Etruscan temples, the height of the columns is five times the radius of the base. This column height reaches seven times inside the temple. The proportion found in classical Greek architectural works, the Doric, Ionic, and Corinthian orders, rises to 1/10-1/11 (Jones, 1989). The grid system created by arranging squares in the plan plane was solved by considering important factors that bind the structure, such as wall openings, wall thicknesses, and wall heights. Thus, a unit measure and scale were created, establishing the modulation system. Technically, the architectural drawing was achieved with a compass, making the drawing easy to read and simplifying the application.

Some examples of structures that can be given in this context include:

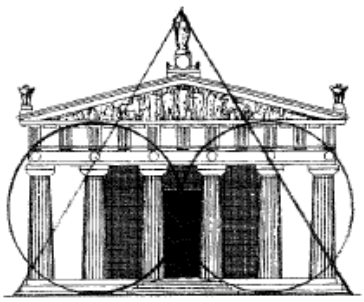


Figure 4. Temple of Zeus at Olympus (Coulton, 1974; Bommelaer, 1985).

The geometric design of the facade of the Temple of Zeus at Olympus is structured with two circles and an equilateral triangle, achieving balance through this method (Figure 4).

Ribat structures were small defensive buildings in the Islamic world that combined social, economic, and religious functions. Particularly prominent in Central Asia and the Transoxiana region, these structures served both as centers for religious education and as protection points along trade routes. Examples such as Ribat-I Melik hold a significant place in the architectural and functional evolution of these buildings (Yavuz, 1997; Ettinghausen et al., 2001; Kuban, 2010). This can be clearly observed in the architectural articulation and ornamental details of the portal of Ribat-ı Melik (Figure 5).

One notable ribat structure, known as "Ribat 1," is located in the Beykend settlement south of Bukhara, a region historically said to have housed more than 1,000 ribats (Figure 6). Situated along the Samarkand-Amul route on the Silk Road, Beykend is now within the borders of Navoiy, Turkmenistan. Studies on this ribat suggest that it might have been constructed in the 10th century or rebuilt on an existing structure in the 12th century (Mirzaakhmedov, 2016).



Figure 5. Ribat-ı Melik.



Figure 6. Beykent Ribat 1 plan (Mirzaakhmedov & Stark, 2013).

The ribat consists of a courtyard and enclosed spaces, with a nearly square courtyard surrounded by rooms of varying sizes. Measuring approximately 75 meters on each side, the structure features two entrances and cylindrical towers at its four corners. The eastern entrance protrudes outward, indicating its significance as the main gate, marked by its monumental iwan design. Rooms on the northern and southern sides of the courtyard follow a similar plan, and the central spaces, often used for accommodations, were likely utilized by travelers. On the western side, rooms identified as kitchens, ovens, and storage facilities were revealed through excavation, indicating their service-related functions (Arapoğlu, 2024).

Anatolian Seljuk caravanserais, which were a continuation of these ribats, were developed into larger and more complex structures. Seljuk architecture expanded the plan schemes of ribats and adapted them to regional conditions, giving caravanserais a distinctive identity (Hillenbrand, 1994; Yavuz, 1997; Ousterhout, 2019).

The Ismail Samani Mausoleum in Uzbekistan: Built in the 9th century, it consists of a cube. The plan features a square layout with a wall thickness of 3 units and a volume of 12 units, resulting in an 18x18 structure (Figure 7).



Figure 7. Plan, Section View, and Photograph of the Ismail Samani Mausoleum (Necipoglu, 1994).

The Gonbad-e Qabus in Iran dates back to 1006-1007. The height of the structure is three times the diameter of the base it sits on (Figure 8).

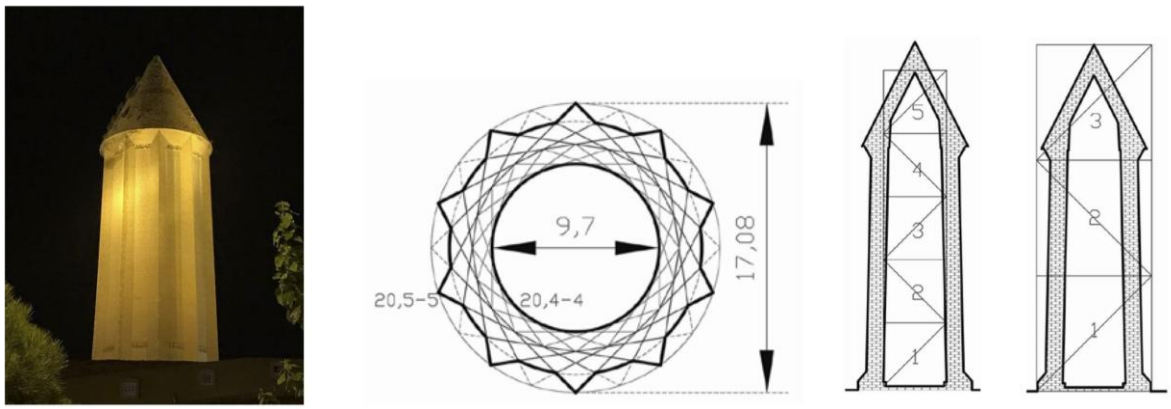


Figure 8. Gonbad-e Qabus (Necipoglu, 1994).

Many people evaluate architectural works based on their exterior appearance. A building is primarily explored from its front facade. The reason the golden ratio is primarily sought on the facade stems from this. The front facade is usually more meticulously designed and grander because it is perceived by more people (Şenyiğit, 2010).

When looking at it, architecture is a derivative of geometry. Proportion, balance, harmony, modulation, composition, and order are mathematical tools in this sense. The geometry obtained by using these tools creates a sense of beauty and art. In addition to these, the ability to draw and understand geometry is sought in architecture. Architecture is an applied art. In this sense, the geometry of architectural works generally has square and rectangular shapes. This was initially understood and applied in Egyptian civilization. The balanced rectangle, the use of the golden ratio, began in Ancient Greece (Tuncer, 2015). The Seljuks used the 2/3 ratio (Figure 9.A).

The Larisa Megaron, built in the 7th century BC and the first type of house, contains a 2a/3a ratio. This is the Seljuk ratio. In its wider types, the 4a/4a ratio was tried (Figure 9.B). The combination

of lines establishes a formal connection between two lengths. This is called proportion, and the mathematical relationship between them is called ratio. Architecture feeds on this connection by establishing a balance between the dimensions, areas, and volumes of lines. Therefore, it can be said that architecture is a proportionally weighted art. Balance, harmony, and beauty are products of this situation. The most commonly used shapes, the balanced rectangle and square, are the manifestations of this sense of harmony and balance. To reinforce intellectual aesthetics, one must have the skills of proportion and ratio. Architecture, an important visual branch, is dependent on harmonious colors, texture, and geometry. The closest ratio to the 60-degree triangle is the Golden Ratio. The Golden Ratio is 58 degrees 17 minutes. The Seljuk triangle has a 2/8 ratio. This corresponds to 56 degrees 19 minutes. Next is the 3x4x5 triangle used by the Egyptians. This corresponds to 53 degrees 7 minutes. It is seen that the Golden Ratio, which is a 60° angle, and the base angle of the 3x4x5 triangle, which is 53°07'48", are very close to each other. The difference between them is less than 2°. In this respect, it is proven that the Seljuk ratio has an international value (Figure 9.C). Unit measures are not only within the boundaries of the structure, but sometimes the plot width also determines this. The grid layout has been used throughout architectural history, and it is still used today in the application of reinforced concrete and steel frames (Tuncer, 2015).

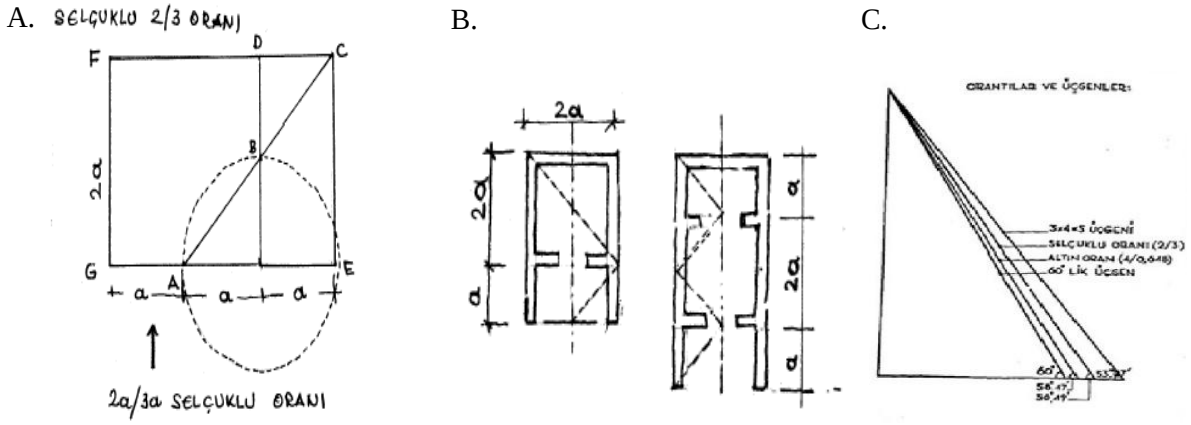


Figure 9. A. Seljuk ratio, B. Larise Larisa Megaron - Troy, C. Ratios and triangles (Tuncer, 2015).

2.2. A method for calculating proportion, modulation, and balance in a medrese facade

The elements of proportion, balance, and modulation in Anatolian Seljuk architecture are the cornerstones of architectural aesthetics and structural functionality. In buildings such as Sultan Han (Aksaray), Buruciye Medrese (Sivas), and Karatay Han (Konya), it is evident that the layout of the courtyard and main entrance is structured with specific proportions, and symmetry and modular design are reflected in both the facade and interior. For example, the spacious courtyard and main entrance area of Sultan Han create a balanced structure that is both functional and aesthetically pleasing (Tuncer, 1981). The geometric motifs used in the facade design of Buruciye Medrese are repeated at specific proportions, providing visual harmony to the structure (Yılmaz, 2017). Similarly, the modulation used in Karatay Han, with the building divided into layers through stone craftsmanship, enhances both the aesthetic appeal and structural integrity of the structure (Çakmak & Şahin, 2018). Additionally, in buildings such as the İnce Minareli Medrese, finely crafted details proportional to facade height are repeated in a modular arrangement, ensuring architectural symmetry and contributing to the slender and elevated visual appearance of the structure (Kuşçu, 2020). These examples underscore the importance of mathematical relationships and aesthetic harmony in Seljuk structures, shaping the architectural understanding of the period (Tuncer, 2015).

One of the most reliable methods in the literature in terms of ratio, balance, and modulation belongs to Orhan Cezmi Tuncer. Orhan Cezmi Tuncer conducted his study by taking on-site measurements. In addition to Tuncer's work, studies by Yılmaz (2017) on the golden ratio in Seljuk madrasas, Çakmak & Şahin (2018) on the use of Seljuk portals in contemporary facades, and Kuşçu (2020) on proportional and modular systems in the Buruciye Madrasa support the importance of

proportional analysis in understanding Seljuk architecture. These works emphasize the significance of mathematical relationships and aesthetic coherence in Seljuk structures, further validating Tuncer's approach. Since this research was conducted during the pandemic, the method was tried to be applied using literature data. Although its original name is Sahip Ata Medrese, it is known as Gök Medrese because of the color of its tiles (Figure 10). It was built in 1271 under the patronage of Vizier Sahip Ata. There are eight-pointed stars on the part that form the lower part of the minaret and frame the crown gate. The crown gate, which contains vegetal and geometric decorations, carries all the characteristics of an Anatolian Seljuk crown gate (Figure 11).



Figure 10. Sivas Gök Medrese crown gate (Anadolu Agency, Access date: March 15, 2024).



Figure 11. Sivas Gök Medrese crown gate (Anadolu Agency, Access date: March 15, 2024).

Apart from deviations of 2-3 cm, its dimensions of 8.00x12.00 m are in the ratio of 2/3, proving this (Figure 14). The bottom row of stones, which can be considered a substructure, does not have decoration. All calculated ratios are made in the order above this row. When each square formed is divided into four equal parts, 24 squares forming the classic crown gate appearance emerge (Figure 12.B).

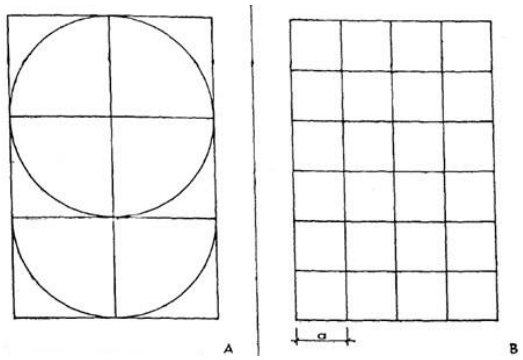


Figure 12. Crown gate proportion (Tuncer, 1981).

We shall designate the side length of the smallest unit square formed in the final arrangement as the "a-unit" measure. It will be observed that all surfaces are constituted through the iterative replication of this fundamental unit. The minaret cubes on the right and left of the crown gate, which provides the 2/3 ratio, are also a-unit tall. Thus, with the frame of the crown gate, it forms 36 units. This reveals a dimension of 12.34 m x 12.34 m (Figure 13.A).

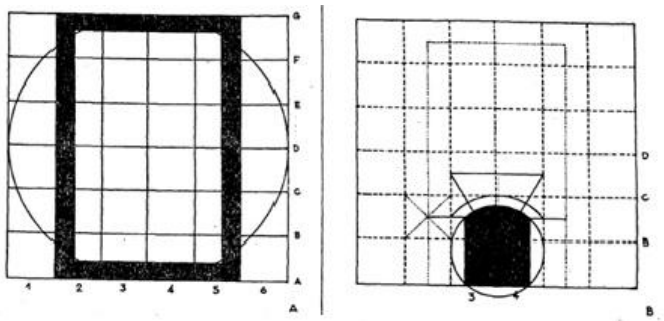


Figure 13. Crown gate proportion 2 (Tuncer, 1981).

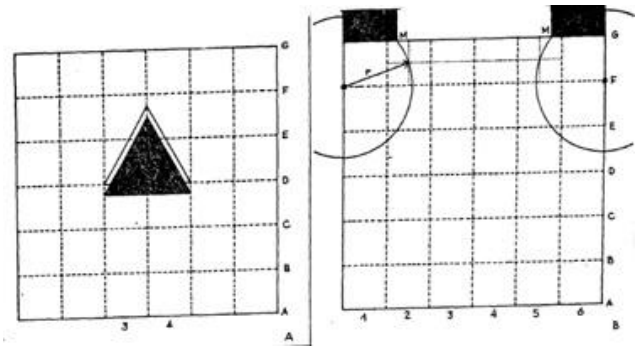


Figure 14. Crown gate proportion 3 (Tuncer, 1981).

When an equilateral triangle is drawn from the 3rd and 4th squares with the middle of the base at the OD, it is seen that the point in the axis corresponds to the center of the arch forming the door arch (Figure 14.B). Its radius is again the *a* unit. When a horizontal line is drawn from the BC middle, the abutment stone is determined, and the door jambs appear.

The equilateral triangle drawn from the 3rd and 4th squares horizontally to D, with its base in the D plane, gives the keystone of the arch surrounding the muqarnas. Shifting this triangle down by the measure of a/4 finds the endpoint of the muqarnas (Figure 12.A). Point M, which is the intersection of the circle with center F, drawn from the middle of squares 2 and 5 in the horizontal FG, is important. The distance MG is the diameter of the circle, and it is proven that this is found with geometric proportions (Figure 13.B). The thickness of the flattened arch in the crown gate is a/4.

The muqarnas begin within the door recess in the middle of the CD height. The steps that form them are within the boundaries of an equilateral triangle. The glazed bricks reflected on the front face of the minaret cube have a diameter and crenel height of a/2 in the circular decoration.

Considering the proportions of the additions made that day when the 6a-diameter circle that includes the crown gate is repeated, it remains high relative to the top of the parapet but too low for the honeycomb termination. According to the measurements at that time, the parapets are 5a above the start of the crenels (Figure 15). It is seen that the facade of the Medrese cannot be squared with the a-unit in the plan. The building is not squared. The qibla side is stepped. The courtyard and iwans do not conform to the known ratio. Tuncer thinks that the reason for this is that the street texture and plan of that day were only suitable for this (Figure 16). Modulation work is only found on the front facade.

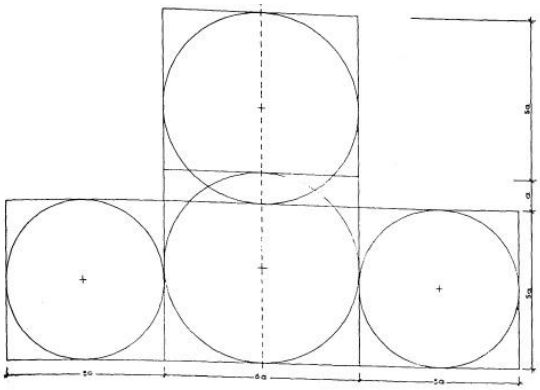


Figure 15. Proportion in the Facade (Tuncer, 1981).

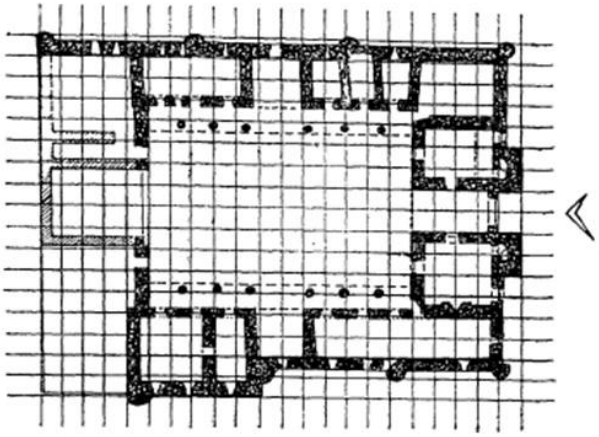


Figure 16. Plan (Tuncer, 1981).

As in antiquity and the Middle Ages, the design of this work is also content with a part, not the whole. There are two types of module work. The first is that a module is determined, and this module dominates the plan, section, and view (especially and usually the view). The second method is that the architectural units are modulated within themselves in appearance. This structure adheres to this. In details:

1/1 upper windows and fountain
1/2 classroom window
2/3 prayer room window
Side wings on the west facade at a ratio of 5a
Crown gate at a ratio of 6a

have been observed. A consistent geometric order and modulation are present on the front part but not found in the plan, section, and other facades (Tuncer, 1981).

There are also similar studies that support these measurements. However, it is observed that these studies also rely on the pioneering work of Tuncer (1981) in this field. The studies that support these measurements are shown in the table below (Table 1).

Table 1. Academic studies related to the subject

Authors	Study Subject
Yılmaz (2017)	Selçuklu Dönemi Medreselerinde Altın Oran-Estetik İlişkisi: Konya Örneği
Çakmak & Şahin (2018)	Selçuklu Portallerinin Günümüz Cephe Elemanı Olarak Kullanılması
Kuşçu (2020)	Sivas Buruciye Medresesi (1271) Ön Yüz Düzeninde Orantu ve Modüler Sistem Arayışı Üzerine Bir Deneme
Gençer (2024)	Anadolu Selçuklu Mimarisinde Birleşik İşlevli Yapılarda Kütle Biçimlenişinin ve Oranlarının Geometrik Analizi
Majewski (2024)	Understanding Geometric Pattern and its Geometry Part 11-Using Anatolian Seljuk Architecture as a Source of Inspiration for Students' Projects in Mathematics

3. Findings

3.1. Proportion, balance, and modulation relationship of the Khans built under the patronage of Kayqubad I

Patron refers to the founder or the person who commissions a structure. It is used for those who have buildings constructed. As in every era, architecture in the Anatolian Seljuk Period was also a demonstration of power and prestige for the ruling authority. The patrons considered the heirs of architecture, were among the sultans, viziers, beys, and commanders (Algan, 2008). The political career of Kayqubad I, one of the important sultans and patrons of the Anatolian Seljuks, progressed in parallel with the architectural works he had built (Yavaş, 2010). The patron Kayqubad I is the tenth ruler of the Anatolian Seljuk State. He is the greatest ruler of the Anatolian Seljuk State, reigning from 1220 to 1237 (Ersoy, 2021). He was particularly interested in architectural works, made plan corrections, directly intervened in the construction process, and determined the locations of buildings that had patron characteristics (Yavaş, 2010).

The Khand built under the patronage of Kayqubad I are as follows:

1. Aksaray Sultan Hanı
   Konya-Aksaray
2. Tuzhisarı Sultan Hanı
   Kayseri-Sivas
3. Alara Han
   Antalya-Alanya

3.2. Proportion, balance, and modulation analysis

Aksaray Sultan Hanı is one of the most monumental examples of Anatolian Seljuk khans. Located between Konya and Aksaray, the Khan is 94 km from Konya and 40 km from Aksaray. It is located in the town of Sultan Hanı, which bears the same name (Rice, 2015).

According to its two inscriptions, Kayqubad I is the Khan’s patron. The hall of the Khan was built in the month of Rajab of the year 626 Hijri. According to the Gregorian calendar, the hall was built in June 1229. The courtyard was completed at the end of 1229. The hall measures 32.50 meters by 55 meters. The courtyard measures 49 meters by 62 meters. Its entire area covers an area of 4475 square meters. The inscription on the courtyard gate indicates that its architect was Muhammad b. Havlan al-Dimashqi.

The crown gate exhibits the Seljuk ratio of 2/3. The door, horizontally divided into seven parts at the threshold level, is supported by two blind two-unit side piers. The arch marked by the radius between the pilasters indicates point A, the horizontal stone row at the upper level of the entrance arch. Drawing a 60-degree line from the pilaster forms an equilateral triangle, with the corner point B being the arch keystone. Starting from the center O, drawing an arc with a radius equal to the door width OD and extending this arc gives point E. Drawing an arc with radius DE and extending this arc gives point F, the end of the frame. The method of forming arcs by shifting the center dates back to Ancient Egypt (Figure 17).

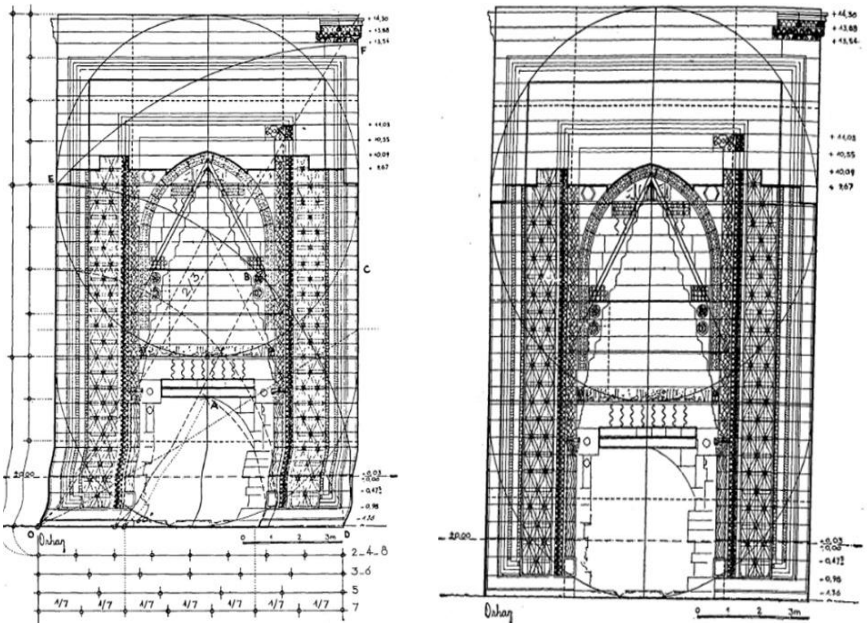


Figure 17. Left: Drawing of the Aksaray Sultan Hanı crown gate, Right: Drawing of the Aksaray Sultan Hanı crown gate 2 (Tuncer, 1982; Khalil & Vahid, 2018).

Since the upper part of the door was reached in a ruined state, the upper part was predicted using the horizontal axis by repeating the geometric and vegetal motifs in the lower parts. It was observed that the 2/3 proportion was achieved in the crown gate with the help of the right upper corner turning stone and muqarnas molding found in the excavation. Thus, the dimensions of the crown gate are determined by the repetition of two squares placed on the base, stacked three times. The line of the arch at the door frame intersects with the top of the first two square series arranged at the base. When the unit squares are divided into four, the equilateral triangle drawn from the middle of the third square from the bottom up marks the end of the muqarnas. A smaller equilateral triangle drawn from the third square marks the arch keystone. All this shows that geometric rules were also included in the design of the Seljuk crown gates (Figure 17).

When the Khan plan is divided into grid modules, the consistently repeating square units in the courtyard section are undefined in the closed section. This may indicate that these two parts were resolved separately. Nevertheless, there is a discernible rhythm when looking at the overall structure (Figure 18). Additionally, it is worth noting that the measurements determining the modulation in the plans of the khans are based on the fundamental proportions and functional requirements of the architectural design. As mentioned in the text, this modulation may not be consistent for every structure. Variations in modulation can result from factors such as the size of the space, functional needs, and sections added to the structure over time.

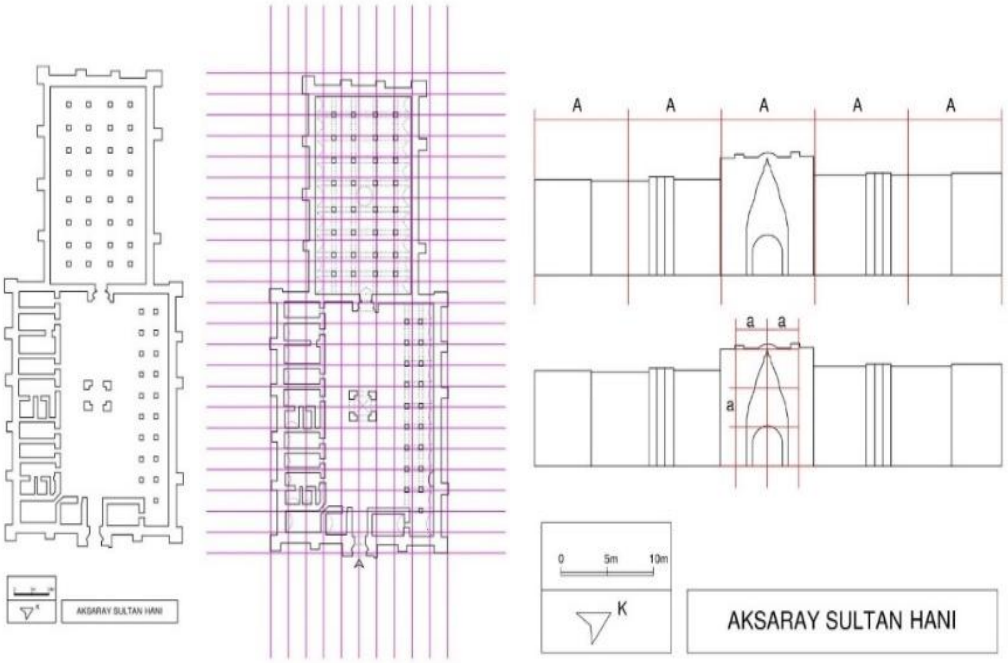


Figure 18. Left: Plan of the Aksaray Sultan Hanı, Right: Facade analysis drawing of the Aksaray Sultan Hanı (Ersoy, 2021).

In the plan and facade analysis of Aksaray Sultan Han, the proportions of the structure are based on specific modules. In the plan, the proportions used in the transition between the spacious courtyard area and the enclosed area support the functionality of the spaces, guiding the user. In the facade analysis, the arches symmetrically placed along the axis and the height of the entrance gate reveal a strong proportional balance, visually reinforcing the structure. These proportions present the building as a balanced whole, both functionally and aesthetically.

Aksaray Sultan Han covers an area of 4,900 square meters and stands out with its 13-meter-high entrance portal. The two-story kiosk mosque located at the center of the courtyard is proportionally positioned between the courtyard and enclosed spaces. Accessed by a double staircase, the mosque features arches adorned with geometric patterns, exemplifying Seljuk stone craftsmanship. This design offers both aesthetic balance and functionality, reflecting the unique proportioning principles of Seljuk architecture (Ertuğ, 1991; Stierlin & Stierlin, 1998; Acun, 2007).

There is balance in the facade. The width created by the crown gate frame and pilasters is one-fifth of the front facade. The end of the gate frame and the right side of the facade are repeated as two-unit repetitions. This does not create a symmetrical and balanced facade (Figure 18).

Looking at the crown gate, the Seljuk proportion of 2/3 is seen. Repeated as two *a* units at the base, it repeats as three *a* units in height (Figure 16). Considering all this, the facade of the structure has a consistent proportion and balance. Although the Khan plan shows consistent grid repetition within the closed and courtyard sections, it is not consistent as a whole. In this sense, it is partially a consistent structure in terms of modulation.

Tuzhisarı Sultan Han is located on the Sivas-Kayseri road, 30-32 kilometers south of the Shah-Rukh Bridge Inn. It is 48-50 kilometers from Kayseri. According to its difficult-to-read inscription, it was built by Kayqubad I between 1232 and 1236. The hall of the khan is 33x45m. The courtyard is 56x42.50m. It covers an area of 3900 square meters (Özergin, 1965).

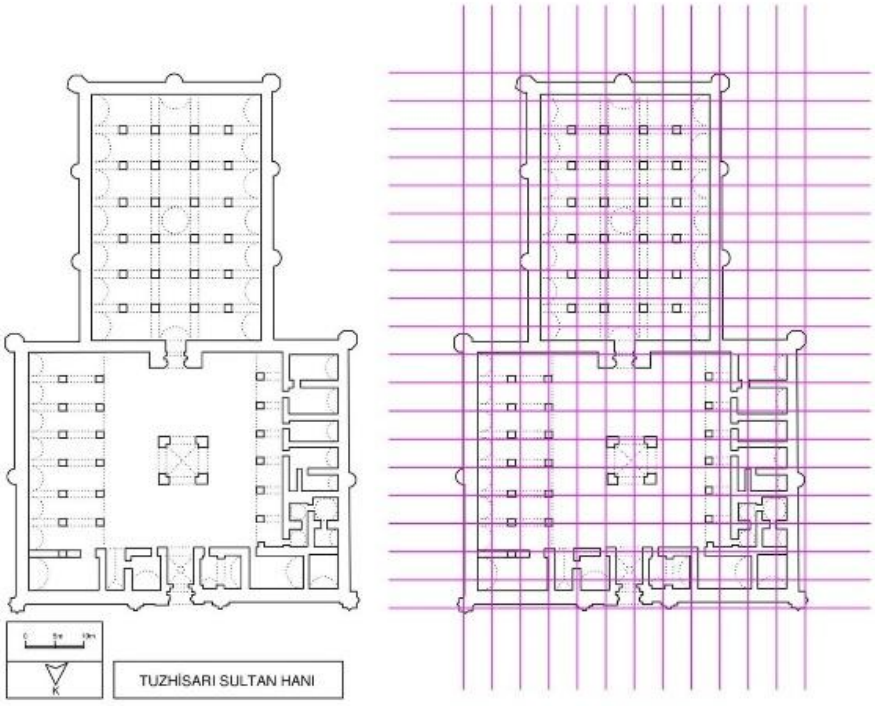


Figure 19. Left: A plan of the Tuzhisarı Sultan Han, Right: Grid system of the plan Tuzhisarı Sultan (Ersoy, 2021).

In the plan of Tuzhisarı Sultan Han, the structure is organized in a modular grid system, with all spaces arranged according to specific proportions. This grid layout provides a structural design that supports both the functional divisions and aesthetic harmony of the building. The modular system applied throughout the entire plan gives the structure a balanced visual appeal, stabilizing it both architecturally and structurally.

Tuzhisarı Sultan Han was built on an area of approximately 3,900 square meters and displays a square plan layout. The courtyard extends in a northwest-southeast direction, with rectangular rooms to the north and south covered by pointed barrel vaults. The modular grid system used in the plan organizes each space according to specific proportions; for instance, the courtyard measures 12 units horizontally and 9 units vertically, while the enclosed area measures 7 units horizontally and 11 units vertically. This proportional arrangement contributes to the building's balanced appearance and structural stability (Gabriel, 1931; Erdmann, 1961).

Additionally, the two-story square-plan kiosk mosque in the center of the courtyard is arranged with aesthetic proportions and supported by four columns. This mosque is adorned with arches featuring geometric motifs, reflecting the craftsmanship typical of Seljuk stonework (TDV İslam Ansiklopedisi). Tuzhisarı Sultan Han bears a resemblance to Aksaray Sultan Han in terms of its layout. It features a classic (hybrid) type plan with both a courtyard and an enclosed area. By examining structures designed with grid plans, as seen in Roman architecture, and referencing the work of Orhan Cezmi Tuncer, this study investigates whether a similar grid plan is present in the layout of Tuzhisarı Sultan Han (Figure 19).

The plan is divided into grids, with the courtyard area measuring twelve units horizontally and nine units vertically, while the enclosed area measures seven units horizontally and eleven units vertically. The main entrance (taçkapı) is not centrally aligned. However, the repeating grid divisions in the courtyard section are consistent in this part. The same unit system is consistently repeated in the enclosed section as well. The column partitions and the outer walls create a balanced composition, forming a total of 178 units in the structure. Overall, the plan appears to be balanced (Figure 19).

On the facade of the structure, there are small columns (sütunces) located to the right and left of the main entrance. The distance from the end of the sütunce on the right side to the end of the outer wall is measured as B units. When this B unit measurement is taken from the end of the sütunce on the left side to the extension of the left outer wall, it does not align with the end of the outer wall (Figure 20).

As shown in the upper diagram, the distance from the sütunce near the main entrance on the left side to the beginning of the buttress at the corner is termed as C units. When the same C unit is applied to the right side under the same conditions, the distance is observed to be less than C units (Figure 23).

Considering all these factors, it is evident that the main entrance is not centrally located on the facade, and the facade itself is not symmetrical or balanced.

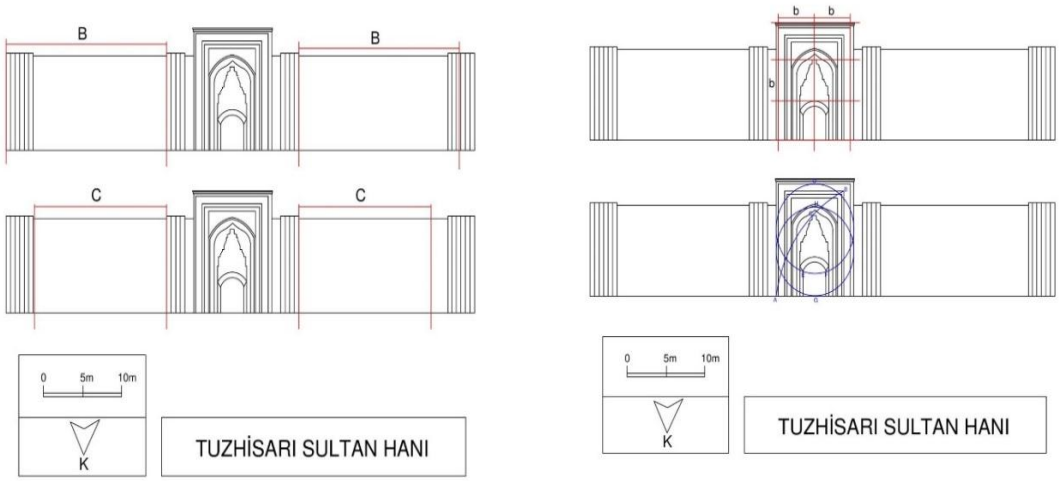


Figure 20. Facade analysis of the Tuzhisarı Sultan Han (Ersoy, 2021).

When examining the crown gate of Tuzhisarı Sultan Han, the base is measured at two b units, while the height of the crown gate is three b units. The same proportion is observed in the crown gate of Aksaray Sultan Han. This proportion is the classic Seljuk ratio of 2/3 (Figure 20).

When the lower base of the crown gate is determined as the radius of the arc, point A, which is the lower left corner, intersects point B, the upper corner of the inner frame of the crown gate, and passes through point C, the upper corner of the muqarnas. The width of the crown gate, taken as the diameter and drawn as a circle tangent to the crown gate arch, touches point G at the base and intersects point H, the keystone of the arch. The same-sized circle drawn tangent to the upper point of the crown gate determines points E and F, the starting and ending points of the door arch, respectively (Figure 20). This analysis reveals that the crown gate has a meticulously thought-out geometric calculation.

Alara Han dates back to 1231-1232 (H.629). The inscription states that it was built under the patronage of Kayqubad I. Alara Han measures 38 m by 50 m, covering an area of 1900 m² (Yavuz, 1991). It is 105 km from Antalya. The central courtyard measures 5 m by 37 m (Özergin, 1965).

Unlike other sultan khans built under the patronage of Kayqubad I, Alara Han was constructed with a different plan type, having a rectangular shape. It has an equal focal plan type, also known as the Constantinian plan type. The galleries surrounding each other symmetrically in the plan provide a symmetrical appearance. With porticos, rooms, stables, and service spaces, it contains all the necessary functions and spaces required for a khan.

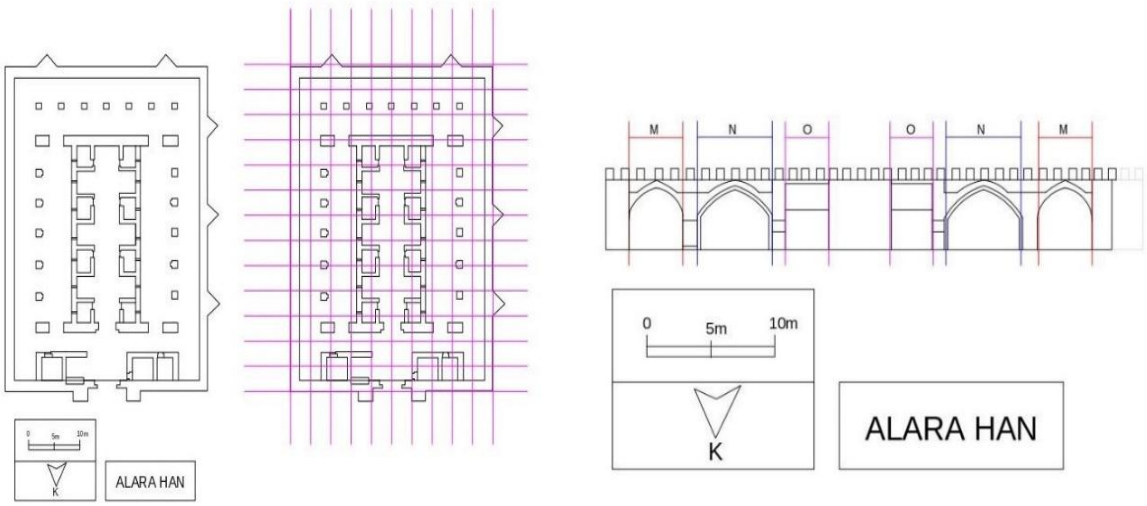


Figure 21. Left: Plan analysis of the Alara Han, Right: Section analysis of the Alara Han (Ersoy, 2021).

Considering the grid repetition seen in Roman architecture and the study conducted by Orhan Cezmi Tuncer, it was investigated whether this feature is present in the plan of Alara Han. The plan was divided into grids. The plan, divided into 10 units horizontally and 13 units vertically, conforms to the grid solution. The grid line passing through the center of the crown gate divides the plan exactly in half. The two units continuing on the right and left of the central line correspond to the central portico section. The 13 units formed horizontally hold the outer walls, creating a balanced appearance. The plan consists of 130 units. Considering the consistency, proportion, and rectangular shape of these repeating units, it is observed that the plan is symmetrical and balanced (Figure 21).

The cross-section of the structure was prepared by cutting through the portico, room, and stable along the window line. On the right side of the section, there is a triangular buttress visible in the appearance. This buttress supports the structure and is located on the western facade of the building. Independently of this, the cross-section consists of the repetition of the portico, room, and stable on the right and left sides. The widths of these repeating volumes on the right and left are equal. The portico scaled by the O unit shows the same measurement on the right and left when the section is centered. The room scaled by the N unit shows the same measurement on the right and left when the section is centered. The stable scaled by the M unit shows the same measurement on the right and left when the section is centered. Considering all these, it is observed that the cross-section of Alara Han also possesses proportion, symmetry, and balance (Figure 21).

There is damage to the tower on the right side of the building facade and the crown gate above it. This damage is directly reflected in the facade drawing. The crown gate is located in the center of the facade, with towers on either side. While the tower on the left is intact, the tower on the right is damaged. The distance from the crown gate to the end of the building wall is the same, which is D units. This repeating D unit on the facade demonstrates the balance and symmetry of the facade (Figure 20).

The distance from the crown gate to the towers is termed F units. The F units repeat twice on both the right and left sides of the crown gate, leaving a small margin at the edges. Due to the pandemic, fieldwork could not be conducted, so millimetric measurements could not be taken. Therefore, this small margin can be disregarded in this context. The measurement of the entire facade, along with the crown gate and its surroundings, is in a ratio of 1:5. The repetition of two F units on the right and left sides of the crown gate shows the symmetry and balance of the facade (Figure 22).

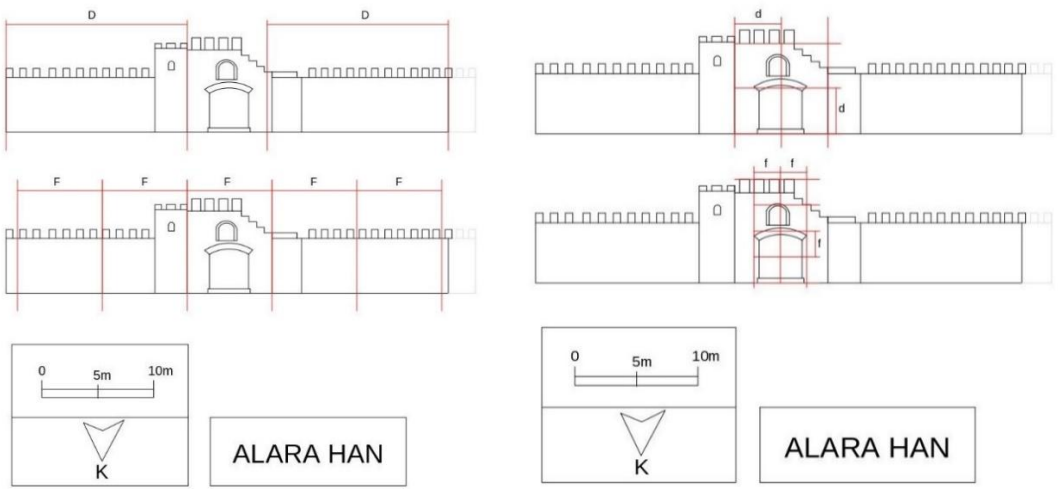


Figure 22. Left: Facade analysis of the Alara Han, Right: Crown gate analysis of the Alara Han (Ersoy, 2021).

Although the Seljuk 2/3 ratio is observed in the crown gates of other khans examined, it is not seen in the crown gate of Alara Han. When looking at the crown gate and its surroundings, the repetition of two d units at the base and two d units in height is observed. Here, the ratio is seen as one-to-one (Figure 22).

Considering only the width of the crown gate, the base of the crown gate is observed to be two f units, and its height is four f units. In the repetition of the f unit, the third f unit from the bottom frames the window above the crown gate. When the two f-unit distance of the base of the crown gate is applied to its height, it coincides with the arch of the entrance gate, showing a one-to-one ratio (Figure 20).

As with the plan, Alara Han is different from the other khans examined in its crown gate as well. However, despite the difference, a proportion is observed in its crown gate. Ratios of 1/1 and 1/2 are observed in the crown gate and its surroundings (Figure 22).

4. Discussion and Conclusion

The geographical position of Anatolia, due to its proximity to different cultures, especially Byzantium and Iran, clearly reveals its influence on architecture. When we examine the social structure of the Anatolian Seljuks, we see that the Turkish population is differentiated into nomadic Turks, semi-nomadic Turks, and urban Turks who came from Central Asia and Iran. These different lifestyles have laid the groundwork for diversified products and production techniques. While nomads have thousands of years of experience in weaving, leatherworking, and metallurgy, semi-nomads have gained knowledge of building techniques and forms, and urban Turks have brought the art and craft knowledge of the Iranian Islamic civilization with them (Kuban, 1981).

The caravan routes passing through Anatolian Seljuk lands have enabled these regions to gain an advanced social and cultural structure. The closed and open markets, bazaars, inns, and caravanserais established along these routes have allowed the region to be economically and culturally nourished (Turan & Kırpık, 2016).

The most distinctive feature of Anatolian Seljuk caravanserais, compared to those in other regions such as Central Asia, Persia, and the Levant, is their unique architectural and functional elements. Caravanserais in regions like Persia and Central Asia, for example, often incorporated extensive decorative elements on their exteriors and had more elaborate façades, reflecting local stylistic preferences. In contrast, due to Anatolia's strategic location and heightened security needs, these structures in the Seljuk period often resembled fortified castles, with thick stone walls, single narrow entrances, and solid towers. Unlike other caravanserais, the Anatolian examples featured minimal external decoration but offered intricate interiors with courtyards, arcades, and large domed spaces. They also balanced open summer areas and enclosed winter rooms, providing year-round

accommodation while functioning as social and commercial hubs, offering free services like food and healthcare, supported by the state (Rice, 2015).

Anatolian Seljuk architecture has gained a unique character through the combination of products and techniques arising from the diversity offered by geography. Architecture, as in every period, was also an important tool for demonstrating the power and prestige of the ruling power in the Anatolian Seljuk Period. The concept of patronage, examined within the boundaries determined by the monarch's period, is particularly significant in this study. Caravanserais, in particular, are multi-functional structures in terms of economy, culture, and architecture, playing critical roles in urban development and cultural transmission. The period of Kayqubad I is noteworthy for the active role he played as a patron in every stage of the construction process (Ertug, 1991).

The golden ratio used in Byzantium was indirectly transferred to Anatolian Seljuk architecture and took on a different form here. When designing a structure, a standard unit is first determined, and the exact proportions of the structures are calculated according to this unit. These ratios and measures are adjusted to ensure symmetry and balance in the structure. Modifications can be made based on this basic measure, and detailed proportioning is done to ensure the aesthetic appearance of the structure (Vitruvius, 2019).

Anatolian Seljuk architecture, particularly its use of geometric proportions and the golden ratio, was not solely influenced by the Byzantine Empire but also bears deep traces of Central Asian and Persian traditions. While the Byzantine legacy played a significant role, particularly in stone masonry and structural elements such as domes, the hallmark of Seljuk architecture lies in its synthesis of various cultural traditions. Concepts like the golden ratio, as seen in many ancient civilizations, were utilized in Seljuk structures to balance both aesthetic and functional principles (Ögel, 1987; Komaroff, & Yalman, 2001). Although the Byzantine influence holds a notable place in Seljuk architecture, this architectural style is far from being limited to Byzantine sources. Instead, elements from Persian, Central Asian, and Islamic traditions were incorporated, creating a rich and unique synthesis that defines the Seljuk architectural identity. This cultural amalgamation is prominently displayed in the Seljuks' famous caravanserais, mosques, and other monumental buildings. These structures exemplify the multilayered and geographically expansive impact of Seljuk cultural heritage (Komaroff, & Yalman, 2001).

This approach to proportion, balance, and modulation has passed from Egypt to the Greeks, gaining an aesthetic appearance with a mathematical expression (Tuncer, 2010). The multiculturalism brought by geography has carried not only geometry and mathematics in architecture but also cultural accumulations. Architecture deals with the deep social values of a culture and expresses these values in a material and aesthetic language.

In terms of method, there are not enough examples in the literature on proportion, balance, and modulation. Among the reliable methods in this field, Orhan Cezmi Tuncer's studies stand out.

Therefore, Tuncer's analyses on the Sivas Gök Medrese were adopted as a methodology in this study. The lack of a detailed examination of proportion, balance, and modulation in Anatolian Seljuk khans previously necessitated this study to be conducted under current conditions and to expand its scope.

The beliefs, lifestyles, needs, and economic structures of society have a decisive impact on the art and architectural works they create. A deep examination of this architectural understanding shows that it carries social and political weight and is shaped by the responsibilities brought by belief. The concept of "patronage" in the Anatolian Seljuk period stands out as an important status symbol in society.

The grid system is a fundamental technique used in architectural design to achieve proportion and modulation. Grid modules are employed to define the placement of key structural elements such as columns, walls, and circulation paths. Through this method, each grid unit is repeated to create proportional unity and balance across the structure. The logic behind the formation of inputs is based on structural requirements and functional purposes (Komaroff, & Yalman, 2001). Grid systems, particularly in Seljuk architecture, combine aesthetics and functionality. The repetition of grid units ensures both structural balance and visual rhythm (Ögel, 1987). Furthermore, grid systems are also used to optimize spatial organization and human circulation (Pinder, 1996). By dividing the plans into grid modules, proportion, balance, and modulation were investigated. Each grid unit was used to create a proportional unity and modulation within the structure by repeating as part of the whole. This method observed how each grid unit affected the structure as a whole. The grid inputs were determined to align

key architectural elements such as columns, walls, and circulation paths. By repeating these units, the method allowed for both spatial coherence and balance, ensuring that each grid's impact on the overall design could be systematically evaluated.

In architectural planning, balance refers to the visual and structural harmony achieved by evenly distributing the visual weight of elements within a space, contributing to both aesthetics and functionality. Symmetrical balance involves mirroring elements along a central axis, creating a sense of order and formality, particularly common in classical architecture. In contrast, asymmetrical balance distributes elements with different forms but equivalent visual weight, adding movement and interest while maintaining harmony. Radial balance arranges elements around a central point, often seen in circular layouts, fostering a sense of unity by directing attention outward from a focal center. Balance in architectural planning is crucial, as it influences the flow and usability of a space, creating an environment that is visually appealing and functional (Rasmussen, 1962; Krier, 1988; Ching, 2014).

Aksaray Sultan Hanı consists of two different masses, including a courtyard part and a completely closed area. When the plan of Aksaray Sultan Hanı is divided with a grid system, it is observed that the grid units arranged in the courtyard section do not align with the spaces in the closed area. This suggests that the closed part while showing symmetrical and balanced characteristics within itself, may not have been planned simultaneously with the courtyard and may have been designed at different times (Table 2).

Table 2. Proportion, balance, and modulation in plan

Khan Name	Proportion in Plan	Balance in Plan	Modulation in Plan
Aksaray Sultan Hanı	Proportional separately in courtyard and closed part	Proportional separately in courtyard and closed part	Proportional separately in courtyard and closed part
Tuzhisarı Sultan Hanı	Proportional	Proportional	Proportional
Alara Han	Proportional	Proportional	Proportional

The plan of Tuzhisarı Sultan Hanı shares similar characteristics with Aksaray Sultan Hanı in shape and plan type. Both structures have a mixed plan type, including a courtyard and a closed area. However, when Tuzhisarı Sultan Hanı is divided into a grid system, the courtyard part and the closed area produce relatively more consistent results. This indicates that the plan is proportional and balanced (Table 2).

Alara Han, on the other hand, is constructed as a single piece with a rectangular form and an equal focal plan type. This plan type, also known as the "Constantinople plan," has four interconnected rings, giving the structure a distinct symmetry. When the plan of Alara Han is divided into a grid system, it is seen that the grids ensure the symmetrical and proportional arrangement of the entire structure (Table 2).

It is necessary first to define the concepts of proportion, balance, and modulation on the facade. Accordingly:

- Proportion on the Facade: Proportion refers to the dimensional relationships established among architectural elements on the facade to create aesthetic harmony. As shown in Table 3, these proportions are observed between features such as door openings, column widths, and arch heights, forming a structured visual unity. This arrangement contributes to a balanced and cohesive facade design.

- Balance on the Facade: Balance on the facade involves the even distribution of visual weight across structural elements. Table 3 illustrates how both symmetrical and asymmetrical balance are achieved. Symmetrical balance is created by placing elements in mirrored positions along a central axis, while asymmetrical balance is achieved by

arranging visually equivalent but varied elements. This balance enhances both the aesthetic and structural stability of the facade.

- Modulation on the Facade: Modulation involves the arrangement of architectural elements in a modular system based on a repeating unit of measurement. In Table 3, this modular system is exemplified by the repetition of elements like arches, columns, or openings. Such rhythmic repetition contributes to the facade's visual flow and aesthetic cohesion.

Observations of the facade of Aksaray Sultan Hanı reveal that the crown gate is symmetrically positioned, and the supporting walls on either side are of equal length. The central position of the crown gate and the equal distance of the buttresses to the gate and wall ends indicate that the facade was designed in a symmetrical arrangement. This structural organization gives the facade a balanced and aesthetic appearance (Table 3).

Table 3. Proportion, balance, and modulation in facade

Khan Name	Proportion in Facade	Balance in Facade	Modulation in Facade
Aksaray Sultan Hanı	Balanced and Symmetrical Facade	Balanced and Symmetrical Facade	Balanced and Symmetrical Facade
Tuzhisarı Sultan Hanı	Asymmetrical Facade	Asymmetrical Facade	Asymmetrical Facade
Alara Han	Balanced and Symmetrical Facade	Balanced and Symmetrical Facade	Balanced and Symmetrical Facade

The facade of Tuzhisarı Sultan Hanı, on the other hand, does not exhibit a symmetrical arrangement because the crown gate is not centrally located. However, the buttresses on the right and left of the crown gate are equidistant from it, and the walls are not of symmetrical lengths, but this section presents a balanced composition when this is overlooked (Table 3).

Despite the deformations on the facade of Alara Han, the symmetrical characteristics of the structure are reflected. The crown gate centers the facade, and the towers on either side of the gate are symmetrically and equally sized. The equal lengths of the walls on either side of the gate indicate strong symmetry and balance throughout the structure (Table 3).

In the crown gate of Aksaray Sultan Hanı, the repetition ratio of two units at the base transforms into a repetition of three units at the height of the crown gate. This observed 2/3 ratio is a characteristic Seljuk architecture ratio and is repeated in many structures (Table 4).

Table 4. Proportion, balance, and modulation in Ccrown gate

Khan Name	Proportion in Crown Gate	Balance in Crown Gate	Modulation in Crown Gate
Aksaray Sultan Hanı	2/3 Seljuk Ratio	2/3 Seljuk Ratio	2/3 Seljuk Ratio
Tuzhisarı Sultan Hanı	2/3 Seljuk Ratio	2/3 Seljuk Ratio	2/3 Seljuk Ratio
Alara Han	1/2 Ratio	1/2 Ratio	1/2 Ratio

Tuzhisarı Sultan Hanı shares similar features with Aksaray Sultan Hanı in many respects. This similarity is also reflected in the crown gates. The crown gate of Tuzhisarı Sultan Hanı repeats two units at the base and three units in height, representing the 2/3 Seljuk ratio (Table 4).

Alara Han exhibits a different architectural structure from other khans. The crown gate of Alara Han has a simpler design. The base ratio of two units is repeated as four units in height, indicating a 1/2 ratio. This suggests that the crown gate of Alara Han does not conform to the characteristic Seljuk ratio

of 2/3. Additionally, the equal focal plan type of Alara Han suggests that this ratio could be influenced by Byzantine proportions (Table 4).

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Research Article

Reevaluating Muqarnas: A Parametric Generative Exploration

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Abstract: Muqarnas, an essential feature in Islamic architecture, seamlessly combines ornamental and structural roles, adorning elements such as portals, domes, and mihrabs. The diverse design configurations of muqarnas are based on a geometric framework that guides the construction process, typically initiated by creating projection plans. Within the scope of this study, the examination of muqarnas projection plans revealed tessellations formed by strategically arranged square and rhombus units inspired by Islamic geometric patterns and early muqarnas prototypes. Analyzing the geometric structure of these tessellations facilitated a systematic approach. The study implemented each step by employing the Grasshopper plug-in in the Rhinoceros program, culminating in generating muqarnas models. This transformative process converted tessellations into tangible three-dimensional geometric units, ready for integration into muqarnas designs. This study deepened the understanding of muqarnas construction and demonstrated the integration between traditional Islamic geometric patterns and contemporary computational design tools. By blending the timeless elegance of Islamic geometric principles with cutting-edge digital methods, this research contributes to the preservation and innovation of cultural heritage, offering new insights into the future of Islamic architectural design. The parametric models represented the geometric transformations intrinsic to muqarnas, reflecting the fusion of tradition and innovation in Islamic architectural design.

Keywords: Architectural geometry, Computational design, Cultural heritage, Design analysis, Muqarnas, Parametric design

Mukarnası Yeniden Değerlendirmek: Parametrik Üretken Bir Keşif

Öz: Mukarnas, İslam mimarisinin önemli bir unsuru olarak hem süsleme hem de yapısal işlevi ile portal, kubbe ve mihrab gibi elemanları süslemektedir. Mukarnas tasarımları genellikle projeksiyon planlarının oluşturulmasıyla başlayan inşa sürecini yönlendiren geometrik strüktürlere dayanmaktadır. Çalışma kapsamında İslami geometrik desenler ve ilk muqarnas prototiplerinden ilham alınarak mukarnas izdüşüm planları incelenmiş, kare ve baklava birimlerinden oluşan tessellasyonların ortaya çıktığı gözlenmiştir. Bu tessellasyonların geometrik yapısının analizi, sistematik bir yaklaşım geliştirilmesine olanak tanımaktadır. Rhinoceros programında Grasshopper eklentisi kullanılarak, her adım sistematik olarak işlenip mukarnas modelleri oluşturulmaktadır. Bu süreç, tessellasyonları üç boyutlu geometrik birimlere dönüştürerek mukarnas tasarımları olarak değerlendirmektedir. Mukarnas üretimleri sağlanmasının yanı sıra, geleneksel İslami geometrik desenler ile çağdaş hesaplamalı tasarım araçları arasında bir bağlantı ortaya koyan bu çalışma kültürel mirasın korunması ve yenilenmesine katkı sunmaktadır. Parametrik modeller, mukarnas tasarımında yer alan geometrik dönüşümlerin somut bir temsilini sağlayarak, İslam mimari tasarımında gelenekselliğin ve aynı zamanda yenilikçiliğin birleşimini yansıtmaktadır.

Anahtar Kelimeler Hesaplamalı tasarım, Kültürel miras, Mimari geometri, Mukarnas, Parametrik tasarım, Tasarım analizi

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1. Introduction

Muqarnas, an architectural feature intricately incorporated into the concave turns of buildings in Islamic architecture, comprises prismatic surfaces with varying design and construction stages depending on the applied material and regional practices. In regions like Iran, Turkmenistan, and Uzbekistan, plaster muqarnas designs are reinforced by steel ropes attached to load-bearing walls. In contrast, Anatolian and Syrian examples showcase the application of stone masses, serving both structural and decorative purposes. Wooden muqarnas examples from Northwest Africa and Andalusia, among the earliest instances, have endured over time. Unlike Anatolian and Syrian counterparts, these wooden muqarnas in Northwest Africa and Andalusia are added to surfaces for decorative purposes, akin to plaster applications. Contemporary muqarnas applications in Andalusia exhibit the transfer of complex geometries using plaster material. Various disciplines have extensively studied Muqarnas. These studies have been classified under three main headings.

1.1. Scholars studying historical and regional aspects of muqarnas

Ettinghausen et al. (2003) conducted extensive research on the early Islamic art Umayyad (661-750 AD) and Samanid (819-999 AD) period. Their work emphasized regional interactions by also discussing in detail elements of the architecture of that period, such as muqarnas. Tabbaa (2001) explored the progression of Sunni architecture during the medieval Islamic period in Iraq, Iran, and Syria. Carrillo (2016) investigated early instances of muqarnas applications in the Near East, tracing their origins to tromp techniques from the Sassanid period (224-651 AD). McClary (2015), including muqarnas, thoroughly examined the architectural features, construction processes, and artistic expression in various styles of Anatolia during the Seljuks.

Massaiu (2018) focused on muqarnas in Sicily during the Norman State (1061-1091 AD), evaluating the Norman state's political and cultural approaches. Haddad delved into the etymology of "muqarnas" and the historical development of Northwest Africa (Maghrib), examining its evolutionary stages until the 16th century. Dallal (2019) examined the muqarnas elements found in regions with early Ottoman architectural works and evaluated their form analyses and developments.

Kılıçoğlu (2022) provides an analysis aimed at classifying the muqarnas structure, examining its geometric foundations within practical applications. This study serves as a resource on the geometric basis and construction processes of muqarnas. Additionally, Kılıçoğlu (2017) sheds light on the traditions of geometric ornamentation in Islamic art, particularly detailing the historical and aesthetic origins of muqarnas dome structures.

1.2. Mathematicians, architects, and computational design experts

Necipoğlu (1996) has provided insightful analysis of Topkapı Scroll, which contains essential information about Islamic geometric patterns, emphasizing Islamic geometric patterns and muqarnas projection plans. Lu & Steinhardt (2007) employed the tessellation approach to analyze specific geometric patterns of Islamic decoration, and it was combined with self-similar transformations to create nearly quasi-crystalline structures. Ajlouni (2012) also investigated this relationship and suggested the presence of a quasicrystal pattern within a structure.

Al-Kashi's book "Miftah al-Hisab" (The Key of Arithmetic) is the first written source containing important information about muqarnas critical for mathematicians and architects in conducting analysis (Dold-Samplonius, 1992). Özdural (1990), Dold-Samplonius (1992), Harb (1978), and Harmsen (2006) further elucidated the fundamental principles of muqarnas units based on Al-Kashi's insights. Ödekan (1977) examines muqarnas-covered portals in pre-Ottoman Anatolian Turkish architecture, highlighting their historical and structural significance in Seljuk architecture. Takahashi (nd) contributed by creating a comprehensive database of muqarnas designs and compiling geometric fiction drawings of muqarnas projection plans, enhancing understanding of its design process.

1.3. Exploration of computational aspects and innovative designs

Ağırbaş et al. (2022) observed that they placed the muqarnas they examined on square grids and spider web grids, creating stars with unequal edges. Yaghan (2010) divided parameters that make up the

muqarnas into fixed and variable categories and redefined them as characteristics and attributes. Within the scope of the study, the aim was to generate new forms by translating characteristic parameters into attributes or by inputting new values into attribute parameters. Yaghan (2011) also emphasizes that pre-designed muqarnas units are positioned in plan projections at angles of 45, 90, and 135 degrees and aimed to constrain the necessary parameters during the transfer of these units from 2D to 3D to obtain new forms. Hamekasi (2013) developed a specialized software tool for creating new muqarnas compositions, expanding the possibilities for three-dimensional designs. Senhaji & Benslimane (2019) conducted studies focused on the three-dimensional modeling of muqarnas based on two-dimensional projection patterns.

Alaçam et al. (2017) examined the vault-like structure of muqarnas through the folding technique and researched the generative tendencies in form-finding. Gökmen et al. (2022; 2023) examined the muqarnas in Kayseri and Sivas using a rule-based approach and concluded that these structures share a unified geometric vocabulary. Consequently, they devised a computational framework for muqarnas coding.

This study demonstrates a novel approach to integrating traditional Islamic geometric patterns with modern computational design tools. It showcases how muqarnas structures can be reinterpreted and transformed into generative designs using a parametric approach. Unlike previous works in literature, this research emphasizes the derivation of muqarnas geometry from its fundamental lines and systematically explores its transformation into three-dimensional forms. The study specifically focuses on analyzing the geometric foundations of muqarnas, a critical element in Islamic architecture, using parametric modeling tools to reinterpret and extend its design potential. Through a step-by-step methodology, it approaches the parametric modeling of muqarnas projection plans, transforming tessellated patterns into 3D units using the Grasshopper plug-in in Rhinoceros.

The research highlights the significance of square and rhomboidal tessellation patterns, which are prominent in muqarnas structures found in Türkiye, particularly those from the Anatolian Seljuks and Ottoman periods. These forms, known for their visual diversity and structural harmony, are analyzed to effectively classify and explain the typological variations of muqarnas. By focusing on these traditional forms, the study preserves their historical importance and leverages them as a foundation for innovative generative design applications. Ultimately, this study contributes to architectural history and computational design by reinterpreting traditional muqarnas structures, bridging the gap between historical craftsmanship and modern technology. It seeks to inspire new design paradigms while preserving the cultural essence of Islamic architectural geometry.

2. About Muqarnas Design Process

Gradually, the muqarnas undergo design based on a projection plan featuring a geometric framework. Portal applications typically employ rectangular projection plans in ax2a dimensions. In these plans, the units at the muqarnas's top align with the midpoint of the projection plan's long side. Various researchers interpret the geometric structure formed by the projection of these units at the vertex differently. Muqarnas designs evolve differently by placing square and rhombus units, starting often with an eight-pointed half star. Projection plans with more pointed stars, particularly in Iranian muqarnas examples, lead to the formation of distinct units.

The units within the geometric setup of the projection plan transition into three-dimensional muqarnas designs, serving two functional roles. Central units, forming niches, act as cells, while complementary units between cells are termed intermediate elements (Harmsen, 2006). Portal muqarnas designs rooted in the Anatolian Seljuks (1071-1308 AD) structures often incorporate square-rhombus patterns within the geometric structure of their projection plans. This type of muqarnas, originating in Islamic architecture with the decorative use of the eight-pointed star on two-dimensional surfaces, persists in contemporary muqarnas applications.

A carefully crafted geometric scheme underpins each muqarnas projection plan. The geometric scheme of muqarnas is typically closely associated with Islamic geometric patterns. The star pattern is one of the most employed geometric motifs in Islamic geometric design. Throughout history, diverse geometric patterns, ranging from 6-pointed stars to 16-pointed stars, have been intricately applied using various techniques on different materials, appearing in architectural structures, decorative elements, and textiles (Jones, 1995). Notably, the 8-pointed star, extensively featured in the geometric compositions

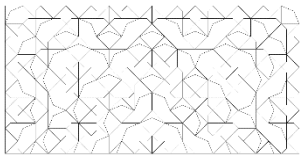
of muqarnas projection plans during the Anatolian Seljuks and subsequent eras in Türkiye, represents a star pattern with roots dating back to the Romans, Sassanids, and Umayyads. Muqarnas geometric setups often commence with half of an 8-pointed star, giving rise to numerous intricate patterns achieved by incorporating square-rhombus modular units in different arrangements.

3. Methodology

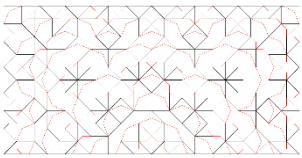
3.1. Square rhombus muqarnas in Turkish architectural designs

In Türkiye, the tradition of incorporating square rhombus units into muqarnas samples dates to the era of the Anatolian Seljuks (1071-1308 AD). This architectural practice involves the projection plan's intricate arrangement of geometric elements. The geometric narrative unfolds with the utilization of the rhombus unit, serving as the foundation for an elegant eight-pointed star at the top. Following this initial formation, square units are strategically introduced to complement and finalize the rhombus configurations, contributing to the overall aesthetic and structural complexity of the muqarnas design.

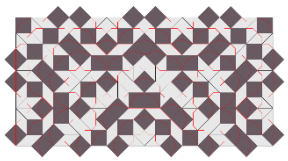
The Rhinoceros program and Grasshopper plug-in are used in the study. Grasshopper is an advanced tool that facilitates parametric design and algorithmic modeling. It enables users to create algorithms in a visual environment, offering flexibility and promoting innovative solutions throughout the design process. The initial step is to examine a muqarnas structure, which involves scrutinizing the geometric scheme within the projection plans. This geometric scheme comprises layer lines and unit lines (Figure 1.a). The unit lines correspond to either square or rhombus units (Figure 1.c). Layer lines play a crucial role by dividing the units on the geometric scheme into distinct segments (Figure 1.b), classifying them based on their designated functions as outlined in Figure 2. Figure 2 indicates that rhombus units are employed in four different manners, while square units serve two purposes. Once the layer lines and units are identified (Figure 1.d), they are put into the Grasshopper tool for analysis, and their respective lengths are computed. These length measurements provide valuable insights into selecting and applying specific rhombus or square units in the muqarnas design (Figure 1.e,f).



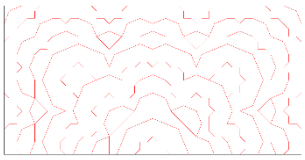
a. Geometric scheme of a muqarnas with layer and unit lines



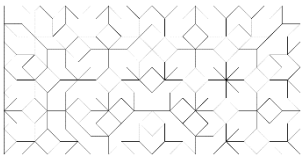
b. Layer lines of a geometric scheme



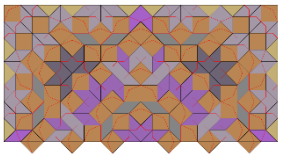
c. Rhombus and square units of a geometric scheme



d. Layer lines for computing steps



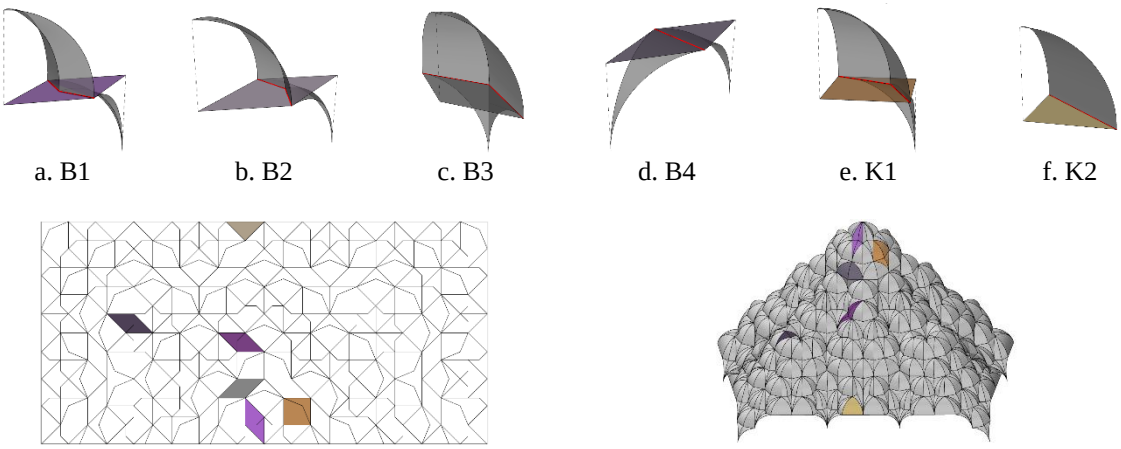
e. Defining units from layer lines



f. Defined units

Figure 1. Construction steps of a muqarnas.

The diverse roles assigned to square and rhombus units within the geometric structure have resulted in numerous interpretations and stylistic variations in muqarnas' designs. The specific functions of these units are meticulously determined by the layer lines present on the muqarnas projection plan, leading to their classification into distinct categories: B1, B2, B3, B4, K1, and K2 units (Figure 2. a,b,c,d,e,f,g and h). Notably, B1, B3, and K1 units span two levels of a muqarnas design, adding a multi-dimensional aspect to the architectural composition. On the contrary, B4 and K2 units are confined within a single level, contributing to the intricacy of specific sections. An exciting observation arises when the muqarnas geometric structure is adapted to a rectangular plan. In this context, square units are deliberately fragmented and repurposed as K2 half-square units. The arrangement of units and the three-dimensional model are illustrated in Figure 2.g and h.

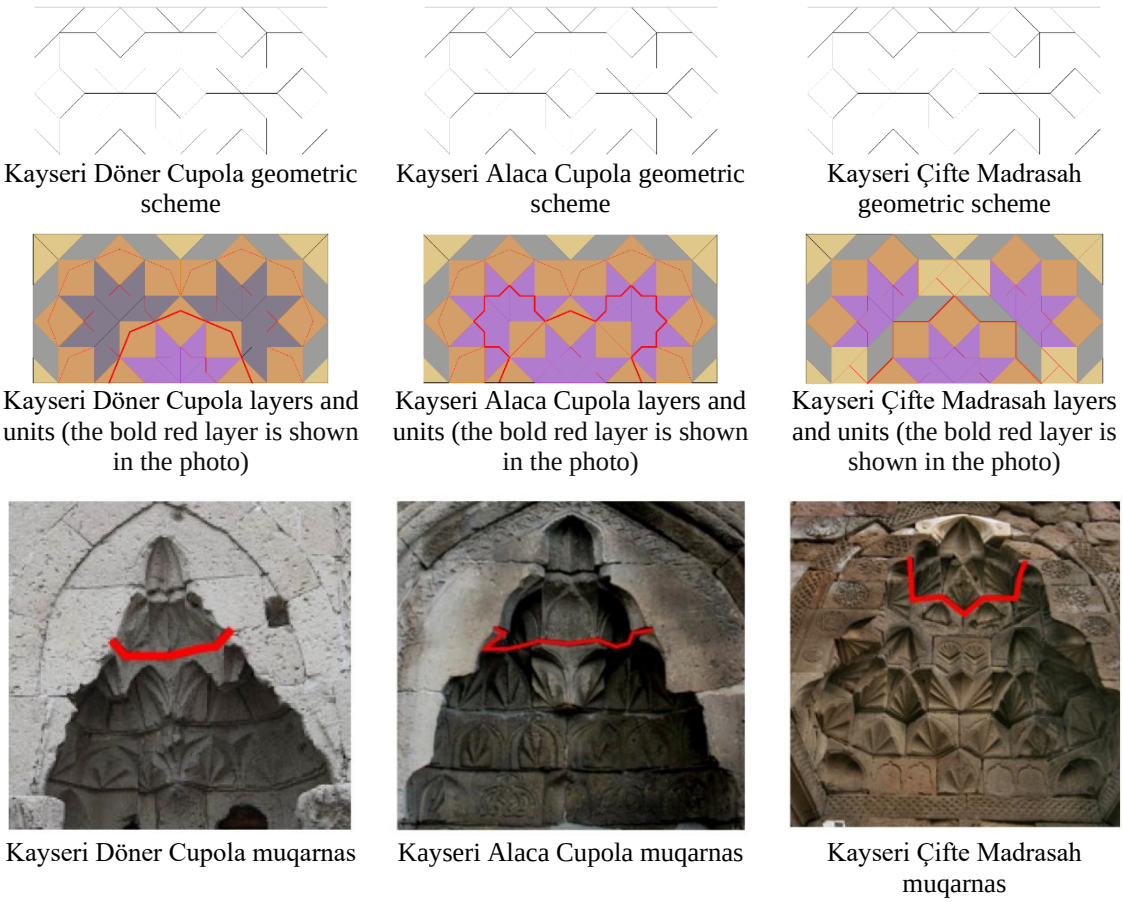


a. B1 b. B2 c. B3 d. B4 e. K1 f. K2

g. Top views of muqarnas units h. Three-dimensional geometries of muqarnas units

Figure 2. Units of a muqarnas

Figure 3 comprehensively explains how square and rhombus units are employed in diverse functions within the projection plans of muqarnas applications in Kayseri. Despite the same geometric scheme among the three selected muqarnas, an intriguing observation emerges as the layer lines are strategically positioned on the square and rhombus units. This placement leads to a remarkable transformation of these units into distinct three-dimensional elements, each fulfilling unique functions within the muqarnas structures. The comparative analysis presented in Figure 3 highlights variations that arise in muqarnas designs, showcasing the dynamic interplay between geometric elements and their spatial functions in the architectural context.



Kayseri Döner Cupola geometric scheme | Kayseri Alaca Cupola geometric scheme | Kayseri Çifte Madrasah geometric scheme

Kayseri Döner Cupola layers and units (the bold red layer is shown in the photo) | Kayseri Alaca Cupola layers and units (the bold red layer is shown in the photo) | Kayseri Çifte Madrasah layers and units (the bold red layer is shown in the photo)

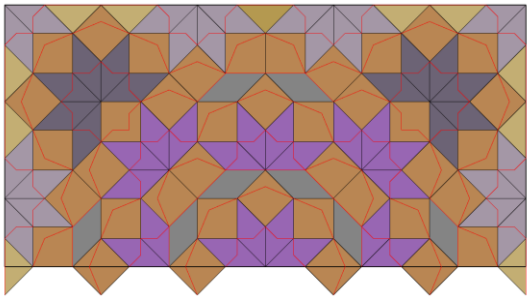
Kayseri Döner Cupola muqarnas | Kayseri Alaca Cupola muqarnas | Kayseri Çifte Madrasah muqarnas

Figure 3. The same square baklava units are designed with different muqarnas examples through their geometric structure (T.C. Kayseri Directorate General of Foundations, 2020).

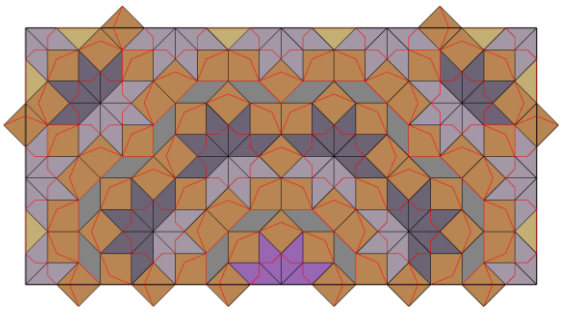
Similar geometric structures in muqarnas applications are evident during the Anatolian Seljuk State era and in subsequent periods, showcasing a lasting influence on architectural design[31]. Notable instances of this recurring similar geometric scheme can be found in various historical landmarks such as Sivas Buruciye Madrasah, Kayseri Tuzhisar Sultanhanı, Kayseri Hacı Kılıç Mosque, Kayseri Alaca Cupola, Kayseri Döner Cupola, and Kayseri Çifte Madrasah. Kayseri Sahibiye Madrasah, Karatay Caravanserai, and Aksaray Sultanhanı also exhibit a continuation of these geometric structures.

The transfer of similar geometric compositions extends to Mardin, where the Kasımiye, Latifiye, and Zinciriye Madrasahs showcase the adaptation of this structural theme into stone, employing the decorative techniques associated with the Artuqids (1102-1409 AD). This demonstrates the recurrence of geometric patterns and the regional variations and cultural adaptations of muqarnas designs.

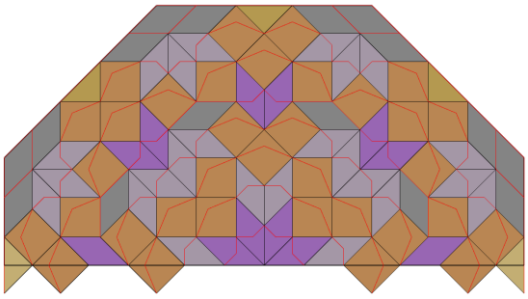
Furthermore, the impact of Artuqid's geometric designs is evident in the muqarnas compositions of the Ottomans, especially in the Diyarbakır region. In this context, muqarnas designs integrate geometric narratives and intricate embellishments that evoke the artistic styles prevalent during the Artuqids era. The muqarnas classified in Figure 4 are examples of those crafted in Türkiye, ranging from the Anatolian Seljuk periods to the Ottomans.



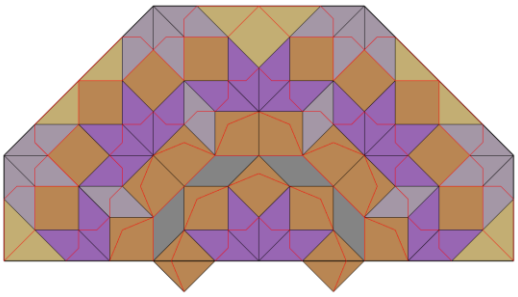
Afyon İmaret Mosque (1472 AD)



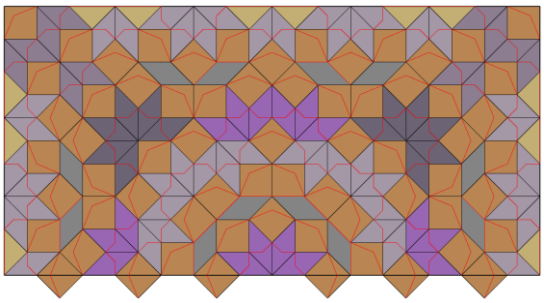
Diyarbakır Behrampaşa Mosque (1572 AD)



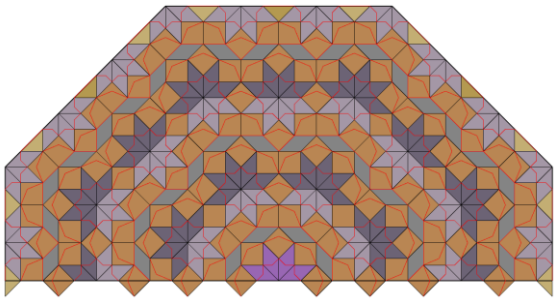
Diyarbakır Behrampaşa Mosque 2 (1572 AD)



Diyarbakır Ali Paşa Mosque (1572 AD)

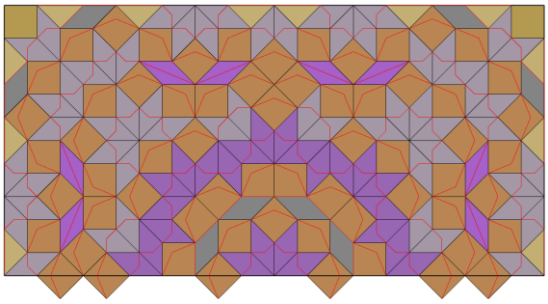


Diyarbakır Melik Ahmet Mosque (1591 AD)

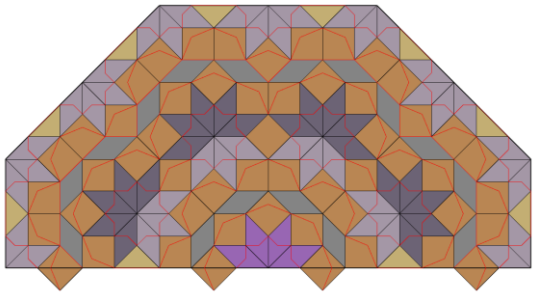


Diyarbakır Grand Mosque (1500s AD)

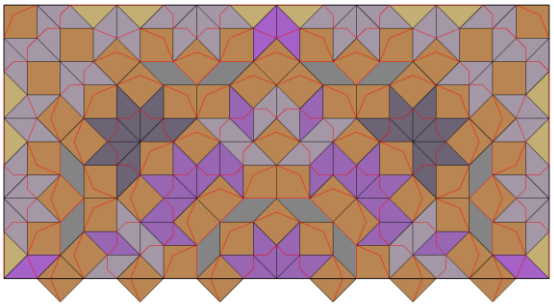
Figure 4. Muqarnas projection plans with square and rhombus units in Turkish geometric designs (Scale 1:50), (muqarnas projected plans are edited by authors after Takahashi (nd)).



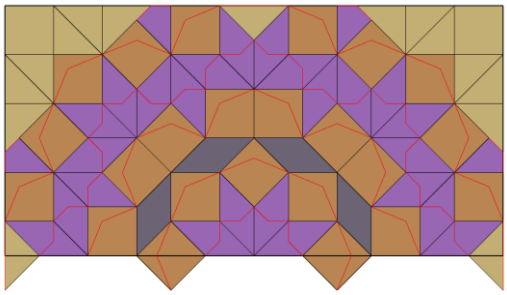
Batman Hasankeyf el Rızk Mosque (1409 AD)



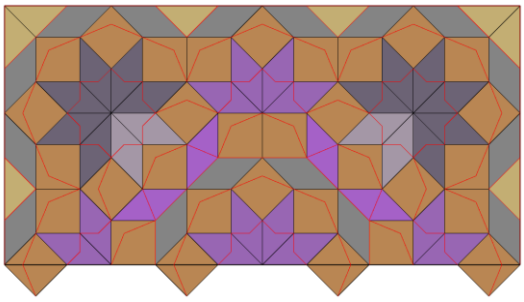
Diyarbakır İskenderpaşa Mosque (1554 AD)



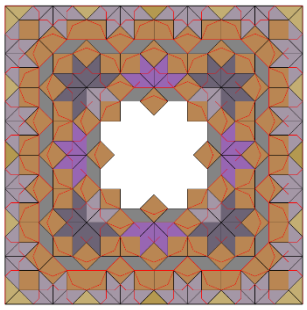
Mardin Kasımiye, Latifiye and Zinciriye Mosques (13-15th c.)



Kayseri Gölük Mosque (1211 AD)



Konya Mevlâna Museum (1584 AD)) and Istanbul Mihrimah Mosque (1566 AD)



Konya Mevlâna Museum (1274 AD)

Figure 4. Muqarnas projection plans with square and rhombus units in Turkish geometric designs (Scale 1:50), (muqarnas projected plans are edited by authors after Takahashi (nd)) (continued).

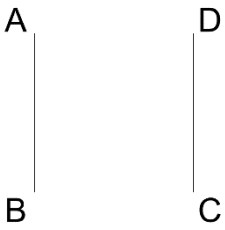
4. Generating Muqarnas Models

4.1. Layers, square and rhombus units

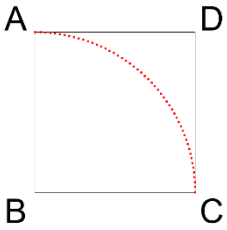
A detailed procedural approach was undertaken to generate a parametric muqarnas model utilizing the Rhinoceros program and transferring the identified layer lines from the selected muqarnas projection plans to the Grasshopper plug-in. The process begins with calculating the lengths of square and rhombus units. Various steps have been developed to separate square and rhombus units along the layer line. The creation of rhombus and square units is based on the ABCD square. The first step is drawing the AC arc. (Figure 5, Step 1,2). This curve intersects with |BD| at point E (Step 3), and line segments drawn from this intersection point to points A and C contribute to forming the layer lines (Step 4,5). Notably, the line segment drawn from E to B corresponds precisely to the measurement of the side of square ABCD (Step 6).

The meticulous completion of |BE| and BC sides, configured to form a 45° equilateral quadrilateral, is instrumental in creating the distinctive rhombus unit, as illustrated in step 7. Furthermore, the intricacies of the design evolve as a perpendicular drop from point E intersects with the diagonal BF of the rhombus, forming a unique geometric configuration (Steps 8-9). From the point of intersection, denoted as H, line segments EH and HC are drawn, yielding two distinct units within the overall geometric composition (Step 10,11).

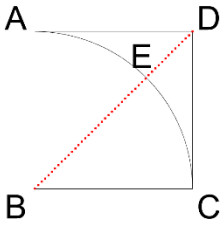
This methodical exploration highlights the thoughtful approach to dividing and utilizing square and rhombus units, showcasing the precision and ingenuity of creating muqarnas projection plans.



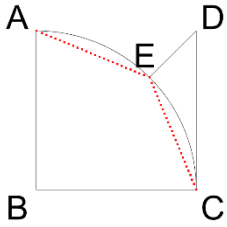
Step 1. Square unit from a Muqarnas plan



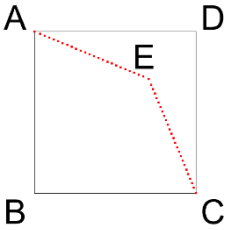
Step 2. AC curve



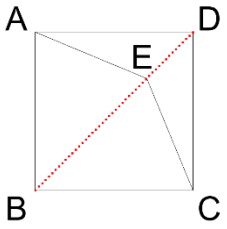
Step 3. The intersection of curve AC and |BE| line at point E



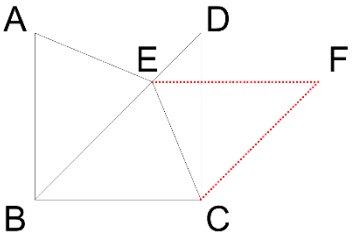
Step 4. |AE| and |EC| lines



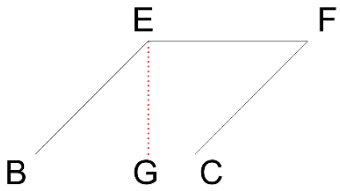
Step 5. Layer of square



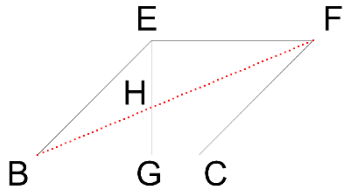
Step 6. |BD| line



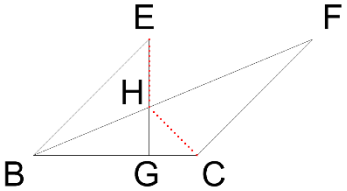
Step 7. Creating EBCF rhombus



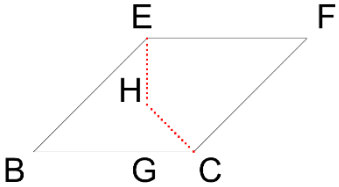
Step 8. |EG| line



Step 9. Intersection of |EG| and |BF| at point H



Step 10. |EH| and |HC| lines



Step 11. Layer of rhombus

Figure 5. Muqarnas units consisting of square and rhombus.

These |AE|, |EC|, |EH|, and |HC| lines play a crucial role as layers in the intricate geometric structure of muqarnas. In both square and rhombus units, these segments are strategically utilized to define and delineate specific elements within the overall design, contributing to the complexity and precision of the muqarnas composition.

4.2. Generating muqarnas

The comprehensive analysis focused on the square and rhombus units, B1, B2, B3, B4, K1, and K2, as outlined in Figure 2. Critical insights into the chosen units were gained by examining the length of the line segments drawn from the initiation to the termination points of the layer lines.

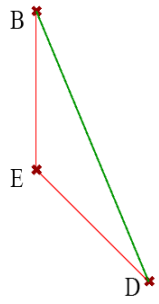
For example, the short diagonal |BD|, determined to be 7.65 units (Figure 6, Step 1), was associated with B1, B3, and B4 rhombus units. Likewise, the long diagonal of 14.14 units represented the K1 unit, and another diagonal of 18.48 units for B1 units served as additional references (Step 6 and 11).

The subsequent steps involved intricate calculations to determine the midpoint F of |BD| and to obtain the length |FD|, represented by the variable y (Step 2). Further refinement occurred by calculating the value of |AF|'s length ($x = y/\tan 22.5°$), deriving points A for B1, B3, and B4 units (Step 3). The asymmetrical application of these rules in the opposite direction facilitated the determination of point C (Step 4). The production of B1, B3, and B4 units entailed creating surfaces from |BD| to points A and C (Step 5).

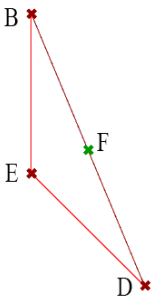
A similar systematic approach was applied to the K1 unit, starting with identifying the midpoint E of the diagonal |BD| (Steps 6 and 7). The subsequent determination of corner points A and C for the K1 unit, denoted by |EC|, was achieved through meticulous length calculations. In the case of the square unit, where the diagonals are equal lengths, the determination of |BE| = |EC| = x paved the way for calculating points C and A in subsequent stages (Steps 8 and 9). The final step involved the production of the K1 unit by creating surfaces from |BD| to points A and C (Step 10).

This intricate process underscores calculations and geometric considerations involved in producing parametric square rhombus units within muqarnas design.

Unlike B1, B3, and B4 units, the computation of the layer line |AC| for the B2 unit involves calculations based on the long diagonal, and the length |CD| is determined along the same diagonal (Step 11). The midpoint E is identified on the line segment |AD| drawn between the layer lines' starting and ending points A and C (Step 12). In the case of the B2 unit, where point C is a crucial element for calculation and is situated on the layer line, determining point A involves calculating the length |EC| in the reverse direction (Steps 13 and 14). Subsequently, the production of the B2 unit is executed by creating surfaces from |BD| to points A and C (Step 15).

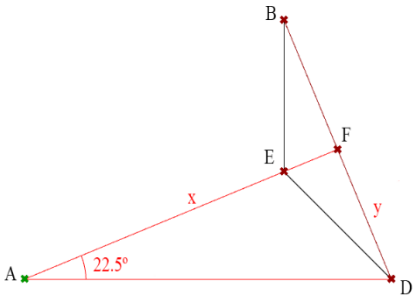


Step 1. Layer line consisting of |BE| and |ED| and the resulting |BD|

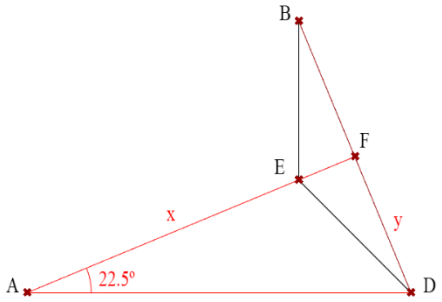


Step 2. F point determination on |BD|

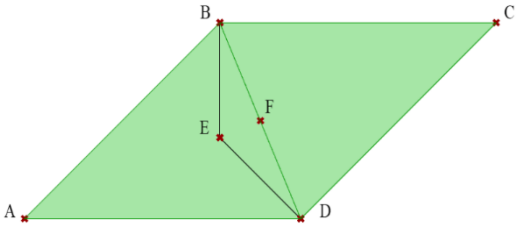
Figure 6. Muqarnas units generating.



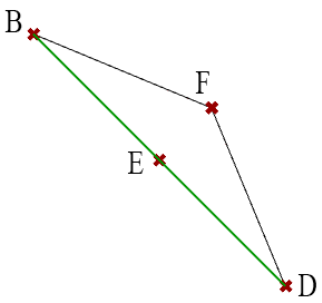
Step 3. The calculation of line X with tan22.5° and the determination of point A



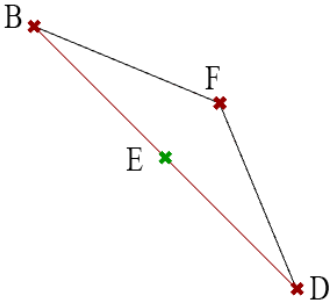
Step 4. The determination of point C



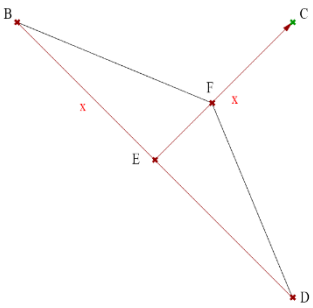
Step 5. The creation of the surface through points and obtaining the rhombus unit



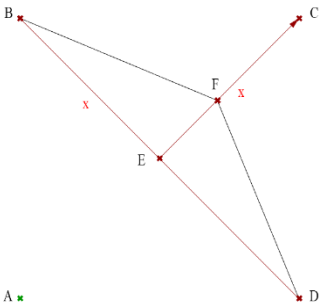
Step 6. The layer line consisting of |BF| and |FD| and the generated |BD|



Step 7. Determining the point E on the line |BD|

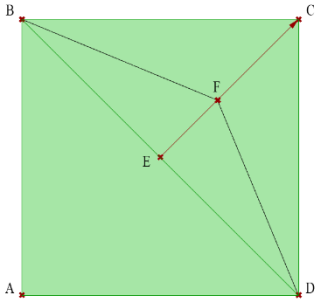


Step 8. Determining point C in a way that |BE|=|EC|

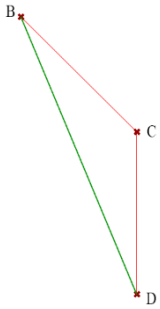


Step 9. Determining point A in a way that it is symmetric to C

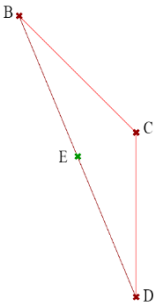
Figure 6. Muqarnas units generating (continued).



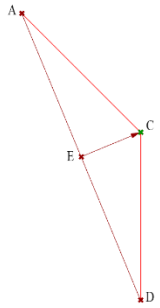
Step 10. Creating the surface through points and obtaining a square unit



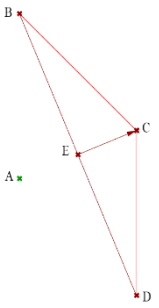
Step 11. Layer line consisting of |BC| and |CD| and the generated |BD|



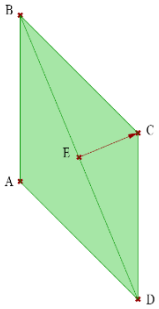
Step 12. Determining the point E on the line segment |BD|



Step 13. Calculating the length of |EC| using tan22.5° and determining the point C



Step 14. Determining the point A



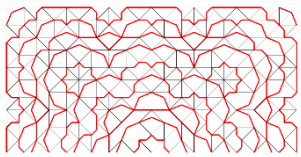
Step 15. Creating the surface through points and obtaining a rhombus unit

Figure 6. Muqarnas units generating (continued).

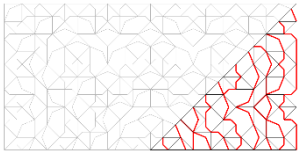
Moving forward, the determination and translation of the acquired B1-B3-B4, B2, K1, and K2 units into the third dimension followed predefined rules outlined in Figure 6. Each layer line incorporated into the code represents a distinct unit in line with the definitions outlined in Figure 5. This intricate process involves transferring each stage to the appropriate height and continuing the progression. While Figure 6 demonstrates the production of two-dimensional B1-B3 and B4 units

similarly, their distinct representation in the third dimension, as clarified in Figure 2, necessitates specific rules during the transfer process.

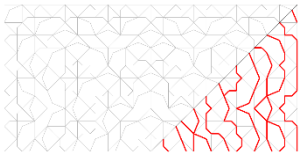
For two-dimensional square and rhombus units that do not intersect with the layers, the corner points are strategically positioned as the lower and upper points of the units in the third dimension. This entails relocating selected diagonal points to the upper or lower layer while keeping the layer line at the required layer. Consequently, the layer line for any unit functions as the base for the point located at the upper level. The creation of front surfaces for three-dimensional units is achieved by covering the curves drawn from the points in the upper level to the corner points of the layer lines forming the base with surfaces. By applying the same procedural steps to the point relocated to the lower level by the layer line, the surfaces of the units at the subsequent level are obtained in Figure 7, Step 4 to Step 8. This elaborate process underscores the intricate calculations and geometric considerations in expanding the parametric muqarnas units into the third dimension.



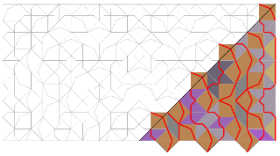
Step 1. Top view of the layers and units



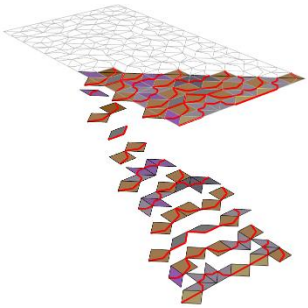
Step 2. The use of a quarter of layers and units



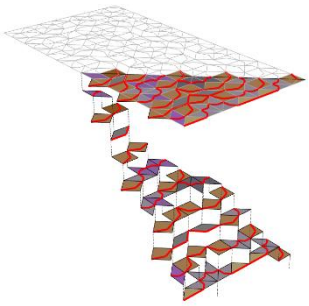
Step 3. The use of a quarter of layers



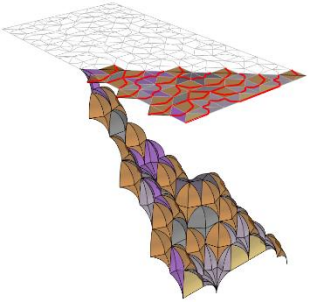
Step 4. Unit determination from layer lines



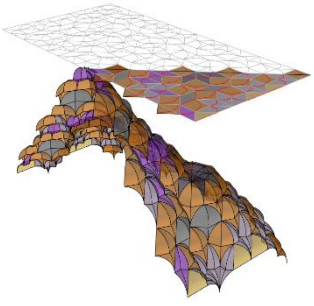
Step 5. Leveling of units generated with layer lines



Step 6. Determining the upper and lower levels of the units



Step 7. Three-dimensionalization of units from level points



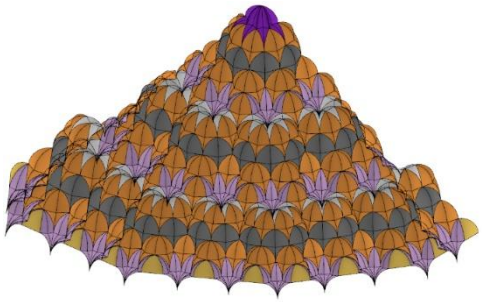
Step 8. Completion of design

Figure 7. Generating steps of the muqarnas model.

A seamless resolution of the muqarnas design process becomes evident upon incorporating the muqarnas geometric configurations selected from Figure 4 into the prepared code (Figure 7). The selected examples have different square rhombus arrangements, and their 3D models create unique designs. Within these muqarnas geometric structures, complex design elements like ‘stalactite’ elements, often fashioned using a combination of B4 and K1 or B3 and B4 units, are completed by adhering to a set of rules defined through layer lines. The muqarnas examples highlighted in Figure 8 exemplify sophisticated and systematic designs prevalent in Türkiye, distinguished by including square and rhombus units in their intricate geometric configurations. This showcases the nuanced craftsmanship and attention to detail in developing these muqarnas designs.



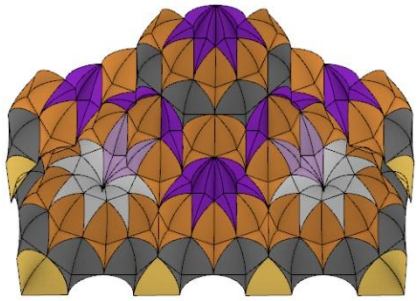
a) Diyarbakır Grand Mosque mihrab muqarnas



b) Diyarbakır Grand Mosque muqarnas model



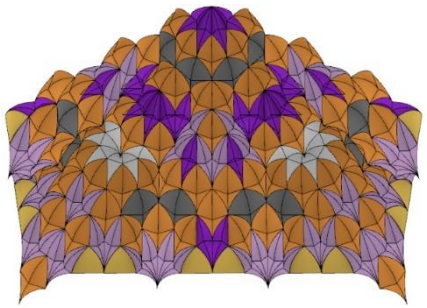
c) Konya Mevlâna Museum portal muqarnas



d) Konya Mevlâna Müzesi muqarnas model



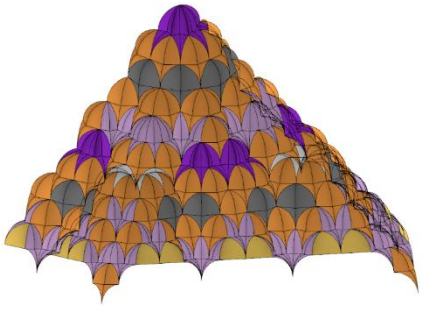
e) Latifiye Memadrasah portal muqarnas



f) Latifiye Madrasah muqarnas model



g) Diyarbakır Melik Ahmet Paşa Mosque portal muqarnas



ı) Diyarbakır Melik Ahmet Paşa Mosque muqarnas model

Figure 8. Generated muqarnas models.

5. Conclusion

This research emphasizes the integration of traditional Islamic geometric patterns into parametric modeling processes, focusing on the transformation of tessellations composed of square and rectangular units into intricate three-dimensional muqarnas structures. By analyzing the strategic combination of 45° rectangular and square units, the study demonstrates how traditional patterns gain new dimensions when adapted with parametric design tools, contributing to the preservation and reinterpretation of cultural heritage within a contemporary architectural context.

The research explores how the positioning of layer lines shapes the spatial forms of muqarnas units. This innovative approach allows for the generation of diverse and unique designs from identical geometric plans by varying the placement of these lines. The resulting parametric framework highlights the flexibility and creative potential of integrating traditional geometric systems with advanced computational tools. Beyond its contribution to contemporary design, the methodology presented in this study holds significant potential for the restoration of historical structures. By offering a systematic approach to generate alternative muqarnas designs from existing geometric plans, the study provides a practical tool for reconstructing lost or damaged elements in historical buildings. This ensures the development of designs that remain faithful to the original structures while accommodating modern restoration requirements. In conclusion, this research bridges the gap between historical craftsmanship and modern technology, offering a versatile framework for both the conservation of cultural heritage and the exploration of innovative architectural designs. It highlights how traditional Islamic geometry can inspire new possibilities, enriching the architectural discourse and providing valuable resources for restoration and contemporary applications.

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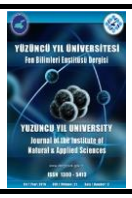
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Araştırma Makalesi

Kamusal Mekân Tasarımında Nöromimari Kriterlerin Algısal İncelenmesi: Rami Kütüphanesi Peyzaj Tasarımı Örneği

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Öz: Kamusal mekânlar, sosyalleşme, dinlenme, temiz havadan yararlanma ve doğayla temas kurma gibi amaçlarla ziyaret edilen, içerisinde kazanılan duygusal ve zihinsel deneyimlerin kullanıcılar için büyük önem taşıdığı mekânlardır. Kamusal alanlar, dinlenme mekânları olmanın ötesinde mimari özellikleri ve atmosferiyle duyulara hitap ederler. Sinir bilimi ile mimarlık arasındaki bağlantı, insanların mekânlarla etkileşimini ve bu etkileşimin insan davranışları ve zihinsel sağlık üzerindeki etkilerini anlamak için bir ortam sağlamaktadır. Nöromimari, insan ve mekân arasında etkili bir iletişim dili oluşturmayı hedeflemektedir. Çalışma alanı olarak; yenilikçi bir tasarıma sahip olması, yeni bir kamusal alan olarak hizmete açılması ve tasarımının geniş kitlelere hitap etmesi çeşitli nedenlerden dolayı seçilen Rami Kütüphanesi peyzaj tasarımının bu bağlamda incelenmesi, kamusal alanların insan davranışlarını ve zihinsel deneyimlerini nasıl etkilediğini anlama açısından katkı sunmaktadır. Çalışmada öncelikle nöromimari ve belirlenen tasarım kriterleri açıklanmış, Rami Kütüphanesi ve peyzaj tasarımı hakkında literatürden elde edilen bilgilere yer verilmiştir. Bu bilgiler doğrultusunda Rami Kütüphanesi peyzaj alanının nöromimari tasarım kriterlerine uygunluğu gözlem yöntemiyle tespit edilip çizelge halinde sunulmuştur. Araştırma sonuçları, nöromimari prensiplerin kamusal alanlarda uygulanmasının kullanıcıların mekânsal deneyimlerini, zihinsel, duygusal sağlığını ve davranışlarını pozitif şekilde etkilediğini aynı zamanda sürdürülebilir mimari yaklaşıma da katkısı olduğunu ortaya koymuştur. Bu bulgular, gelecekte tasarlanacak kamusal mekânların daha bilinçli şekilde planlanması için referans noktası teşkil edeceği düşünülmektedir. Nöromimari araştırmalardan elde edilen verilerin değerlendirilmesiyle, mimarlar ve şehir plancıları, kamusal mekanları tasarlarken insan davranışları ve duygusal deneyimleri nöromimari perspektiften de dikkate alarak daha etkili mekanlar tasarlama yolunda önemli bir kılavuz edinebileceklerdir.

Anahtar Kelimeler: Kamusal mekân, Nöromimari, Peyzaj tasarımı, Rami Kütüphanesi, Sinir bilimi

Perceptual Analysis of Neuroarchitectural Criteria in Public Space Design: The Example of Rami Library Landscape Design

Abstract: Public spaces are places that are visited for purposes such as socializing, resting, enjoying the fresh air, and contact with nature, where emotional and mental experiences are of great importance to the users. In addition to being places of rest, public spaces appeal to the senses through their architectural features and atmosphere. The connection between neuroscience and architecture provides an environment for understanding the interaction of people with spaces and the effects of this interaction on human behavior and mental health. Neuroarchitecture aims to create an effective communication language between people and space. The study of the landscape design of the Rami Library in this context contributes to the understanding of how public spaces affect human behavior and mental experiences. The study first explained neuroarchitecture and its design criteria and presented the information obtained from the literature about the Rami Library and the landscape area. In line with this information, the Rami Library's landscape area compliance with neuroarchitecture design criteria was determined through observation and presented as a chart. The research results show that applying

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neuroarchitecture principles in public spaces positively affects users' spatial experiences, mental and emotional health, and behavior and contributes to a sustainable architectural approach. These findings provide a reference point for more conscious planning of public spaces to be designed in the future. By evaluating the data obtained from neuroarchitecture research, architects and urban planners will be able to obtain an essential guide for designing more effective spaces by taking into account human behavior and emotional experiences when designing public spaces.

Keywords: Landscape design, Neuroarchitecture, Neuroscience, Public space, Rami Library

1. Giriş

Kamusal alanlar, toplumun ortak kullanımına açık olan ve genellikle sosyal ve kültürel etkileşimin merkezi haline gelen mekânlardır. Bu alanlar, yalnızca fiziksel mekânlar değil, aynı zamanda toplumsal bütünleşmenin ve kültürel paylaşımın zeminini oluşturan dinamik yapılardır. Kent dokusunun oluşturulmasında kilit bir rol oynayan bu alanlar, insanların kentle bütünleşmesini sağlar ve onların çevresiyle etkileşimini düzenler. Ayrıca, planlama ve düzenleme süreçleriyle özenle tasarlanan kamusal alanlar, kentsel yapıların denge ve yönlendirilmesinde önemli bir rol üstlenmektedirler (Karayılmazlar & Çelikyay, 2018). Bu bağlamda, kamusal alanların işlevselliği ve kullanıcı odaklı tasarımı, kentsel yaşam kalitesini doğrudan etkileyen unsurlar olarak karşımıza çıkmaktadır.

Kentsel alanlardaki insanların yaşam kalitesi, bireylerin kamusal alanlarla olan etkileşimiyle doğrudan bağlantılıdır. Ferah ve ark. (2023), kamusal alanlardaki etkinliklerin kalitesi ve çeşitliliğinin, bu alanların toplumsal işlevselliğini artıran temel unsurlar olduğunu belirtmiştir. Kamusal alanlar, çeşitli toplumsal faaliyetlerin gerçekleştiği ve sosyal etkileşimin yoğun olduğu ortak mekânlar olarak tanımlanır. Bu alanlar, sokaklar, alışveriş merkezleri, meydanlar, spor sahaları, oyun parkları, kütüphaneler gibi farklı türdeki paylaşılan kullanım alanlarını kapsamaktadır. İnsanların toplanarak sosyalleştiği, iletişim kurduğu, kültürel etkileşimlerin yaşandığı bu kamusal alanlar, toplumun ortak yaşamını ve kimliğini şekillendirmektedir (Özbek, 2004).

Kamusal mekânlar, bireylerin çeşitli sosyal etkinliklerde bulunma veya sadece dinlenme amaçları doğrultusunda kullandığı mekânlar olup, kişilere gün ışığından, temiz havadan ve doğal çevrenin sunduğu psikolojik rahatlamadan yararlanma fırsatı sunarlar. Bu mekânlar, insanların stresi azaltmalarına, zihinsel ve fiziksel iyilik hallerini artırmalarına ve genel refahlarını geliştirmelerine olanak tanımaktadır (Kandemir, 2010). Bu mekânlar, kullanıcıların kolaylıkla algılayabileceği ve tam anlamıyla anlayabileceği şekilde tasarlanmalıdır; böylelikle mekânın kullanıcıları üzerinde algılama, düşünme, kavrama ve yorumlama gibi zihinsel süreçleri harekete geçirebilirler. Kamusal alanların işlevselliği ve estetiği, toplumun ihtiyaçlarına uygun olup aynı zamanda psikolojik olarak destekleyici olmalıdır. Bu alanların tasarımında, kullanıcılar ile mekân arasındaki etkileşim göz önünde bulundurulmalıdır. Kentin ortak mekânları ve kullanım alanlarının tasarımı, kent sakinlerinin yaşam kalitesini artırmaya yönelik olmalıdır ve böylelikle kentlerin daha yaşanabilir bir hale gelmesi ve sakinlerinin memnuniyetinin sağlanması hedeflenmelidir (Karayılmazlar & Çelikyay, 2018). Bu doğrultuda, kamusal alanların tasarımında yalnızca işlevsellik ve estetik değil, aynı zamanda kullanıcıların duygusal ve bilişsel ihtiyaçları da dikkate alınmalıdır. İnsanların bu mekânlarla anlamlı bir bağ kurabilmesi, kamusal alanların birer sosyal çekim merkezi haline gelmesini sağlayacaktır. Ayrıca, mekânların psikolojik olarak destekleyici bir deneyim sunması, bireylerin bu alanlarda geçirdiği zamanın kalitesini artırırken, toplumsal bağları güçlendirme potansiyelini de barındırmaktadır. Kentlerin daha yaşanabilir olması için, tasarım süreçlerinde kullanıcı deneyimlerini merkeze alan ve bireylerin mekânlarla olan etkileşimlerini bütüncül bir perspektifle ele alan yaklaşımlar benimsenmelidir. Böylece, kamusal alanlar yalnızca birer fiziksel geçiş noktası olmaktan çıkarak, bireylerin kendilerini ait hissedebileceği ortak yaşam alanları haline gelebilir.

Kent yaşamındaki bireylerin zihinsel ve psikolojik refahını artırma hedefi, kentsel tasarım süreçlerinde giderek daha fazla önem kazanmaktadır. Öztürk ve ark. (2022), açık yeşil alanların kent-doğa etkileşimini yeniden canlandırmada önemli bir rol oynadığını vurgulayarak, bu alanların bireylerin doğayla bağlantı kurmasını sağlayarak yaşam kalitesine katkı sunduğunu ifade etmektedir. Benzer şekilde, Özyavuz (2016) kentsel yaşamda sunulan rekreatif ve kültürel imkanların, bireylerin stres azaltmasına, ruh sağlığını iyileştirmesine ve toplumla daha derinlemesine etkileşim kurmasına olanak

tanıdığını belirtmektedir. Bu yaklaşımlar, kentsel tasarım süreçlerinde bireysel refahı ve toplumsal etkileşimi destekleyen çözümlerin önemini açıkça ortaya koymaktadır.

Kamusal mekânların insan refahı üzerindeki etkilerini anlamak için nöromimari, mimarlık ve sinirbilim arasındaki ilişkiyi inceleyen yenilikçi bir yaklaşım olarak öne çıkmaktadır. Kentlerin ve kenti oluşturan unsurların tasarımında insanların daha mutlu olmalarını sağlamak için nöroloji ve psikoloji bilgilerinin dikkate alınması gerekmektedir (Akman, 2021). Mimarlık sanatsal ifadeye dayanan bir tasarım disiplinidir. Bu da insanlar ve çevreleri arasındaki ilişkiyi anlamaya yönelik birçok soru ve şüphe doğurmaktadır: Çevre ve insan arasındaki ilişki nedir? Tasarlanan mekanlar insanlar tarafından nasıl algılanır? Mekânın kişinin refahı ve ruh sağlığı üzerindeki etkisi nedir? (Olszewska ve ark., 2014). Bu sorulara yanıt sunabilen nöromimari; insan davranışlarını, sağlığını ve refahını en üst düzeye çıkarabilecek ortamların tasarımını hedeflemektedir. Nöromimari araştırmalarında, EEG (elektroensefalografi), fMRI (fonksiyonel manyetik rezonans görüntüleme) gibi beyin görüntüleme yöntemleriyle birlikte HRV (kalp atış hızı değişkenliği), GSR (galvanik deri tepkisi), ET (göz takibi), EMG (elektromiyografi) gibi çeşitli psiko-fiziksel ölçümler kullanılmaktadır. Bu yöntemler, mimari algı ile duyusal deneyim arasındaki ilişkinin ayrıntılı bir biçimde anlaşılmasını ve ideal mimari kriterlerin belirlenmesini hedeflemektedir (Ritchie, 2020). Ayrıca, bu ileri teknolojik yöntemler, anket, mülakat ve gözlem gibi geleneksel araştırma teknikleriyle bir arada kullanılarak elde edilen verilerin hem öznel hem de nesnel bağlamda ilişkilendirilmesine olanak sağlamaktadır.

Nöromimari, sinirbilimciler ile mimarlar arasındaki iş birliğini ifade eden ve insan ile mekân arasında etkili bir iletişim dili kurma hedefiyle ortaya çıkan bir yaklaşımdır (Sözer & Turcan, 2022). Bu bağlamda, kamuya açık alanların nöromimari açıdan incelenmesi, insanların bu mekanlarla etkileşime geçerken nasıl hissettiklerini, düşündüklerini ve tepki verdiklerini anlamak için bir pencere sunmaktadır. Bu çalışmanın amacı kamusal alan tasarımının insan zihnindeki etkilerini anlamak, nöromimari tasarım kriterlerini Rami Kütüphanesi peyzaj alanı özelinde değerlendirerek tasarımcılara bu kriterlerin uygulanması konusunda referans olabilmek, tasarımların bu bilgilerle zenginleştirilmesini sağlamaktır. Araştırma bulguları, Rami Kütüphanesi peyzaj alanının nöromimari tasarım kriterlerine bazı yönleriyle uygunluk sağlarken, bazı unsurlar açısından eksiklikler barındırdığını ortaya koymaktadır. Bu bağlamda, kullanıcıların mekânsal deneyimlerini ve psikolojik refahını olumlu etkileyen tasarım unsurlarının yanı sıra geliştirilmesi gereken alanlar da belirlenmiştir. Rami Kütüphanesi peyzaj alanı gibi yenilikçi bir mekânın nöromimari açıdan incelenmesi kent içerisindeki ortak mekanların insan davranışları ve zihinsel deneyimler üzerindeki etkilerini anlamada önemli bir örnek olacağı düşünülmektedir. Aynı zamanda hem mimarlık hem de nörobilim alanındaki bilgi birikimini bir araya getirerek bu disiplinlerin karşılıklı etkileşimini anlamamıza katkı sağlayacaktır. Elde edilen bulguların, kamusal mekan tasarımını zenginleştirmede katkı sağlaması beklenmektedir.

2. Materyal ve Yöntem

Örneklem olarak yenilikçi bir tasarıma sahip olması, yeni bir kamusal alan olarak hizmete açılması, çevresel ve toplumsal açıdan dikkate değer bir örnek teşkil etmesi ve tasarımının geniş kitlelere hitap etmesi sebebiyle Rami Kütüphanesi peyzaj alanı seçilmiştir. Araştırmanın yöntemi, nitel bir yaklaşımı benimsemekte olup kamusal alan tasarımı, Rami Kütüphanesi peyzaj tasarımı, nörobilim ve mimarlık ilişkisi konularında mevcut literatürün incelenmesini içermektedir. Çalışmanın teorik çerçevesi kapsmında nöromimari kavramı ve önerilen tasarım kriterleri, Rami Kütüphanesi ve kamusal alanların tasarımı hakkında yayınlanmış akademik makaleler, kitaplar ve tezlere başvurulmuştur. Bulgular Rami Kütüphanesi internet sitesi, alan hakkında yapılmış önceki çalışmalar, Caps office'ten elde edilen bitkilerin listesi ve saha gözlemleri sonucu elde edilmiştir. Alan çalışması Temmuz 2024'te yaklaşık üç gün boyunca sabah, öğlen ve akşam saatleri olmak üzere toplam 8 saatlik nöromimari parametreleri kapsamında yapılan gözlemle gerçekleştirilmiştir. Yapılan gözlem iki ana başlık altında ele alınmıştır: tasarımcı açısından fiziksel elemanların değerlendirilmesi ve kullanıcıların mekânla etkileşimlerinin gözlemlenmesi. Bu çerçevede, hem kullanıcı hem de tasarımcı odaklı bir yaklaşım benimsenmiştir. Literatürde mevcut nöromimari alanındaki çalışmalar ve fiziksel veya sanal ortamlara maruz kalma sırasında nöral aktivitelerden elde edilen sonuçlar çalışma için çerçeve sağlamaktadır. Bu makale, nöromimari bakış açısıyla kamusal alan tasarımının bireyler üzerindeki etkilerini algısal bağlamda inceleyerek, belirlenen tasarım kriterlerinin fiziksel çevre ve kullanıcı deneyimleri arasındaki ilişkiyi nasıl şekillendirdiğini ortaya koymayı hedeflemektedir.

Nöromimari araştırmalarında EEG (elektroensefalografi), fMRI (fonksiyonel manyetik rezonans görüntüleme) gibi ölçüm yöntemleri yaygın olarak kullanılmakta ve bu yöntemlerin mekân tasarımında sağladığı katkılar bilinmektedir. Ancak bu çalışmada, tasarım elemanlarının fiziksel niteliklerinin ve kullanıcı davranışlarının gözlemlenmesi yoluyla, nöromimari kriterlerin sahadaki uygulamaları ve kullanıcı deneyimi algısal bağlamda değerlendirilmiştir. EEG, fMRI gibi ileri teknolojili yöntemlerin kullanımı, laboratuvar ortamı ve bütçe kısıtlamaları nedeniyle bu çalışmada uygulanmamıştır. Bu durum, mevcut çalışma için sınırlayıcı bir faktör olmakla birlikte, gelecekte yapılacak araştırmalarda nöromimari kriterlerin daha ayrıntılı ve objektif bir biçimde incelenmesi için bir fırsat sunmaktadır. Bu tür ölçüm yöntemlerinin kullanımı, mekân tasarımının kullanıcı üzerindeki etkilerinin daha ayrıntılı bir biçimde ortaya konmasına olanak sağlayacaktır.

Nöromimari için kesin olarak belirlenmiş tasarım kriterleri bulunmamakla birlikte, Giray Küçük & Yüceer (2022)'nin çalışması bu konuda önemli bir referans olarak alınmıştır. Bu çalışmadan hareketle, belirli tasarım kriterleri oluşturulmuştur. Tasarım kriterlerinin belirlenmesi sürecinde, diğer ilgili çalışmalardan da faydalanılmıştır. Elde edilen veriler doğrultusunda, 10 adet kriter tanımlanmıştır. Bu doğrultuda, nöromimari tasarım kriterlerini ve insan üzerindeki etkilerini içeren çizelge oluşturulmuştur (Çizelge 1). Çizelge 1'deki oluşan kriterler doğrultusunda, kütüphanenin peyzaj alanı tasarımında nöromimari kapsamında güçlü ve zayıf yönleri ortaya koyulmuştur. Nöromimari konu bağlamında 2 araştırma sorusu belirlenmiş olup bu doğrultuda alan incelemesi yapılmıştır:

1. Nöromimari ilkelerinin kamusal mekanlarda dikkate alınması kullanıcıların mekânsal deneyimlerini ve refah düzeyini ne derecede etkilemektedir?
2. Nörömimari prensiplerinin kamusal mekanların tasarımında uygulanması kullanıcıların mekân algılarını ve davranışlarını nasıl etkilemektedir?

Bu sorulardan yola çıkarak Rami Kütüphanesi'nin peyzaj tasarımı belirlenen nöromimari ilkeler doğrultusunda incelenmiş olup halihazır harita üzerinde işaretlenmiştir (Şekil 6). Sonuç kısmında ise yerleşim planından elde edilen bulgular ve saha gözleminden ortaya çıkan parametreler doğrultusunda Rami Kütüphanesi peyzajındaki kullanılan peyzaj elemanlarının nöromimari kriterlerine uyumlu, kısmen uyumlu veya uyumlu olmadığı Çizelge 3 olarak sunulmuştur.

3. Nöromimari Kavramı ve Prensipleri

3.1. Nöromimari kavramı

Nöromimari, sinirbilimciler ve mimarların iş birliğiyle, mekânın insanlarla etkileşimini inceleyen bir disiplin olarak gelişmiştir. Bu disiplin, insan psikolojisi ve davranışlarını yalnızca mekânın fiziksel özellikleri üzerinden değil, mekân-insan ilişkisi bağlamında anlamayı hedefler. Sözer & Turcan (2022), bu yaklaşımın, mimari unsurların insan psikolojisi ve davranışı üzerindeki etkilerini anlamaya odaklandığını belirtmektedir. Bu durum, mimari tasarım sürecinin yalnızca işlevsel ve estetik kaygılarla değil, aynı zamanda insan-çevre etkileşimini geliştirme amacıyla ele alınması gerektiğini göstermektedir. Nörobilim, sinir sisteminin anatomisi, işlevi ve insan davranışlarının sinirsel süreçlerle bağlantısını araştıran disiplinler arası bir bilim dalıdır. Son yıllarda mimarlık ile nörobilim arasındaki ilişki, mekânın insan yaşamı üzerindeki etkilerini inceleyen yeni bir alan olarak gelişmiştir. Bu disiplin, mekânların duygusal, bilişsel ve fiziksel etkilerini değerlendirerek insan-çevre ilişkisinin anlaşılmasını hedeflerken EEG (elektroensefalografi), fMRI (fonksiyonel manyetik rezonans görüntüleme), HRV (kalp atış hızı değişkenliği) gibi yöntemlerin kullanılmasıyla nörobiyolojik veriler elde edilmektedir (Yavuz, 2022).

Mimarlık ve nörobilim arasındaki bu ilişki, mekânın yalnızca fiziksel bir yapı olmaktan öte, insan davranışlarını ve zihinsel süreçlerini şekillendiren bir etkileşim alanı olduğunu ortaya koymaktadır. Mekânın insan üzerindeki etkileri, sadece anatomik ya da işlevsel süreçlerle değil, bireylerin duyusal algıları ve duygusal tepkileriyle de doğrudan ilişkilidir. Bu bağlamda, mekânın organizasyonel rolü kadar, insan deneyimini şekillendiren duyusal ve bilişsel etkilerinin de anlaşılması önemlidir. Bu yaklaşım, bireylerin çevreyle kurduğu etkileşimlerin daha kapsamlı bir şekilde analiz edilmesine ve tasarım süreçlerinde bu bulguların etkin bir şekilde kullanılmasına olanak tanımaktadır.

Feizabadi ve ark. (2017), tasarımcıların sinirbilim uzmanlarıyla iş birliği yaparak, mekânı deneyimleyen insanların zihinsel süreçlerini etkileyebileceğini ifade etmektedir. Bu bakış açısı, mimarların yalnızca fiziksel mekânlar tasarlayan kişiler olmadığını, aynı zamanda insan davranışlarını yönlendirme potansiyeline sahip aktörler olduğunu göstermektedir. Nörobilim, mimarlıkta geleneksel

anlayışları genişleterek araştırmacılara yeni bakış açıları sağlamaktadır. Son on yılda literatürde nöromimari olarak tanımlanan bu alan, nörobilimdeki ilerlemeleri mimari araştırmalara dahil ederek mekânsal değerlendirmelere ve tasarımlara yeni bir paradigma getirmektedir. İnsanın çevreye reaksiyonlarının, zihinsel süreçlerin yönlendirdiği davranışlar bağlamında değerlendirilmesi, mimari tasarım araştırmalarına yeni perspektifler sunmaktadır (Yavuz, 2022). Bu durumda sinir bilimi, insan deneyimini derinlemesine anlamak ve mimarların yapılı çevre tasarımı sürecinde rehberlik etmesi için bir araç olarak kullanılmaktadır. İnsanın çevreye verdiği tepkilerin ve zihinsel süreçlerin yönlendirdiği davranışların, mimari tasarım araştırmaları için önemli bir veri kaynağı olmasını sağlamaktadır.

Mimarlık; tasarlanıp tamamlandığında bireyleri etkileyen bir disiplindir. İnsan bir mekânda hareket ettiğinde, algıladığı, kokladığı, dokunduğu, duyduğu ve tattığı her şey mimariyi canlandırır ve insan deneyimiyle bütünleşir. Bu anlamda yapılı çevre insanların o mekânı algılamasıyla hayat bulmaktadır (Ritchie, 2020). Bu nedenle, yapılı çevrelerin insanların duyusal algılarıyla hayat bulduğu ve bu algıların tasarım süreçlerinde dikkate alınması gerektiği açıktır. Nöromimari tasarım ilkelerini kamusal mekânların tasarımında göz önünde bulundurmak, mekân kullanıcılarına daha iyi bir deneyim sağlamaktadır. Bu bağlamda nöromimarinin önerdiği tasarım kriterlerini tasarımlarda dikkate almak, bu mekânların insan zihninde ve duygusal durumunda olumlu bir etki bırakmasına yardımcı olmaktadır.

3.2. Nöromimarinin önerdiği tasarım kriterleri

Elde edilen veriler doğrultusunda, geometri-form, ses, renk, aydınlatma, doğayla temas ve biyofilik tasarım, termal konfor, dokunsal uyaranlar, oran-ölçü ve yön bulma olmak üzere 10 adet kriter tanımlanmıştır. Geometri kriteri için simetri-asimetri, düzen-karmaşa ve eğrisellik olmak üzere 3 alt başlık, oran-ölçü kriteri için ise büyüklük-tekrar olmak üzere 1 alt başlık belirlenmiştir. Bu doğrultuda, nöromimari tasarım kriterlerini ve insan üzerindeki etkilerini içeren çizelge oluşturulmuştur (Çizelge 1).

Çizelge 1. Nöromimarinin önerdiği tasarım kriterleri

Nöromimari Kriter	Alt Başlık	Açıklama	Etki	Kaynak
Geometri/ Form	Simetri-Asimetri	Simetrik tasarım ögeleri ve geometrik merkezler tercih edilir.	• Nörolojik aktivite artışı. • Duygusal ve bilişsel davranışta olumlu etki.	Higuera-Trujillo ve ark., 2021
	Düzen-Karmaşa	Motif, desen ve süslemeyle orta seviyede oluşturulmuş karmaşa daha tercih edilebilir bir unsurdur.	• Üst bilişsel merkezlerdeki aktivite artışı.	Coburn ve ark., 2017
	Eğrisellik	Mimari tasarımda eğrisel yüzeylerin tercih edilmesini önermektedir.	• Korku, öfke, endişe ve kaygı gibi duygu alanlarını yöneten amigdala bölgesinin, keskin hatlara sahip yapılarla karşılaşıldığında benzer bir aktivite göstermesi. • Eğrisel formların erişilebilir olarak algılanması.	Coburn ve ark., 2017; Ritchie, 2020
Ses		Çevredeki düşük gürültü seviyeleri olumlu sonuçlar doğurmaktadır. Mekanlar oluşturulurken işlevi destekleyen sesler, akustik düzenlemeler ve doğa sesleri kullanılır.	• Doğa seslerinin stresi azaltması. • Az gürültülü ortamların iletişimi, genel rahatlığı, memnuniyeti ve konsantrasyonu artırması, kan basıncını düşürmesi ve oksijen seviyelerini artırması. • Düşük sesli ortamların dikkat seviyelerini artırması • Su sesinin sakinleştirici ve iyileştirici etkisi.	Ritchie, 2020; Feizabadi ve ark., 2017; Assem ve ark., 2023; Burmil ve ark., 1999
Renk		Renklerin farklı etkileri göz önünde bulundurularak renk seçimi yapılır.	• Renk eksikliği olan mekanların rahatsız edici atmosfer oluşturabilmesi. • Sıcak renklerin bilişsel işlevi arttırması, soğuk renklerin bilişsel uyarılmayı azaltması. • Kırmızı tonların, kalp atış hızını artırarak dikkat ve algı düzeyini yükseltmesi. Mavi ve yeşil tonların, nöral aktivitede azalma yaratması ve rahatlama hissini artırması. • Nötr renklerin sakinlik hissini artırması.	Salingaros, 2006; Higuera-Trujillo ve ark., 2021; Jalil ve ark., 2012

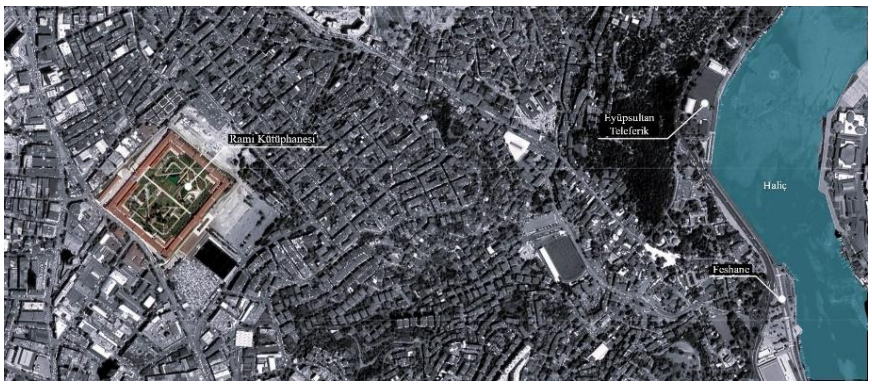
Çizelge 1. Nöromimarinin önerdiği tasarım kriterleri (devam)

Nöromimari Kriter	Alt Başlık	Açıklama	Etki	Kaynak
Aydınlatma		Doğal ışık kullanımı önerilir. Mekânda amaca uygun aydınlatma kullanılmalıdır.	• Parlak ışığın kan basıncını yükseltmesi, uyarılabilirliği artırması. • Doğal ışığın iyileştirici etkisi. • Dolaylı ışığın mekânda ferahlık etkisi ve hoşnutluk hissini artırması.	Sözer, 2020; Higuera-Trujillo ve ark., 2021; Park ve ark., 2018; Shin ve ark., 2015
Doğayla Temas ve Biyofilik Tasarım		Bitki kullanımı, su öğesi ve biyofilik tasarım unsurları tercih edilmelidir. Doğal formların ve malzemelerin kullanılması önerilir.	• Doğal ortamların stres ve kaygıyı azaltması. • Suyun görsel ve işitsel açıdan rahatlatıcı etkisi. • Doğal çevrelerin, olumsuz duygusal durumları ve fizyolojik uyarılmayı azaltması.	Kellert ve ark., 2008; Chow, 2015; Ulrich ve ark., 1991
Termal Konfor		Uygun termal konfor şartları sağlanmalıdır.	• Yüksek veya düşük ısı koşullarının stresi artırması. • Uygun termal koşulların memnuniyet ve üretkenliği desteklemesi.	Chow, 2015; Bueno ve ark., 2021
Dokunsal Uyaranlar		İç ve dış mekanlarda kullanılan malzemelerin dokunsal yapısı, insanların duyusal deneyimlerini şekillendirir. Doğal malzemelerin kullanılması vurgulanır. Amaca uygun malzeme seçimi önerilir.	• Doğal malzemelerin kalp atış hızı ve ter tepkisini azaltması, konforlu ve rahatlatıcı atmosfer oluşturması. • Pürüzsüz ve yumuşak yüzeylerin sakinlik, rahatlama hissi uyandırması. • Pürüzlü ve sert yüzeylerin güçlü, dayanıklı bir izlenim bırakması.	Higuera-Trujillo ve ark., 2021; Papale ve ark., 2016
Oran-Ölçü	Büyüklük-Tekrar	Dengeli ve ölçülü bir tasarım sağlanmalıdır.	• Dengeli oranların nöral aktiviteyi artırması ve insanların zihinsel ve duygusal refahını desteklemesi. • Büyüklük ve tekrarın sonsuzluk hissi uyandırması. • Geniş alanlar ve büyük yapıların düşüncelerin yoğunluğunu azaltması, beyin ağlarının aktivitesini baskılaması. • Mekânın yürüme mesafesinin artmasının ferah bir algı oluşturması, stres seviyesinin düşmesi.	Higuera-Trujillo ve ark., 2021; Takano & Nomura, 2022
Yön Bulma		Mekanlar, yön bulmayı kolaylaştıracak şekilde düzenlenmelidir.	• Simetrik ve basit formların mekânsal algılamayı ve yön bulmayı kolaylaştırması. • Simetrik yapıların hızlı algılanması ve yön bulma sürecini hızlandırarak beyindeki kaygı seviyelerini azaltması. • Kaybolmanın kaygıya yol açması. • Ayna simetrisinin oryantasyonu kolaylaştırması.	Sözer, 2020; Jeffery, 2019
Koku		Mekânın amacını destekleyen koku seçimi yapılmalıdır. Kokunun mimariye bilinçli olarak dahil edilmesi, kullanıcı deneyimini zenginleştirir.	• Hafif kokulu bitkilerin insanlar tarafından tercih edilmesi. • Hafıza, bellek üzerindeki etkisi ve anıları tetikleyebilmesi. • Kokunun beyin aktiviteleri ve bilişsel işlev üzerindeki etkisi • Duygudurum üzerinde pozitif veya negatif etkisi.	Qin ve ark., 2014; Erwine, 2016; Kafaei ve ark., 2024

4. Rami Kütüphanesi

4.1. Geçmişten günümüze Rami Kütüphanesi

İstanbul'un Eyüpsultan ilçesinde konumlanan Rami Kütüphanesi, restorasyon, renovasyon ve yeniden inşa çalışmalarının tamamlanmasıyla, kentin en önde gelen kültürel merkezlerinden biri haline gelmiştir (Şekil 1). 2023 yılında kapılarını açan Rami Kütüphanesi, modern kütüphane işlevlerini içeren, çok yönlü ve çok kültürlü bir alan kullanımıyla dikkat çekmektedir. Türkiye'nin en büyük kütüphanelerinden biri olarak nitelendirilen Rami Kütüphanesi, geniş bir mekânsal zenginlik sunmanın yanı sıra kapsamlı bir kütüphane programına da ev sahipliği yapmaktadır (Ay, 2021).

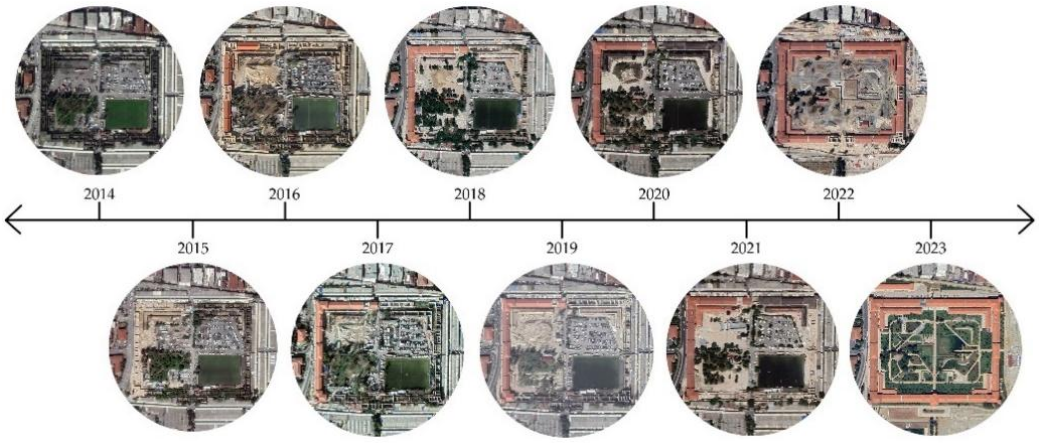


Şekil 1. Rami Kütüphanesi uydu görüntüsü (Yandex, 2024).

Mimarı belirsiz olsa da 1757-1774 yılları arasında III. Mustafa döneminde inşa edilen Rami Kışlası, II. Mahmud döneminde yenilenmiş ve Asakir-i Mensûre Ordusu için kullanılmıştır. Kışla, mimarlık tarihinde yer alan önemli askeri yapılar arasındadır (Çelik, 2018). 1828-1829 Osmanlı-Rus Savaşı sırasında Sultan II. Mahmud'un karargâhı olarak hizmet veren kışla, 1836-1837 yıllarında Mühendishane talebelerinin Mekteb-i Harbiye'ye taşınmasıyla askerî bir üs olma özelliğinin yanı sıra bilimsel bir merkez haline dönüşmüştür. Bu dönüşüm, kışlanın sadece askeri amaçlar için değil, aynı zamanda eğitim ve bilimsel çalışmalar için de önemli bir rol üstlendiğini göstermektedir (T.C. Kültür ve Turizm Bakanlığı, t.y.). Kışla, 1960'lara kadar asli fonksiyonunu sürdürmüştür. 1977'de Anıtlar Yüksek Kurulu tarafından birinci derecede eski eser olarak tescillenmiştir (Subaşı, 2022). 1980'lerin başında, İstanbul Belediyesi'ne devredilen yapı, 1986'da geçici olarak kuru gıda toptancıları için ayrılmıştır (Ay, 2021). Bu dönemde, binanın orijinal plan ve cephesine zarar veren bazı müdahaleler gerçekleştirilmiş, iç avluya ek beton yapılar eklenmiştir (Subaşı, 2022). 1990'da kışla ve çevresi "Rami Kültür Merkezi" olarak belirlenmiş ancak uzun yıllar boyunca gıda toptancılarının zarar verici eylemlerine maruz kalmıştır (Ay, 2021).

1993 yılında kabul edilen Rami İmar Planı'nda, bölgesel ölçekte kültürel ve sosyal amaçlarla kullanılması öngörülen bir alan olarak belirlenen Rami Kültür Merkezi, İstanbul Büyükşehir Belediyesi tarafından İstanbul'un 2010 Avrupa Kültür Başkenti olma çalışmaları çerçevesinde kütüphane ve müze olarak restore edilmesi için onay almıştır (Subaşı, 2022).

Şekil 2, Rami Kütüphanesi'nin 2014 yılından günümüze kadar dönüşüm sürecini göstermektedir. 2014 yılında 1. Etap restorasyon projesi başlamıştır. 2. etap 2017'de, 3. etap restorasyonu ise 2021 yılında başlamış ve proje üç aşamalı bir süreçle tamamlanmış olup, 2023 yılında sonuçlandırılmıştır (Kütüphaneler ve Yayımlar Genel Müdürlüğü, t.y.).



Şekil 2. Rami Kütüphanesi restorasyon çalışmaları kronolojisi (Uydudan Türkiye, 2024).

Dikdörtgen plana sahip olan kışlanın ortasındaki avlu, peyzaj çalışmalarıyla yeniden düzenlenerek İstanbul'a yeni bir yeşil alan kazandırılmıştır. Toplamda 220 dönümlük bir arazide yer alan Rami Kütüphanesi, 36 bin m²'lik kapalı alan ve 51 bin m²'lik avlusuyla her yaş grubundan ziyaretçiye hizmet sunmaktadır (T.C. Kültür ve Turizm Bakanlığı, t.y.).

4.2. Rami Kütüphanesi peyzaj alanı

Ulusal Peyzaj Mimarlığı Ödülleri Genel Kategori dalında 2023 yılında proje ödülüne layık görülen "Rami Kütüphanesi Peyzaj Projesi" Caps Office tarafından tasarlanmıştır (Şekil 3). Rami, yalnızca bölgesel açıdan değil aynı zamanda İstanbul'un genelinde önemli bir kamusal yeşil alan olmanın ötesinde, çeşitli etkinliklere ve sosyal yaşam aktivitelerine ev sahipliği yapma niteliği taşımaktadır (Anonim, 2023).



Şekil 3. Rami Kütüphanesi (Çınar, 2023).

Kütüphanenin avlusu, çeşitli kültürel ve sosyal fonksiyonlarla bütünleşmektedir. Merkezde yer alan Ulusal Arşiv Binası, ana yaya aksında konumlanmış, araştırma salonu ve kafeterya gibi tesisler avlunun alt kısmında simetrik bir düzenlemeyle yer almaktadır (Şekil 4). Yeşil çatı, kamusal kullanıma açık yeşil alanı desteklemekte ve ziyaretçilere gezilebilir bir ortam sunmaktadır (Çınar, 2023).



Şekil 4. Ulusal arşiv binası ve kafeterya.

Tarihi kışla binası, restore edilerek kütüphane ve çok amaçlı bir yaşam merkezi olarak yeniden tasarlanmıştır. Avlu, iç mekân tasarımının dış mekanla etkileşimini yansıtan dinamik bir peyzaj alanı olarak düzenlenmiştir. Avlu içinde oluşturulan farklı kotlar, çeşitli etkinliklere ve kullanımlara olanak tanıyarak, herkesin ihtiyaçlarına uygun farklı kullanım senaryolarını destekleyen zengin bir çeşitlilik sunmuştur. Bu sayede, sakin ve kalabalık, gürültülü ve sessiz kullanım taleplerine cevap verebilecek bir ortam sağlanmıştır (Anonim, 2023). Ana yaya aksı ve 4 ana kapının avluya açıldığı meydanlar haricindeki avlu, çok yönlü bir alan olup, eğitim, kültür, iş birliği, sosyalleşme ve eğlencenin sentezlendiği bir kent parkı niteliği taşımaktadır. Avlu, kışla avlusundan kültürel bir kent parkına dönüşmüş, topoğrafya düzenlemeleri ve mevcut ağaçların korunmasıyla farklı manzaralar sunan alt bölgeler oluşturulmuştur. Kütüphaneden bağımsız olarak kentli kullanıcılar tarafından deneyimlenebilen bu alan kentsel bir merkez haline gelmiştir (Çınar, 2023).

Rami Kütüphanesi'nin peyzajı, modern bir tasarım anlayışını tarihsel dokularla bütünleştirerek sunmaktadır. Alanda konumlandırılan biyolojik gölet ve yeşil altyapı kışla avlusunu yeniden canlandırmıştır. Geleneksel park unsurlarından farklı olarak, standart çözümler yerine her yaş grubuna hitap eden ve doğal malzemelerden üretilen öğelerle peyzajı zenginleştiren bir yaklaşım benimsenmiştir. Bu sayede, kullanıcıların kendi mekânsal deneyimlerini keşfetmelerine ve yaşamalarına olanak tanıyan yaratıcı ve ilham verici bir peyzaj kurgusu oluşturulmuştur.

Avluda önerilen doğal peyzaj düzenlemesi, kullanıcıları çeşitli aktivite alanlarıyla buluşturarak sosyal etkileşimi ve etkinlikleri teşvik etmektedir. Yeşil amfiler, piknik masaları, dinlenme alanları, performans meydanları, ortak çalışma alanları, çocuk oyun alanları, sergi alanları, biyolojik gölet ve tematik eğitim platoları gibi birçok alt mekân, avluda farklı etkinliklerin eş zamanlı olarak gerçekleşmesine imkân tanımaktadır. Ağaçlarla çevrili bu alan, mevsim geçişlerinde kente özgü manzaralar sunmaktadır. Avlu içindeki tüm gezinti yolları, patika yolları ile entegre edilmiş dinamik kot değişikliklerine sahip toprak yollar olarak tasarlanmıştır. Bu düzenleme, çeşitli yaş gruplarını bir araya getiren avlu peyzajı, kent mobilyaları ve amfi oluşumları ile desteklenmiştir. Gölet, faunayı desteklerken, ahşap oyun alanları ve yeşil alanlar çocuklar için keşif ve oyun ortamı sağlamaktadır (Çınar, 2023). Geniş ve zengin bitki örtüsüyle dikkat çeken peyzaj alanında 520 adet yapraklı ağaç, 52 ibreli ağaç, 93.302 adet çalı ve toplam 438 m2 yerörtücü bitki olmak üzere dört farklı bitki grubu kullanılmıştır (Caps Office, Şekil 5).



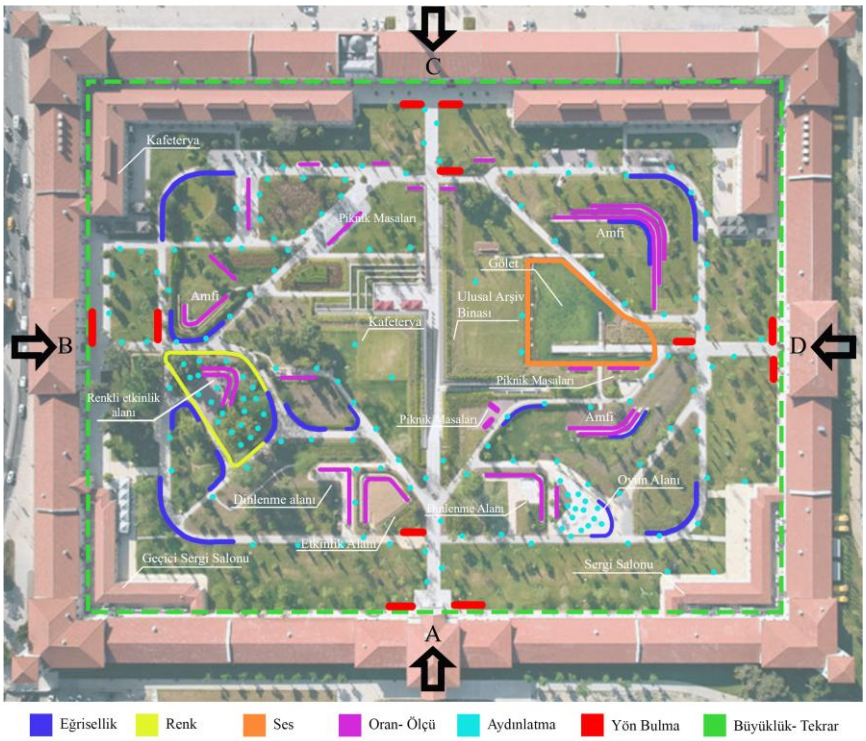
Şekil 5. Bitki çeşitliliği.

Çizelge 2, kullanılan bitki çeşitliliğinin özet halini sunmakta ve alan içerisinde yer alan kokulu bitkilerin insan üzerindeki psikolojik ve fizyolojik etkilerini açıklamaktadır. Çizelgeye tüm bitkiler eklenmemiş olup, makale başlığı altında önem arz eden kokulu ve sayıca fazla olan bitkiler listeye dahil edilmiştir.

Çizelge 2. Alanda kullanılan bazı bitki türleri (Caps office, Yazarlar)

Yapraklı ağaçlar				
İsim	**Orjin**	**Adet**	**Açıklama**	**Kaynak**
Mimoza	İthal	13	Depresyon ve anksiyeteye etkisi	Anonim, 2020
Erguvan	İthal	28	Sakinlik ve konsantrasyona etkisi	Anonim, 2016
Manolya	İthal	1	Konsantrasyon artırıcı etkisi	Cho ve ark., 2015
Gümüşi, amerikan, büyük yapraklı ıhlamur	İthal	78	Kokulu	
Gürgen	İthal	47	Dayanıklı ve uzun ömürlü, toprak koruma ve erozyon kontrolü	
Anadolu sığla	İthal	41		
Mabet ağacı	İthal	28	Konsantrasyon artırıcı etkisi	
Süs eriği	İthal	37		
İbreli ağaçlar				
İsim		**Adet**	**Açıklama**	**Kaynak**
Fıstık çamı	Yerli	10	Canlılığı artırıcı etkisi	Hyun-Ju ve ark., 2010
Ladin	Yerli	11		
Atlas ve himalaya sediri	Yerli	18	Sıcağa ve kuraklığa dayanıklı olması	
Kalem servi	Yerli	6	Fiziksel çalışmalarda olumlu etkisi	Sugawara ve ark.,1999
Çalılar				
İsim	**Orjin**	**Adet**	**Açıklama**	**Kaynak**
Bodur abelya	Yerli	5.868	Kokulu	
Sarı katırtırnağı	Yerli	1.143	Kokulu	
Altuni ve alacalı yapraklı kareks	Yerli	16.314	Grup halinde su kenarında kullanımı	
Yayılıcı ardıç	Yerli	17.00	Zihinsel çalışmalarda olumlu etkisi	Sugawara ve ark.,1999
Yer örtücü yayılıcı hanımeli	Yerli	11.655	Canlandırıcı ve ferahlatıcı etkisi	Ross, 2009
Parlak yapraklı kartopu	Yerli	1.848	Renkli çiçekli, Dekoratif bitki, kokulu ve güzellik sembolü	
Yerörtücü bitkiler				
İsim	**Toplam m2**	**Adet**	**Açıklama**	**Kaynak**
Mayasıl otu	146	37.000	Beyinde serotonin seviyesini artırarak kişinin psikolojik durumunun iyileştirmesi	Anonim, 2024
Damkoruğu	146	36.050	Hızlı yayılan sukulent bir bitki olduğu için kaya bahçeleri ve dikey bahçelerde kullanıma uygun bir bitki türü.	Sağlam & Öztürk, 2023
Kekik	146	10.920	Biliş ve ruh hali üzerinde olumlu etkisi	Singletary, 2016

Şekil 6'da Rami Kütüphanesi peyzaj alanının nöromimari kriterler bağlamında incelendiği noktalar işaretlenmiştir. Fotoğraf üzerinde, yön bulma kriterinin incelendiği rehberlik elemanlarından kapsamlı olanları ve aydınlatma kriterinin değerlendirildiği aydınlatma elemanlarının bulunduğu noktalar belirlenmiştir. Ayrıca, eğrisellik, renk, ses, büyüklük-tekrar kriterlerinin incelendiği alanlar da tespit edilmiştir. İşaretlenmeyen kriterler ise tüm peyzaj alanı genelinde değerlendirilmiştir. Halihazır plan üzerindeki işaretlenen lejantlar, her bir kriterin mekânın farklı bölgelerinde nasıl uygulandığını ve hangi bölgelerde değerlendirildiğini görsel olarak açıklamaktadır.



Şekil 6. Rami Kütüphanesi'nin nöromimari kriterler plan şeması.

5. Bulgular

5.1. Geometri/ form kriterine yönelik bulgular

Rami Kütüphanesi peyzaj alanı dikdörtgen biçimde düzenlenmiş olup kütüphane yapısıyla çevrelenmektedir. Avlu çevresinde kesintisiz biçimde alanı gezme imkânı sağlayan ana yaya yolu, dört adet ana kapı ve her köşe için tasarlanan aktivite alanları makro ölçekte bir simetriye sahiptir. Kütüphanenin avluya açılan kapısından çıkıldığında sağa ve sola ayrılan yaya yolu, insan ölçeğinde de bu düzenlemeyi güçlendirmektedir. Avlu içerisinde yer alan amfilerin formu kendi içerisinde bir simetriye sahiptir. Ancak gözlemler, kullanıcıların mekânda dolaşırken bu simetrik düzeni algılamakta güçlük çektiğini göstermektedir. Peyzaj alanı planı simetrik olarak algılanmakta fakat mikro ölçekte bakıldığında kullanılan su ögesi ve ayrılan parseller simetriyi bozmaktadır. Algılanan geometri göz önüne alındığında simetrik düzenleme, kullanıcıların mekânda deneyimlediği hareket akışında tam olarak hissedilememekte ve mekânsal algı üzerinde sınırlı bir etkisi olduğu gözlemlenmektedir.

Peyzaj düzenlemesinde kullanılan döşeme desenleri, malzeme kullanım biçimi ve alan içerisinde yer alan modern heykeller süsleme ögeleri kapsamında değerlendirilmiştir. Orta düzeyde oluşturulmuş karmaşa, nörobilimsel açıdan daha tercih edilebilir bir unsur olarak değerlendirilmekte ve üst bilişsel merkezdeki aktiviteyi artırmaktadır. Bu bağlamda Rami kütüphanesi avlusu düzen ve karmaşa kriterine uygun olarak değerlendirilmiştir. Özellikle zeminde uygulanan malzemelerle meydana getirilen desenler bir karmaşa oluşturmuş ve ilgi çekici tasarımı desteklenmiştir (Şekil 7). Düzen-karmaşa kriterinin kamusal bir mekânda dikkate alınmasının, kullanıcıların mekânsal deneyimlerini zenginleştirdiği düşünülmektedir.

Avlu içerisindeki dolaşım yollarının ve yeşil alan parsellerinin köşeleri yuvarlak hatlara sahiptir. Korku, öfke, endişe ve kaygı gibi duygu alanlarını yöneten amigdala bölgesi, keskin hatlara sahip alanlarla karşılaşıldığında benzer bir aktivite göstermekte olduğu söylenebilir (Çizelge 1). Kamusal alan kullanımında amaçlanan sakinlik ve doğal çevrenin sunduğu psikolojik rahatlamadan yararlanma durumuna paralel bir yaklaşım görülmektedir. Nöromimari de eğrisel yüzeylerin tercih edilmesini önermektedir. Bununla birlikte eğrisel formların düz hatlara göre daha erişilebilir olarak algılanması etkinlik alanlarının tasarımında öne çıkmaktadır. Bu bağlamda Rami Kütüphanesi peyzaj alanın tasarımında geometri/form kriterlerinden eğrisellik göz önünde bulundurulmuştur.



Şekil 7. Zeminde oluşturulan karmaşa.

5.2. Ses kriterine yönelik bulgular

Mekân içerisinde alanın konumu itibariyle sessiz bir bölgede bulunmasının da etkisiyle herhangi bir rahatsız edici gürültüye rastlanmamıştır. Avluyu çevreleyen kütüphane binasının da etkisiyle şehir gürültüsünden uzaktır. Gözlemin yapıldığı gün ve saatlerde, alanda herhangi bir sesli etkinlik veya etkinlik alanında yüksek sesle yapılan bir faaliyet gözlemlenmemiştir. Düşük gürültü seviyesinin rahatlık ve konsantrasyonu artırdığı, stresi düşürdüğü göz önüne alındığında alan içerisinde kullanıcıların bu yönde tepki gösterdiği ve duygu durumlarının olumlu yönde etkilendiği gözlemlenmiştir. Az gürültülü ortamlarda iletişimin arttığı göz önüne alındığında kamusal alan içerisinde düşük gürültü seviyesinin olması olumlu bir yaklaşım olarak görülmüştür. Avlunun bazı bölümleri heyecan verici bir etkinlik alanı olarak düzenlenmesine karşın bu durumu destekleyen ses unsurları kullanılmamıştır.

Doğanın sesine sahip doğal çevrelerin rahatlama ve stres üzerinde olumlu etkileri olduğu bilinmektedir (Çizelge 1). Özellikle avlu içerisinde su ögesinin çevresinde duyulan kuş sesleri bu durumu destekleyici niteliklidir. Peyzaj alanı içerisinde kullanılan gölet etrafında, gölet ve kullanıcılar arasında görsel ilişki bulunmakta fakat işitsel bir ilişkiyi kısmen sağlamaktadır. Bu bağlamda peyzaj alanının ses unsurları açısından hem olumlu hem de olumsuz yanları bulunduğundan, ses kriterine kısmen uygun olduğu sonucuna varılmıştır (Çizelge 3).

5.3. Renk kriterine yönelik bulgular

Mekanlarda renk ve doku yoksunluğu, kullanıcılar için hoş olmayan bir ortam yaratarak rahatsızlık hissi uyandırabilmektedir. Rami Kütüphanesi'nin peyzaj alanında geniş bir renk paletinin tercih edilmediği görülmektedir. Alan içerisinde bitki örtüsünün yeşil rengi hakimdir. Yeşil tonların nöral aktivitede bir azalma yaratma eğiliminde olduğu kanıtlanmıştır (Çizelge 1). Bu bağlamda, peyzajda kullanılan geniş yeşil alanlar rahatlama hissini artırmaktadır. Nötr renk paletinin genellikle dingin bir atmosfer sağladığı ve mimari dokuya derinlik kazandırdığı bilinmektedir. Yürüyüş yollarında gri taş rengi, kullanılan elemanlarda ahşabın doğal rengi olduğu gibi uygulanmıştır. Kullanılan renkler dikkat çekicilikten uzak olup sakin bir atmosfer oluşturmaktadır. Avlu içerisinde kullanılan oturma elemanları arasında renkli tasarıma sahip olan bir etkinlik alanı bulunmaktadır ve bu durum burayı renk açısından farklılaşan özgün hale getirmektedir (Şekil 8).

Sıcak renklerin bilişsel işlevi arttırdığı, canlandırıcı ve enerji verici bir etkisi olduğu bilinmektedir (Çizelge 1). Bu alanda kullanılan kırmızı, turuncu oturma elemanları dikkat ve algı düzeyini yükseltme eğilimindedir. Etkinlik alanı olarak kullanılan bölgede tercih edilen bu renkler alanın işlevini desteklemektedir. Nöromimari alanı, mimarların renk seçimiyle mekânın hissiyatını değiştirip şekillendirdiği görüşündedir. Kamusal alan olarak kütüphane avlusunda rahatlatıcı ve dinlendirici bir atmosfer oluşturulması mekânda kullanılan renklerle de desteklenmiştir. Mekân içerisinde nöral aktivite üzerinde olumsuz etki yaratan renklerden kaçınılmıştır.



Şekil 8. Etkinlik alanı.

5.4. Aydınlatma kriterine yönelik bulgular

Görsel etkiler, ışığın şiddeti, niteliği ve yönü ile doğrudan ilişkilidir. Gündüz saatlerinde peyzaj alanında doğrudan gelen güneş ışığı etkilidir. Ancak günışığını kesmek için herhangi bir gölgeleme elemanı kullanılmadığı görülmektedir. Bu bağlamda kullanıcılar açısından mekânsal deneyim zayıflayabilmekte ve zihinsel yorgunluk hali oluşabilmektedir. Bu durum, kullanıcıların belirli alanlarda doğrudan güneş ışığına maruz kaldıkları ve bu nedenle rahatsızlık yaşadıklarının gözlemlenmesiyle desteklenmiştir. Kullanıcıların sıcak havalarda gölge alanlar arayarak peyzaj alanının kenarlarında toplanmayı tercih ettikleri, doğrudan ışığa maruz kalan oturma alanlarının ise nispeten daha az kullanıldığı tespit edilmiştir. Gece saatlerinde ise doğrudan parlak bir ışık kullanımı söz konusu değildir. Yol kenarlarında yolu aydınlatmak üzere yerden yaklaşık 40-50 cm yükseklikte konumlandırılmış aydınlatma elemanlarının yanı sıra, yer yer yaklaşık 250-300 cm yükseklikte yer alan daha yüksek aydınlatma elemanları, duvarlar üzerinde kullanılan aydınlatmalar ve bazı bitki kümelerini aydınlatmak için kullanılan elemanlar görülmektedir (Şekil 9a). Göletin bulunduğu alanda kullanılan yapay aydınlatmaların duvarı aydınlatacak şekilde kullanılması doğal ahşap malzemeyi vurgulamakta, su üzerinde görsel bir etki oluşturmaktadır (Şekil 9b).

Mekânın aşırı aydınlık bir mekân olarak düzenlenmemesi zihnin sakinliğine yol açıp mekânsal deneyimi güçlendirmektedir. Gece saatlerinde kullanılan loş ışığın insanlar üzerinde rahatlatıcı bir etki bırakması bu açıdan olası görülmektedir. Nöromimarinin önerdiği tasarım ilkelerinden aydınlatma ilkesi, kamusal alan içerisinde gece saatlerinde etkili bir şekilde uygulanmış olmakla birlikte, gündüz saatlerinde güneş ışığının kontrol altına alınmaması gibi eksiklikler nedeniyle kritere kısmen uygunluk göstermektedir.



Şekil 9. Aydınlatma elemanlarından örnekler.

5.5. Doğayla temas ve biyofilik tasarım kriterine yönelik bulgular

Kamusal alan içerisinde bolca kullanılan yeşil alan, mekân estetiğini artırmakta ve ruhsal anlamda kullanıcı deneyimlerini zenginleştirmesini desteklemektedir. Özellikle yeşil alanlar, kullanıcıların dinlenme, rahatlama ve doğayla bağ kurma ihtiyaçlarını karşılamasına olanak tanımaktadır. Örneğin, yeşil alanlarda yürüyüş yapan ya da banklarda oturarak çevreyi gözlemleyen kullanıcıların huzur ve dinginlik duygusu yaşadığı gözlemlenmiştir. Doğa ile bu tür bir etkileşim, stresten uzaklaşma ve zihinsel rahatlama sağlamaktadır. Düzenlenmiş peyzajlı bahçede yürümenin rahatlama ve stres azaltma potansiyeli olduğu bilinmektedir (Çizelge 1). Ayrıca, alanda kullanılan gri ve kahverenginin yumuşak, gözü rahatsız etmeyen tonlarının kullanımı, doğayla fiziksel ve zihinsel bağ

kurmaya imkan tanıyan alanların oluşturulması ve doğal malzeme tercihi biyofilik tasarım unsurlarına dikkat edildiğini göstermektedir. Bu bağlamda kullanıcıların doğayla temasının birincil derecede önem taşıdığı görülmektedir.

Avlu içerisinde yeni önerilen Ulusal Arşiv Binası'nın araziye entegrasyonu, tasarımındaki en kritik unsurlardan biridir (Şekil 10). Bina ve karşısındaki kafeterya kütüphane binasıyla yarışmayacak şekilde avlu kotunun altında planlanmıştır. Araziyle uyumlu bir ilişki kurarak bir bütünlük oluşturmaktadır. Oluşturulan yeşil çatı kamusal kullanımı destekler niteliktedir. Doğal çevreyle kurduğu etkileşim ve erişim stres, kaygı seviyelerinin azalmasına yardımcı olmaktadır.



Şekil 10. Ulusal Arşiv Binası'nın araziye entegrasyonu (Çınar, 2023).

Su ögesinin kullanımının stres seviyesini azalttığı ve mekâna aidiyet duygusunu artırdığı bilinmektedir (Çizelge 1). Bu bağlamda ana giriş kapısına yakın konumlandırılan göletin ziyaretçiler üzerinde bıraktığı duyusal ve duygusal etkilerin olumlu yönde olduğu görülmektedir (Şekil 11). Kullanıcılar için huzur ve sakinlik ortamı yaratılmasına katkı sağlamaktadır.



Şekil 11. Su ögesi (Biyolojik gölet).

Alan içerisinde doğal arazi kotundan yararlanarak oluşturulan çocuk oyun alanları, çocukların doğal çevrede oyun oynamalarını sağlamakta ve onların fiziksel ve zihinsel gelişimlerini desteklerken aynı zamanda doğayla olan bağlarını güçlendirmektedir (Şekil 12). Doğal arazi kotlarının kullanımı, çocuklara hem keşif hem de oyun oynama fırsatı sunarak çocukların mekâna aidiyet duygusunu pekiştirirken, onların rahatlama ve stres azaltma potansiyelini de artırmaktadır.



Şekil 12. Oyun alanları.

5.6. Termal konfor kriterine yönelik bulgular

Termal konfor, mekân ve insan ilişkisi üzerinde oldukça önemli bir etkiye sahiptir. Mekânda bulunan sıcaklık ve nem gibi termal faktörler, insanların konfor düzeylerini belirlemektedir. Rami Kütüphanesi peyzaj alanının tasarımında özellikle sıcak havalarda, ağaçların oluşturduğu gölgeler, alanın serinletilmesinde önemli bir rol oynamaktadır. Ağaçlar, kullanıcıların güneşten korunmasını sağlamakta ve gölge alanlar oluşturarak termal konfora katkıda bulunmaktadır. Ayrıca, kullanılan ağaçlar, rüzgârın hızını azaltabilir veya yönlendirebilir, bu da ağaçlık alanlarda rüzgârın etkilerinin daha az hissedilmesine neden olabilir. Soğuk havalarda, ağaçların rüzgârın etkilerini azaltarak ortamın daha sıcak hissedilmesine yardımcı olacağı düşünülmektedir. Ancak, oluşturulan etkinlik alanları ve oturma elemanları üzerinde tüm hava koşullarında kullanımlarına devam edilebilmesi için herhangi bir üst örtü düşünülmemiştir (Şekil 13). Yüksek ısı koşullarında oluşacak konforsuz sıcaklık, kullanıcıların stres seviyelerini artırarak memnuniyetsizlik yaratabilir. Bu durumun, kullanıcıların çok sıcak havalarda mekânı terk edip bina içerisine yönelmesine neden olduğu gözlemlenmiştir. Aynı şekilde, yağmurlu veya karlı havalarda peyzajın kullanıcılar tarafından kullanılamayacağı düşünülmektedir. Ağaçların oluşturduğu gölgeler, termal konfor sağlamak için tek başına yeterli olmamaktadır. Bu bağlamda, Rami Kütüphanesi peyzaj alanı termal konfor kriterine uygunluk sağlamamakta ve termal konfor şartlarının iyileştirilmesi için ek önlemler alınması gerektiği düşünülmektedir.



Şekil 13. Güneşli havada kullanılmayan oturma elemanları.

5.7. Dokunsal uyaranlar kriterine yönelik bulgular

Peyzaj alanı, beton, toprak, taş ve ahşap gibi dengeli bir doğal malzeme paletine sahiptir. Özellikle ahşap malzemenin kullanımı organik bir his sağlamaktadır ve konforlu, rahatlatıcı bir atmosfer oluşturmaktadır. Kullanılan geniş çim alanlar dokunsal uyaranlar arasında öne çıkan unsurlardır. Pürüzlü yüzeylerin güç ve dayanıklılık hissiyle ilişkilendirildiği bilinmektedir (Çizelge 1). Bu nedenle, yürüyüş yollarında pürüzlü dokudaki taş ve beton kullanımı kullanıcılara sağlamlık ve güç ile ilgili bir izlenim vermektedir. Öte yandan toprağın yumuşak bir yüzey sunması mekânda sakinlik hissini pekiştirmektedir. Mekânda yoğun olarak kullanılan ahşap, çakıl ve taş gibi doğal malzemeler, dokunsal uyaranlar açısından önemli bir rol oynamaktadır. Doğal malzemelerin azalan kalp atışı ve ter tepkisi gibi etkileri bulunduğundan kullanıcılar üzerinde rahatlatma sağladığı düşünülmektedir. Rami kütüphanesi peyzaj alanı, duyuları harekete geçiren bir ortam yaratan çeşitli dokunsal uyaranları bünyesinde barındırmaktadır (Şekil 14).



Şekil 14. Rami Kütüphanesi'nin peyzaj alanındaki zemin döşemelerinde kullanılan malzeme çeşitliliği.

5.8. Oran- ölçü kriterine yönelik bulgular

Peyzaj alanı, kamusal alan olarak diğer kent parklarıyla kıyaslandığında daha geniş bir alana yayıldığı görülmektedir. Mekân yaklaşık 51.000 m^2'dir. Avlu, geniş bir alan olmasına karşın, malzeme kullanımı, oluşturulan yaya aksları ve işlev gruplarıyla belirlenmiş daha küçük alt mekânlara ayrılmıştır. Bu düzenleme sayesinde kullanıcılar için mekânın algılanabilirliği artırılmış ve herhangi bir yönlendirme sorunu yaşanmadığı gözlemlenmiştir. Peyzaj tasarımı geniş bir alana yayılmış olmasına rağmen, etkili yönlendirme ve erişim planlamasıyla kullanıcıların çıkışa kolaylıkla ulaşabildiği gözlemlenmiştir. Dört ana kapıya kolay erişim sağlayan peyzaj düzenlemesi, yürüme mesafesinin fazla olmasına rağmen herhangi bir fiziksel yorgunluğun veya buna bağlı stresin oluşmasını önlemektedir. Dolayısıyla, yürüme mesafesinin fazla olması, etkili bir yönlendirme ve erişim planlaması sayesinde kullanıcılar için stres artırıcı bir faktör oluşturmamaktadır.

Kullanılan kent mobilyalarında ve diğer ögelerde de uygunsuz ve rahatsız edici bir orana rastlanmamıştır. Mekânda, özellikle avluyu çevreleyen kütüphane yapısının kat yüksekliği bağlamında, insan ölçeğinde ögelerin kullanılması denge ve uyum yaratmaktadır. Kütüphane binasının az katlı olması alanın genişliğini vurgulayıp aynı zamanda peyzaj alanının tümünü çevreliyor oluşu kullanıcılara güven hissi vermektedir.

Büyük ve tekrar eden tasarımların, insan algısı üzerinde sonsuzluk hissi uyandırdığı bilinmektedir (Çizelge 1). Bu bağlamda kütüphane cephesinin tutarlı düzeni bir ritim duygusu oluşturmakta, alan çevresi boyunca tekrarlanan pencereler ve sabit cephe düzeni mekânda sonsuzluk algısını desteklemektedir. Alanın büyüklüğü, düşüncelerin yoğunluğunu azaltarak içsel düşünceyle ilişkilendirilen beyin ağlarının aktivitesini baskılamaktadır. Bu durumda toplum içerisinde katılım ve sosyalleşmeyi artırabilmektedir. Gözlemler, kullanıcıların avlu içinde yavaş tempolu yürüyüşler yaptığını, dinlenme alanlarında oturarak çevreyi izlediğini ve birbirleriyle sohbet ettiğini göstermiştir. Ayırca mekânda yürüme mesafesinin fazla olması kullanıcılar üzerinde ferah bir algı oluşturarak stres seviyelerinin düşmesine katkı sağlamaktadır. Bu durum kamusal alan tasarımındaki sosyalleşme ve rahatlama amaçlarını desteklemektedir.

5.9. Yön bulma kriterine yönelik bulgular

Giriş ve çıkış noktalarında yer alan haritalar, kullanıcıların alanı rahatça tanımasını ve çevreleri hakkında kontrol duygusu kazanmasını sağlamaktadır. Bu bağlamda etkili yön bulma, kamusal alan içerisinde kullanıcı refahını ve sosyal bağlantıları desteklemektedir. Alanın plan düzleminden kolaylıkla gözlenebilmesinin yanı sıra peyzaj tasarımının simetrik yapısı, mekânın algılanmasını kolaylaştırmakta, kullanıcıların karmaşıklık hissi yaşamadan hareket etmelerine olanak tanımaktadır. Okunaklı bir plana sahip olan avlu hızlı algılanmaktadır. Bu durumun beyindeki stres ve kaygı seviyelerini azalttığı düşünülmektedir. Ayrıca, peyzaj alanındaki akıcı yürüme yolları mekânda bir bütünlük oluşturmakta ve yön bulmayı kolaylaştırmaktadır. Mekânda sıkça kullanılan yönlendirici işaretler de bu düşünceyi desteklemektedir (Şekil 15). Gözlem sonuçları kullanıcıların haritaları inceleyerek istedikleri alana hızla yönlendiğini, yürüme yollarında akıcı bir hareket sağlandığını ve yönlendirici işaretleri takip ederek etkinlik alanlarını veya çıkış noktalarını kolayca bulduklarını göstermektedir. Bu kullanıcı davranışları, yönlendirme unsurlarının mekân içerisindeki etkili kullanımını doğrulamaktadır.



Şekil 15. Yönlendirici işaretler.

Peyzaj alanında konumlandırılan enstalasyonlar, bulundukları noktalarda odak noktası oluşturarak, özellikle buluşma noktaları yaratmada kritik bir rol oynamaktadır. Mekânda yer alan ara yolların karmaşıklığı, kullanıcıda kaybolma düşüncesi uyandırmakla birlikte, bu yolların ana yollar ile kesişim noktaları yönlendirici tabelalar ve çeşitli enstalasyonlarla desteklenerek yön bulmayı kolaylaştırmaktadır. Yönlendirici elemanların yaya yollarının stratejik noktalarında konumlandırılması ve avluların numaralandırılması, yönlendirme konusunda büyük önem arz etmektedir. Alanda tespit edilen çeşitli enstalasyonlar, mekânı estetik olarak güçlendirmenin yanı sıra yönlendirici özellikleri ve buluşma noktaları olarak ön plana çıkmaktadır (Şekil 16).



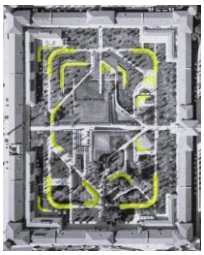
Şekil 16. Enstalasyon örnekleri.

5.10. Koku kriterine yönelik bulgular

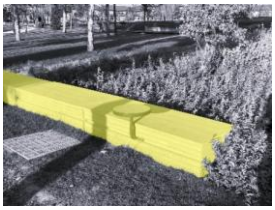
Rami Kütüphanesi peyzaj alanında özenle seçilmiş çeşitli bitki türleri bulunmaktadır ve bu bitkilerin bir kısmı kokulu bitkilerdir. İnsanlar genellikle çevrelerindeki kokulara karşı duyarlıdır ve bu kokuların zihinsel ve duygusal durumlarını etkileyebileceği bilinmektedir (Çizelge 1). Yoğun kokular kamusal alanlarda rahatsızlık yaratabilirken, doğal ve hafif kokuların kullanılması, mekânın sakinliğini artırarak dinlenme alanları için daha etkili bir atmosfer oluşturabilmektedir. Rami Kütüphanesi peyzaj alanında mimoza, erguvan, ıhlamur, kekik gibi hafif kokulu bitkilerin kullanılması kamusal alanın dinlenme işlevini desteklemektedir. Rami Kütüphanesi peyzaj alanında, çam, servi, ardıç ve hanımeli gibi duygudurum üzerinde canlandırıcı etkisi bulunan bitkiler de bulunmaktadır. Bu bitkiler, kullanıcıların zinde kalmalarını veya harekete geçmelerini sağlama konusunda etkilidir. Kütüphane avlusunda düzenlenen çeşitli etkinliklerle de bağlantılı olarak, bu bitkilerin kullanımı alandaki dinamik ve enerjik atmosferi desteklemektedir. Bu bağlamda, koku öğesi bilinçli bir şekilde alan tasarımına entegre edilerek kullanıcı deneyimi zenginleştirilmiştir. Kokunun bu şekilde tasarıma dahil edilmesi, mekânın amacına hizmet eden bir ortam oluştururken, kullanıcıların mekân algılarını ve davranışlarını olumlu etkileyeceği düşünülmektedir.

Rami Kütüphanesi peyzaj tasarımı, eğrisellik, düzen-karmaşa, renk, biyofilik tasarım, dokunsal uyaranlar, oran-ölçü, yön bulma ve koku gibi birçok kriterde nöromimari kriterlere uygunluk bağlamında başarılı bir tasarıma sahiptir. Bu özellikler, alanın kullanıcılar üzerinde olumlu bir etki bırakabileceğini ve kamusal mekân tasarımının insan deneyimini zenginleştirebileceğini göstermektedir. Simetri-asimetri, ses ve aydınlatma kriterlerine kısmen uygun olması, mimari bir denge oluşturulduğunu ancak nöromimari tasarım kriterleri olarak bu alanlarda belirgin bir yönelimin olmadığını göstermektedir. Termal konfor ilkesine uygun bulunmaması ise bu konuda tasarımın kullanıcı ihtiyaçlarını tam anlamıyla karşılayamadığını ve bu eksikliğin mekânsal deneyimi olumsuz yönde etkileyebileceğini göstermektedir. Çalışmada elde edilen bulgular Çizelge 3'te ayrıntılı olarak açıklanmaktadır.

Çizelge 3. Rami Kütüphanesi peyzaj alanının nöromimari kriterlere uygunluk bakımından elde edilen bulguların sonuçları

Nöromimari Kriter	Alt Başlık	Açıklama	Fotoğraf	Kritere Uygunluk
Geometri/Form	Simetri-Asimetri	Makro ve mikro ölçekte simetrik olması.	 	Kısmen
	Düzen-Karmaşa	Alan içerisinde desen ve süsleme ögelerinin kullanımı.		Uygun
	Eğrisellik	Peyzaj düzenlemesinde ve kullanılan peyzaj ögelerinde eğrisel formlara yer verilmesi.		Uygun
Ses		Alan içerisinde düşük gürültü seviyesinin bulunması. Tüm noktalarda ses unsurunun etkin biçimde kullanılması.		Kısmen
Renk		Kamusal alan içerisinde kullanılan renklerin alandaki işlevleri ve yaratılan atmosferi desteklemesi.		Uygun
Aydınlatma		Tüm kullanım saatlerinde aydınlatmanın, mekânsal deneyimi zenginleştiren bir unsur olarak kullanılmış olması.	 	Kısmen
Doğayla Temas ve Biyofilik Tasarım		Kamusal alan kullanımında amaçlanan sakinlik ve doğal çevrenin sunduğu psikolojik rahatlamadan yararlanma durumuna paralel bir yaklaşım bulunması. Tasarımda, doğal malzemeler, doğal renk paleti, suyun kullanımı gibi biyofilik tasarım unsurlarına dikkat edilmesi.	 	Uygun

Çizelge 3. Rami Kütüphanesi peyzaj alanının nöromimari kriterlere uygunluk bakımından elde edilen bulguların sonuçları (devam)

Nöromimari Kriter	Alt Başlık	Açıklama	Fotoğraf	Kritere Uygunluk
Doğayla Temas ve Biyofilik Tasarım		Kamusal alan kullanımında amaçlanan sakinlik ve doğal çevrenin sunduğu psikolojik rahatlamadan yararlanma durumuna paralel bir yaklaşım bulunması. Tasarımda, doğal malzemeler, doğal renk paleti, suyun kullanımı gibi biyofilik tasarım unsurlarına dikkat edilmesi.	 	Uygun
Termal Konfor		Farklı hava koşullarına uygun mekanların düşünülmesi.	 	Uygun değil
Dokunsal Uyaranlar		Çeşitli dokunsal uyaranlarla duyuları harekete geçiren bir ortam sunması.	 	Uygun
Oran-Ölçü	Büyüklük-Tekrar	Kullanılan kent mobilyalarının ve diğer ögelerin dengeli ve orantılı olması. Cephe tasarımının büyük ve tekrar eden elemanlarının, mekânda bir ritim ve süreklilik algısı oluşturarak kullanıcıların alanı tutarlı ve düzenli bir şekilde deneyimlemesine olanak tanıması.	 	Uygun

Çizelge 3. Rami Kütüphanesi peyzaj alanının nöromimari kriterlere uygunluk bakımından elde edilen bulguların sonuçları (devam)

Yön Bulma	**Mekân içerisinde etkin bir mekânsal yönlendirme bulunması.** **Yön bulma tasarımının kamusal alan içerisinde kullanıcı refahını ve sosyal bağlantıları desteklemesi.**	 	**Uygun**
Koku	Nöromimarinin önerdiği bir kriter olarak koku unsurunun alanda etkin biçimde kullanılması.		Uygun

6. Tartışma

Araştırmanın ‘Nöromimari ilkelerinin kamusal mekanlarda dikkate alınması kullanıcıların mekânsal deneyimlerini ve refah düzeyini ne derecede etkilemektedir?’ sorusundan yola çıkılarak, Rami Kütüphanesi’nde nöromimari kriterlere uygunluk gösteren noktalarda kullanıcıların mekânsal deneyimlerinin zenginleştiği ve kullanıcı memnuniyetlerinin arttığı gözlemlenmiştir. Örneğin, oran-ölçü, yön bulma, dokunsal uyaran çeşitliliği, doğayla temasın sağlanması ve koku gibi nöromimari kriterlerin uygulanması kullanıcıların mekânsal deneyimlerini ve rahatlık düzeylerini artırmaktadır. Bu unsurlar, kullanıcıların kendilerini mekânda daha huzurlu ve rahat hissetmelerine, dolayısıyla mekânı daha fazla ve verimli kullanmalarına katkı sağlamaktadır. Ancak, aydınlatma kriterinin gündüz saatlerinde yeterince karşılanmaması ve termal konfor şartlarının uygun olmaması, kullanıcı deneyiminde olumsuz bir etki yaratmaktadır. Bu eksiklikler, kullanıcıların mekânda uzun süre vakit geçirmeye yönelik motivasyonlarını azaltmakta ve bazı durumlarda mekânı terk etme eğilimi göstermelerine neden olmaktadır. Bu bağlamda nöromimari prensiplerin kamusal alanlarda dikkate alınması kullanıcı deneyimi için önemli bir rol oynamaktadır.

Bununla birlikte, nöromimari kriterlerin uygulanmasının yalnızca kullanıcı deneyimine değil, sosyal sürdürülebilirliğe de dolaylı yoldan fayda sağladığı gözlemlenmiştir. Kütüphane peyzaj alanının sosyal etkileşimi teşvik eden alanları, kullanıcılar arasında daha fazla iletişim sağlamaktadır. Özellikle az gürültülü ortamlar, bireyler arası iletişimi artırmakta ve topluluk içi bağların güçlenmesini sağlamaktadır. Yön bulma tasarımı ise, kamusal alan içerisinde kullanıcı refahını ve sosyal bağlantıları desteklemektedir. Kullanıcıların mekân içinde rahatça hareket edebilmeleri ve kendilerini güvende hissetmeleri, kullanıcı deneyiminin yanı sıra sosyal sürdürülebilirliğe de önemli katkılar sağlamaktadır. Sonuç olarak, nöromimari kriterlere uygun tasarlanan kamusal mekânların, dolaylı olarak sosyal sürdürülebilirliği de destekleyerek bireylerin refah düzeyini ve yaşam kalitesini yükseltmektedir.

Araştırma, "Nöromimari prensiplerinin kamusal mekânların tasarımında uygulanması, kullanıcıların mekân algılarını ve davranışlarını nasıl etkilemektedir?" sorusuna da yanıt aramaktadır. Araştırma bulguları, nöromimari prensiplerin Rami Kütüphanesi’nde etkin şekilde kullanıldığı noktalarda, kullanıcıların mekân algılarını ve davranışlarını olumlu yönde etkilediğini ortaya koymuştur. Alan çalışmasında, kullanıcıların mekânsal algılarının nöromimari kriterlere uygun olarak tasarlanmış alanlarda daha olumlu olduğu ve bu mekanlarda daha fazla zaman geçirdikleri tespit edilmiştir. Mekânın ferahlığını artıran düzenlemeler, doğayla bütünleşmiş alanlar ve ergonomik tasarlanan unsurlar, kullanıcıların mekanla ilgili algılarını olumlu yönde şekillendirmiştir. Bu olumlu algılar, kullanıcıların mekân içinde daha konforlu ve güvenli hissetmelerine, mekânı estetik algılamalarına dolayısıyla mekanla daha yoğun ve pozitif etkileşimlerde bulunmalarına yol açmıştır. Ayrıca, bu tür tasarımların sosyal etkileşimi teşvik ettiği, bireylerin daha fazla sosyalleştiği ve topluluk hissinin güçlendiği gözlemlenmiştir. Kullanıcıların Rami Kütüphanesi peyzaj alanında geçirdikleri süre boyunca sergiledikleri davranışlar, nöromimari prensiplerin uygulandığı kamusal mekanların, bireylerin hem kişisel hem de sosyal davranışlarını olumlu yönde etkilediğini doğrulamaktadır.

Rami Kütüphanesi peyzaj alanı tasarımının nöromimari kriterlere tam anlamıyla uygunluk göstermediği tespit edilmiş olup, hem güçlü hem de zayıf yönlere sahip olduğu görülmektedir. Tasarım, kullanıcıların mekânsal algılarını ve sosyal etkileşimlerini olumlu yönde destekleyen çeşitli unsurlar barındırsa da, termal konfor açısından eksiklikler içermektedir. Özellikle açık alanlarda güneş kırıcı elemanların eksikliği, kullanıcıların alanı yaz aylarında yoğun güneş ışığına maruz kalmadan deneyimlemelerini zorlaştırmakta ve mekânsal sürekliliği olumsuz etkilemektedir. Bu bağlamda, termal konfor ilkesinin dikkate alınmasına yönelik olarak gölgelik alanların artırılması, soğuk hava koşullarında kullanıcı deneyimini iyileştirmek amacıyla kapalı veya yarı kapalı dinlenme alanlarının tasarlanması, peyzaj alanının her mevsimde kullanıcı dostu bir şekilde işlev görmesini sağlayacaktır. Bu tür müdahalelerin kullanıcı memnuniyetini artıracağı, kullanıcıların mekan algılarını ve davranışlarını olumlu yönde etkileyeceği düşünülmektedir.

Bu çalışmada Rami Kütüphanesi peyzaj tasarımı, yaz mevsimindeki gözlemler doğrultusunda değerlendirilmiştir. İlerleyen dönemlerde farklı mevsimlerde ve koşullarda yapılacak kapsamlı araştırmalar, hem tasarımın insan üzerindeki etkilerinin hem de kullanıcı deneyimlerinin daha bütüncül bir şekilde anlaşılmasına katkı sağlayacaktır. İlerleyen çalışmalarda, EEG, fMRI, göz takibi gibi yöntemlerin kullanımı, kamusal mekan tasarımlarının insanlar üzerindeki nörolojik ve psikolojik etkilerinin daha iyi anlaşılabilmesi adına büyük bir önem taşımaktadır. Literatürde, bu tür tekniklerin bireylerin bilişsel ve duygusal tepkilerini objektif olarak ölçmekte önemli bir rol oynadığı vurgulanmaktadır. Bununla birlikte, bu çalışmada, Rami Kütüphanesi peyzaj tasarımının fiziksel elemanları ve kullanıcıların mekân içerisindeki deneyimleri gözlem yöntemiyle ele alınmış ve nöromimari kriterlere uygunluğunun algısal açıdan değerlendirilmesi yapılmıştır. Çalışma, nöromimari perspektiften kamusal alan tasarımının insanlar üzerindeki etkilerine odaklanarak, belirlenen kriterlerin fiziksel çevre ile kullanıcı deneyimleri arasındaki ilişkiyi nasıl şekillendirdiğini ortaya koymayı amaçlamıştır. Bu çalışmanın sınırlılığı EEG, fMRI, HRV gibi nörobilimsel yöntemlerin kullanılmamış olmasıdır. Gelecek araştırmalarda, gözlemlerin ve kullanıcı deneyimlerinin, bu gibi ölçüm teknikleriyle desteklenmesi, nöromimari tasarım kriterlerinin kullanıcı odaklı tasarım süreçlerine daha güçlü bir şekilde entegre edilmesine katkı sağlayacaktır.

7. Sonuç

Nöromimari, mimari tasarımın insan beyninin işleyişine, duyusal algılarına ve davranışlarına nasıl etki ettiğini anlamak amacı taşıyan bir disiplindir. Yapılı çevre içerisinde kullanıcının davranış biçimlerini nöral aktivite ölçümlerine dayandırarak, insan odaklı tasarım parametrelerini belirlemek nöromimarinin kapsamını oluşturmaktadır. Nöromimari, yapı tasarımında insan merkezli, işlevsel ve duyarlı yaklaşımların geliştirilmesine katkı sağlamaktadır.

Kamusal alanlar, mimari tasarımları aracılığıyla insan zihninde kapsamlı bir duyusal deneyim sunarak, ziyaretçilerde iç huzuru, dinginliği, motivasyonu, katılımı ve hayranlığı harekete geçirebilmektedir. Bu alanlar, görsel estetikleri, akustik özellikleri, doku ve malzeme seçimleri ile sadece görmeyi değil, aynı zamanda duymayı, dokunmayı, koku almayı ve hatta tatmayı içeren yedi duyu üzerinde etki bırakabilmektedir. Ziyaretçilerin duygusal ve zihinsel refahları, kamusal alanların düşünülmüş detayları aracılığıyla, olumlu yönde etkilenebilmektedir.

Rami Kütüphanesi peyzaj alanının nöromimari özelliklerinin incelenmesi, kamusal alan tasarımının insan deneyimi üzerindeki etkilerini anlamak için atılmış bir adımdır. Araştırıma sonuçlarına göre kamusal mekanların etkili bir şekilde tasarlanabilmesi için tasarım süreçlerinde nöromimari prensiplerin kullanımı, kullanıcılarda zihinsel ve fiziksel açıdan olumlu etki uyandırmak amacıyla önemli bir role sahiptir. Araştırma bulguları, nöromimari prensiplerin kamusal mekanlarda kullanımının kullanıcıların mekânsal deneyimlerini, zihinsel ve duygusal refahını, davranışlarını olumlu yönde etkilediğini göstermiştir. Bu çalışmanın, tasarımcılar için kamusal mekân tasarımında daha bilinçli, etkili ve anlamlı kararlar alabilmeleri için kaynak olacağı düşünülmektedir. Kamusal alanların nöromimari açıdan incelenmesi, insanların bu mekanlarla etkileşime geçerken nasıl hissettiklerini, düşündüklerini ve tepki verdiklerini anlamak için bir pencere sunmaktadır. Bu bağlamda, nöromimari prensipler üzerine yapılacak yeni çalışmalar, kamusal mekânların insan refahı ve toplumsal bağların güçlendirilmesi açısından nasıl daha etkili hale getirilebileceğine dair önemli veriler sağlayacaktır. Rami Kütüphanesi peyzaj alanı tasarımında kullanılan unsurların insan zihni ve davranışı üzerindeki potansiyel etkilerini anlamanın, gelecekteki peyzaj projelerinin daha insan merkezli ve sürdürülebilir olmasına katkı sağlayacağı düşünülmektedir.

Mimarlar mekân tasarımlarında işlevsellik ile kullanıcı odaklı yaklaşımlar arasında bir denge kurmaya çalışmaktadırlar. Tasarımın işlevselliği, kullanıcı ihtiyaçlarını karşılamak ve mekânla daha derin bir bağ kurmalarını sağlamak amacıyla düşünülmektedir. Bu bağlamda kamusal alanlar, sadece işlevsel mekânlar olmanın ötesinde, sosyal katılımı teşvik eden, kullanıcıların duygusal ve zihinsel ihtiyaçlarını karşılayan alanlar olarak ele alınmalıdır. Nöromimari tasarım prensipleri yardımıyla bahsedilen unsurları destekleyen mimari çözümler, insanların mekanlarla daha derin bir bağ kurmalarına ve ruhsal refahlarını artırmalarına katkıda bulunmaktadır. Mimarların tasarımlarında estetik, konfor ve insanın ruhsal sağlığına yönelik unsurları dikkate alması, mekânların yalnızca işlevselliği değil, duygusal ve zihinsel boyutları da desteklemesini mümkün kılmaktadır. Bu tasarım yaklaşımı ile kamusal alanlar sadece fiziksel ihtiyaçları karşılayan yerler olmanın ötesine geçerek, kullanıcıların zihinsel ve ruhsal sağlığına katkıda bulunan, onların yaşam kalitesini artıran mekânlar haline dönüşmektedir.

Bu çalışma, nöromimari ve kamusal alan tasarımı arasındaki ilişkinin anlaşılmasına yönelik bir başlangıç sağlamış olup, gelecekte bu alanda yapılacak çalışmalara katkı sağlayacağı düşünülmektedir., Farklı mevsim koşullarında, çeşitli kamusal alanlarda ve farklı kültürel bağlamlarda nöromimari prensiplerin uygulanmasının etkilerini inceleyen çalışmaların gerçekleştirilmesi, bu alanda bilgi birikimini artıracaktır. Ayrıca, EEG (elektroensefalografi), fMRI (fonksiyonel manyetik rezonans görüntüleme), GSR (galvanik deri tepkisi), HRV (kalp atış hızı değişkenliği) gibi ölçüm tekniklerinin kullanıldığı araştırmalar, bireylerin mekânsal deneyimlerini daha ayrıntılı bir şekilde analiz etmeye olanak tanıyarak, tasarım süreçlerinin bilimsel temellere dayandırılmasını sağlayacaktır. Araştırmanın sonuçları kamusal alan tasarımında insan odaklı yaklaşımların geliştirilmesi ve nöromimari perspektiften daha etkili tasarım kararlarının alınması için yol gösterici bir rehber oluşturmaktadır.

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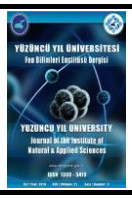
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Araştırma Makalesi

İzmir İli Pamuk Alanlarında Görülen Zararlı ve Faydalı Akarların Popülasyon Gelişimi

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Öz: Bu çalışma, İzmir ili, Menemen ve Bergama ilçelerindeki pamuk ekim alanlarında, 2019-2020 yılları arasında yürütülmüştür. Çalışmalar her iki ilçeden 6'şar adet olmak üzere, toplamda 12 pamuk tarlasında haftalık örneklemeler yapılarak tamamlanmıştır. Çalışmalar sonucunda zararlı olarak *Tetrancyhus urticae* Koch (Acari: Tetranychidae)'nin kırmızı formunun pamuk tarlalarında baskın tür olduğu görülmüştür. İki noktalı kırmızıörümcek *T. urticae*'nin, haziran ayı ilk haftası ile birlikte popülasyonu artmaya başlamış ve haziran ayının ilk yarısında popülasyon tepe noktasına ulaşmıştır. Bu dönemde zararlıya karşı yapılan yoğun pestisit uygulamalarının avcıları baskı altına alması sonucu, *T. urticae*'nin popülasyonunu artış gösterdiği belirlenmiştir. Pamuk ekim alanlarında Coccinellidae, Chrysopidae, Nabidae, Thripidae ve Aelothripidae familyalarına ait avcı böcek türleri ile Phytoseiidae familyasına ait avcı akar türlerine ait bireyler saptanmıştır. Phytoseiidae familyasına bağlı türlerden %78 bulunma oranı ile en yaygın tür *Phytoseiulus persimilis* (Athias/Henriot) (Acari: Phytoseiidae) olarak belirlenmiştir. Ayrıca pamuk alanlarında, avcı türlerin, pestisit uygulamasının yapılmadığı Ağustos sonu ve Eylül ayı başlarında avcı türlerin *T. urticae* popülasyonunu kontrol altına almayı başardığı gözlenmiştir.

Anahtar Kelimeler: İzmir, Pamuk, Phytoseiidae, Popülasyon gelişimi, *Tetranychus urticae*

The Population Development of Pest and Predatör Mites Observed in Cotton Fields of İzmir Province

Abstract: This study was carried out in cotton fields in Menemen and Bergama districts of İzmir Province between 2019-2020. The studies were completed by weekly sampling in a total of 12 cotton fields, 6 from each district. As a result of the studies, it was observed that the red form of *Tetrancyhus urticae* Koch (Acari: Tetranychidae) was the dominant species in the cotton fields. The population of the two-spotted red spider *T. urticae* started to increase in the first week of June and the population reached its peak in the first half of June. It was observed that the intensive pesticide applications made against the pest during these dates increased the population of *T. urticae* as a result of suppressing the predators. Species belonging to the families Coccinellidae, Chrysopidae, Nabidae, Thripidae and Aelothripidae from beneficial insects and individuals belonging to the family Phytoseiidae from predatory mites were determined in the trial areas. Among the species belonging to the Phytoseiidae family, the most abundant species with a 78% prevalence rate was determined as *Phytoseiulus persimilis* (Athias/Henriot) (Acari: Phytoseiidae). It was also observed that in cotton fields, predator species managed to control the *T. urticae* population in late August and September when pesticide application was not made.

Keywords: Cotton, İzmir, Phytoseiidae, Population development, *Tetranychus urticae*

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1. Giriş

Pamuk (*Gossypium hirsitum* L.), insanların hem yaşamlarında yoğun olarak kullanımları ile hem de yarattığı iş imkanları nedeni ile ekonomik öneme sahip önemli bir üründür. Pamuk, lif üretimi nedeni ile tekstil sektörünün, çekirdeğindeki yağı nedeni ile yağ ve yem sanayisinin, linteri yönünden de kağıt sanayisinin hammaddesidir (Anonim, 2020a). Türkiye, 2019-2020 pamuk üretim döneminde, dünya pamuk üretiminde altıncı, birim alandan elde edilen verimde beşinci, tüketimde altıncı, ithalatta ise dördüncü sıradadır (Anonim, 2020b). 2019 yılında Güneydoğu Anadolu Bölgesi, tüm pamuk ekim alanları içindeki oranı % 60 olurken, Çukurova % 20, Ege Bölgesi'nin ise oranı % 19 olmuştur (TÜİK, 2020). 2019 yılı itibarı ile ülkemiz pamuk üretiminin %85'i, Şanlıurfa (%37), Aydın (%11), Hatay (%10), Diyarbakır (%11), Adana (%9) ve İzmir (% 6) illerinde üretilmiş ve bu iller en fazla üretim yapan 6 il olmuştur (TÜİK, 2020).

Ülkemiz pamuk üretiminde ise İzmir, oldukça geniş bir alana sahiptir ve 2019 yılında 252.945 da alanda ekim yapılmış, 141.920 ton ürün hasat edilmiş ve bundan 561 kg/da verim elde edilmiştir. İzmir ilinde pamuk üretiminin en yüksek olduğu ilçeler ise Menemen (82.129 da) ve Bergama (79.169 da) ilçeleri olmuştur (TÜİK, 2020). Pamuk üretiminde diğer etmenlerin yanında hastalık ve zararlıların neden olduğu verim kayıplarından dolayı üretim azalmaktadır. Zararlılar içerisinde ise Acari takımı içerisindeki Tetranychidae familyasına bağlı türler oldukça önemli bir konuma sahiptirler ve pamuğun gelişmesini, verimi ve ürün kalitesini bozarak pazar değerini düşürmektedirler (Sulek ve Cakmak, 2022; Sulek et al., 2023; Yüksel et al., 2024). Ülkemizdeki pamuk ekim alanlarında, *Tetranychus cinnabarinus* Boisduval. 1867 ve *Tetranychus urticae* Koch. 1836 (Acari. Tetranychidae) olmak üzere arak iki kırmızıörümcek türü baskın olarak bulunmaktadır. Doğu Akdeniz Bölgesi pamuk üretim anlarında pamuk kırmızıörümceği, Ege ve Güneydoğu Anadolu Bölgeleri'nde ise iki noktalı kırmızıörümcek hakim türdür (Mart, 2017). *T. urticae* daha önceleri *T. cinnabarinus*'tan ayrı bir tür olarak belirtilmiş ancak günümüzde *T. cinnabarinus*'u içine alan kompleks bir tür olarak ele alınmaktadır (Seeman & Beard, 2011). Doğal dengenin korunduğu ya da geniş etkili tarımsal savaş ilaçlarının kullanılmadığı tarım alanlarında bu akarların sorun olmadığı, popülasyon yoğunluğunun düşük seviyelerde kaldığı bilinmektedir. Zararlı akarların bu alanlarda kontrol altında tutulmasında en önemli etken ise avcı akarlardır (Jeppson et al., 1975; Şekeroğlu, 1984; Kasap & Çobanoğlu, 2007; Tiftikçi et al., 2022; Yaşar et al., 2024). Avcı akarlar içerisinde Phytoseiidae familyasında yer alan türler, kırmızıörümceklerin en önemli avcıları olarak bilinirler. İkinci Dünya savaşı sonrası, zararlı organizmalar ile savaşımda pestisit kullanımı ilk başvurulan mücadele yöntemi olarak düşünülmekteydi. Ancak, pestisitlerin, çevreye verdiği zarar, mevcut zararlıların pestisitlere karşı dayanıklılık kazanması ve geniş etkili tarımsal savaş ilaçlarının kullanımı doğal düşmanların popülasyonlarını azaltmaktadır. *T. urticae* yumurtalarının pestisitlere karşı daha az zarar görmesi, akarın hızlı üremesi ve zararlının insektisitlere karşı dayanıklılık kazanması, ilaçlamalardan sonra azalan avcı popülasyonu nedeni ile yoğun pestisit uygulamaları kırmızıörümceklerin popülasyon yoğunluğunun artmasına neden olmaktadır. Bu nedenle bu çalışmada, İzmir ili pamuk alanlarında bulunan fitofag akar türlerinin popülasyon değişiminin belirlenmesi ve kırmızıörümcek popülasyonu üzerinde etkili olan predatör akar türlerinin etkinliğinin saptaması amaçlanmıştır.

2. Materyal ve Yöntem

Çalışmanın ana materyalini; İzmir ili Menemen ve Bergama ilçelerindeki pamuk alanları, zararlı ve yararlı akar türlerinin biyolojik dönemleri ve predatör böcekler ile arazi ve laboratuvarda kullanılan malzemeler oluşturmuştur. Arazi çalışmaları 2019-2020 yılları arasında pamuk üretim sezonunda İzmir İli, Menemen (6 pamuk tarlası) ve Bergama (6 pamuk tarlası) ilçeleri sınırlarındaki toplam 12 pamuk tarlasında gerçekleştirilmiştir. Pamuk bitkisinde bulunan zararlı akar türlerini ve popülasyon değişimini belirlemek amacıyla İzmir ilinin pamuk üretimi yapılan Menemen ve Bergama ilçelerine haftada bir kez gidilmiştir. Çalışmalara bitkinin dört gerçek yaprağa ulaştığı Mayıs ayı itibarı ile başlanmış, Ekime kadar haftalık örneklemeler ile kırmızıörümcek popülasyonu takip edilmiştir. Çalışmalarda Menemen ilçesinin 3 farklı mahallesinden (Kesik 2, Tuzçullu 2 ve Maltepe 2) ve Bergama ilçesinin de 3 farklı mahallesinden (Aşağıkırıklar 2, Süleymanlı 2, Göçbeyli 2) ve her mahalleden ikişer tarlada olmak üzere Menemen ilçesinde 6; Bergama ilçesinde 6 tarlada olmak üzere toplam 12 tarlada çalışmalar yürütülmüştür. Akar örnekleri tarlayı temsil edecek şekilde her bir tarladan 50 adet yaprak örneği

alınarak, kese kağıtlarına yerleştirilmiş, üzerine örneğin alındığı ilçe, köy, tarih ve tarla numarası yazılarak naylon poşete konup, buz kutusu içerisinde laboratuvara getirilmiştir. Alınan yaprak örnekleri sayımları yapılana kadar +4°C'deki buzdolabına yerleştirilmiş ve daha sonra akarların yumurta, ergin öncesi ve ergin dönemleri olmak üzere sayımları yapılmıştır. Ancak grafik ve yorumlarda değerler toplam birey üzerinden değerlendirilmiştir. Pamuk bitkisinde predatör akarların belirlenmesi amacıyla; Menemen ve Bergama ilçelerinden popülasyon değişimlerinin saptandığı tarlalar hariç en az 5 farklı pamuk alanından toplam 100 yaprak tesadüfen toplanmıştır. Yaprak üzerindeki yararlı akarlar binoküler mikroskop altında kontrol edilerek yaprak üzerindeki akar örnekleri %70'lik etil alkole alınarak temizlenmesi sağlanmış ve daha sonra preparasyon işlemleri (Düzgüneş, 1980) ve teşhis çalışmaları yapılmıştır. Teşhisleri yapılamayan akar türlerinin tanıları Doç. Dr. İsmail DÖKER (Çukurova Üniversitesi) ile yapılmıştır.

3. Bulgular

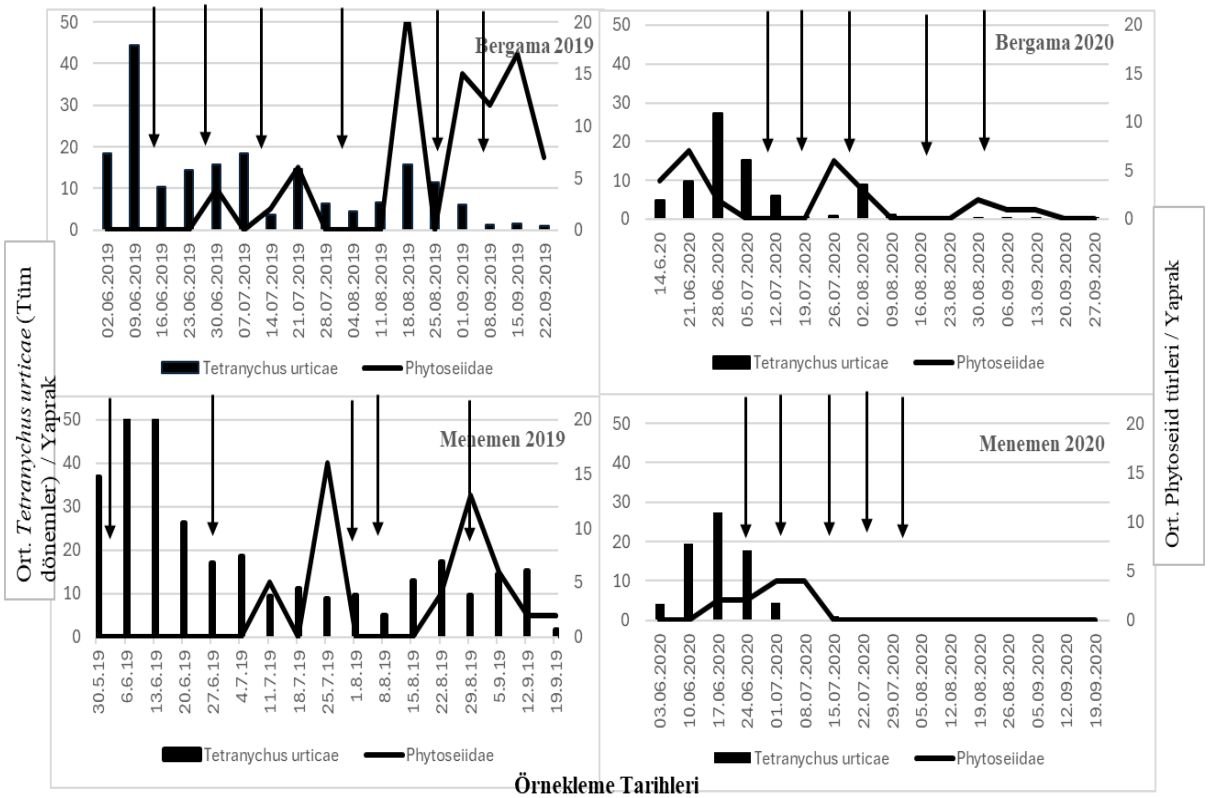
İzmir ili pamuk alanlarında bulunan fitofag akar türlerinin ve bunlar üzerinde beslenen avcı türlerin popülasyon değişiminin belirlenmesi amacı ile yapılan çalışmalar sonucunda, İzmir ili Menemen ve Bergama ilçelerindeki pamuk alanlarında zararlı akar türleri içerisinde iki noktalı kırmızıörümcek *T. urticae* (Acari: Tetranychidae) (kırmızı form)'nin baskın tür olduğu belirlenmiştir. Bu zararlı ile birlikte bulunan faydalı türlerden, Phytoseiidae familyası türleri içinde %78 bulunma sıklığı ile en yaygın tür olarak *Phytoseiulus persimilis* Athias-Henriot olurken, bu türü %17 bulunma sıklığı ile *Neoseiulus californicus* (McGregor) ve %5 bulunma sıklığıyla *Neoseiulus barkeri* Hughes izlemiştir. *P. persimilis*, kırmızıörümceklere özelleşmiş bir avcı akardır ve tüm dünyada kırmızıörümceklerin en etkin avcısı olarak bilinmektedir. Bu avcı akarın, İzmir ili pamuk üretiminin en yoğun olarak yapıldığı Menemen ve Bergama ilçelerindeki alanlarda saptanması zararlı akarların biyolojik mücadele imkanları açısından oldukça önemlidir.

2019 yılı üretim sezonu içerisinde, 30 Mayıs tarihinde Menemen ilçesinde yapılan örneklemelerde *T. urticae* popülasyonu görülmeye başlamış ve bu tarihlerde yaprak başına ortalama 36.88/akar ile zararlı popülasyon oluşturmaya başlamıştır. 02.06.2019 tarihinde Bergama pamuk alanlarında yapılan gözlemlerde ise *T. urticae* popülasyonu yaprak başına ortalama 18.52/akar olarak belirlenmiştir. Bu tarihlerden sonra zararlının popülasyonu sırası ile Bergama ilçesinde yaprak başına ortalama 44.42 ve Menemen ilçesinde ise 52.37/akar ile en yüksek yoğunluğa ulaştığı saptanmıştır. Daha sonra yapılan gözlemlerde ise ilaçlamaların da etkisi ile zararlı popülasyonunun azalarak sezon süresince devam ettiği gözlenmiştir (Şekil 1). Üretim sezonu içerisinde Bergama ilçesinde yapılan 6 pestisit uygulamasının da etkisi ile avcı akarlar popülasyon oluşturamamıştır. Ancak sezon sonuna doğru Bergama ilçesinde yaprak başına ortalama 21/akar ve Menemen ilçesinde ise 16/akar seviyesine ulaşabilmiştir (Şekil 1).

2020 yılında yapılan çalışmalarda ise 3 Haziran tarihinde Menemen ilçesinde yapılan gözlemlerde yaprak başına ortalama 4.08/akar ile *T. urticae*'nin popülasyonu görülmeye başlamıştır. Bergama pamuk alanlarında ise 21 Haziran tarihinde yapılan gözlemlerde *T. urticae* popülasyonu yaprak başına ortalama 4.71/akar olarak belirlenmiştir. Haziran sonuna doğru yapılan gözlemlerde ise zararlının popülasyonu Bergama ilçesinde yaprak başına ortalama 27.24/akar ve Menemen ilçesinde ise 27.46/akar ile en yüksek yoğunluğa ulaşmıştır. 2020 yılında da pamuk alanlarında farklı tarihlerde yapılan 5 farklı pestisit uygulamasının etkisi ile zararlı popülasyonunun azalarak sezon sonuna kadar devam ettiği görülmüştür (Şekil 1). 2020 yılı üretim sezonu süresince avcı akarlar popülasyon yoğunluğu ise Bergama ilçesinde yaprak başına ortalama 6/akar ve Menemen ilçesinde ise 4/akar seviyesine ulaşabilmiştir (Şekil 1).

Çalışmalar sonucunda İzmir ili Menemen ve Bergama ilçelerindeki pamuk alanlarında zararlı akar türleri içerisinde iki noktalı kırmızıörümcek *T. urticae* (kırmızı form)'nin baskın tür olduğu ve örneklemeler süresince yoğun bir popülasyon oluşturduğu belirlenmiştir. Ayata (2015) Şanlıurfa ili pamuk alanlarında yaptığı çalışmalarda *T. urticae*'nin örnekleme yapılan bütün ilçelerde yaygın olarak bulunduğunu ilçelere bağlı olarak yaprak başına ortalama 0.005 ile 4.09 akar/yaprak arasında değişen oranlarda popülasyon oluşturabildiğini bildirmiştir. *T. urticae*, dünya genelinde en fazla aktif maddeye karşı direnç geliştirilen tür olarak bilinmektedir (Van Leeuwen et al., 2010) ve "direnç şampiyonu" olarak tanımlanmaktadır (Dermauw et al., 2013). Pamuk sezonu boyunca yapılan gözlemlerde, kırmızıörümceklerle mücadelede üreticilerin yoğun olarak kimyasal savaşıma başvurduğu görülmüştür

(2019 yılında 6 ve 2020 yılında 5 pestisit uygulaması). Kırmızıörümceklerin döl süresinin kısa olması, gelişme sürelerinin hızlı olması ile ve ayrıca kullanılan pestisitlerden, çeşitli nedenlerle yumurtaların daha az zarar görmesi sonucu bu zararlılara karşı yapılan kimyasal mücadelede yeterince başarılı olunamadığı bilinmektedir (Shih et al., 1976). *T. cinnabarinus*' un popülasyonunu kontrol edebilmek için, zararlının popülasyon gelişimi takip edilerek, koruyucu amaçlı olarak uygun zamanlarda ve dönemlerde yapılacak bir kimyasal mücadele, zararlının gelişimini yavaşlatabileceği bildirilmektedir (Çakmak et al., 2005). Kullanılacak pestisitlerin ise geniş etkili olmayan, seçici ve kontak etkili akarisitler olarak seçilmeli, doğal düşmanların yoğun olduğu durumlarda ise zorunlu olmadığı halde pestisit kullanımına başvurulmamalıdır (Akyazı & Ecevit, 2005). İzmir ili pamuk üretiminin en yoğun olarak yapıldığı Menemen ve Bergama ilçelerindeki alanlarda, *P. persimilis*'in saptanması zararlı akarların biyolojik mücadele imkanları açısından oldukça önemlidir. Phytoseiid türler içerisinde *P. persimilis*, diğer türlere göre kırmızıörümceklere özelleşmiş bir avcı olması nedeni ile biyolojik savaşımda tercih edilen bir predatör akar türüdür (Jarasik, 1990; Zhang & Sanderson, 1995; Viss & Barrera, 1997). Bu çalışmalarda 2019 yılında zararlı popülasyonunun en düşük olduğu ve kimyasal uygulamalarının yapılmadığı Ağustos ayı sonu ve Eylül başlarında, *P. persimilis*'in sezon içerisindeki en yüksek popülasyon yoğunluğuna ulaşarak zararlı üzerinde baskı oluşturduğu gözlenmiştir. Yoğun pestisit kullanımı, zararlı türlerin popülasyonlarının devam etmesinin yanı sıra yararlı popülasyonlarını baskı altına alarak olumsuz sonuçların ortaya çıkmasına neden olmaktadır (Osborne et al., 1999; Guo et al., 1998).



Şekil 1. 2019-2020 yılları İzmir ili pamuk alanlarında *Tetranychus urticae* ve Phytoseiidae türlerinin popülasyon değişimi (↓ ilaç uygulamaları).

4. Tartışma ve Sonuç

Bu çalışmada saptanan sonuçlara baktığımız zaman, İzmir ili pamuk üretim alanlarının oldukça geniş olmasından dolayı, *T. urticae* ile mücadelede gelişigüzel ve yoğun olarak kullanılan pestisitler hem üreticiye olan maliyeti hem de doğayı tahrip ederek geriye dönülemez zararlar verebilmektedir. Bu nedenlerle pamuk alanlarındaki akar türlerinin belirlenerek, zararlıların popülasyonlarının yükseldiği dönemlerde uygun mücadele yöntemleri ile de destekleyerek biyolojik mücadeleye yönelmek ve bu

faydalı türleri koruyarak desteklemek zararlılarla yapılacak mücadele çalışmalarında oldukça önemli ve başarılı olacaktır.

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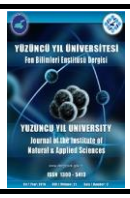
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Araştırma Makalesi

Microcystis aeruginosa ve Biyokömür Uygulamalarının Buğday Rizosferindeki Bazı Enzimler ve Temel Gelişme Özelliklerine Etkileri

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Öz: *Microcystis aeruginosa* ve biyokömür uygulamalarının buğdayın rizosfer bölgesindeki bazı toprak enzimleri üzerine ve temel bitki büyüme özelliklerine etkileri incelenmiştir. Araştırma serada tesadüf parselleri faktöryel deneme desenine göre 3 tekrarlı olarak yürütülmüştür. Biyokömürün üç dozu (kontrol, % 1, % 2), *M. aeruginosa*'nın 4 dozu (kontrol, % 0.5, %1 ve % 1.5) kullanılmıştır. Biyokömür ekimle birlikte, *M. aeruginosa* ise çimlenme sonrası topraklara uygulanmıştır. Hasat ekimden 60 gün sonra yapılmıştır. Uygulamalar incelenen özellikler üzerinde farklılık göstermiştir. En fazla yeşil aksam ağırlığı %2 biyokömür uygulamasından elde edilirken, kök ağırlığı en yüksek %2 biyokömür x %0.5 *M. aeruginosa* uygulamasında belirlenmiştir. Biyokömürün %2 x *M. aeruginosa* %1'in birlikte uygulanması ile en yüksek bitki boyu, %2 biyokömür x %1.5 *M. aeruginosa* uygulaması ile en yüksek kök uzunluğu elde edilmiştir. Uygulamalar yaprakların klorofil içeriklerini kontrole göre artırmıştır. Rizosferdeki en yüksek β-glukosidaz, alkalin fosfataz ve dehidrogenaz aktivitesi biyokömür %2 x *M. aeruginosa* %1.5 uygulamalarında belirlenmiştir.

Anahtar Kelimeler: Biyokömür, Buğday, Doz, *M. aeruginosa*, Rizosfer

Effects of Microcystis aeruginosa and Biochar Treatments on Some Enzymes and Basic Growth Characteristics in Wheat Rhizosphere

Abstract: The effects of *Microcystis aeruginosa* and biochar treatments on some soil enzymes and basic plant growth characteristics in the rhizosphere of wheat were investigated. The experiment was conducted in the greenhouse according to the random factorial plots experimental design with 3 replications. Three doses of biochar (control, 1%, 2%) and 4 doses of *M. aeruginosa* (control, 0.5%, 1% and 1.5%) were used. Biochar was applied at sowing and *M. aeruginosa* was applied to the soil after germination. Harvesting was done 60 days after sowing. The treatments showed differences on the studied traits. While the highest green part weight was obtained from 2% biochar treatment, the highest root weight was determined in 2% biochar x 0.5% *M. aeruginosa* treatment. The highest plant height was obtained with 2% biochar x 1% *M. aeruginosa* and the highest root length was obtained with 2% biochar x 1.5% *M. aeruginosa*. The treatments increased the chlorophyll content of the leaves compared to the control. The highest β-glucosidase, alkaline phosphatase, dehydrogenase activities in the rhizosphere were determined in biochar 2% x *M. aeruginosa* 1.5% treatment.

Keyword: Biochar, Dose, *M. aeruginosa*, Rhizosphere, Wheat

1. Giriş

Mevcut tarımsal uygulamalar hem bitki büyüme uyarıcılarını hem de bitkileri farklı stres koşullarından koruma için gübreler ve pestisitler gibi sentetik kimyasalların uygulanmasına bağımlı olup, halkın gıda ihtiyacını karşılamasını kolaylaştırmıştır (Ashour ve ark., 2023; Hassan ve ark., 2021). Oysa, tarımda kimyasalların tekrar eden kullanımları bitkilerde ve toprakta birikerek, insanlar için tehlikeli olabilecek zararlı ürünlerin çevreye salınmasına neden olmuştur (Pan ve ark., 2019). Örneğin, azotlu gübrenin yaklaşık %50'si bitkiler tarafından kullanılmakta, kalan %50'sinin ise yüzey sularına karıştığı açıklanmıştır (Abo-Shady ve ark., 2023). Bu nedenle, nüfusun gıda gereksinimlerini

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sınırlı kaynaklarla ve çevre kalitesini kötüleştirmeden karşılamak büyük bir zorunluluk olarak karşımıza çıkmaktadır (Nawaz ve ark., 2024; Parmar ve ark., 2023).

Siyanobakteriler, çevre dostu olup, düşük maliyetli üretimleriyle tarım uygulamalarında ideal bir çözümdür. Binlerce yıl önce, siyanobakteriyel biyokütle tarımda yaygın olarak kullanılmış, günümüzde ise siyanobakteriyel özütlerden elde edilen yararlı ürünlerin artması dünya çapında araştırıcıların dikkatini çekmiştir (Kumar ve ark., 2022). Araştırıcılar, bitki koruma etmeni olarak ve biyo-uyarıcı potansiyelleri açısından değerlendirilen siyanobakteriler gibi biyolojik bazlı ürünlere odaklanmışlardır (Gorka ve ark., 2018). Siyanobakteriler ve yeşil alglerle yapılan biyogübrelemenin, asma çeliklerinin köklenmesini ve ayçiçeği tohumlarının çimlenmesini artırabildiği; çeltik, arpa, yulaf, domates, turp, pamuk, mısır, biber, marul, buğday, asma ve mısırda gözlemlendiği gibi bitki büyümesini iyileştirebildiği belirtilmiştir (Grzesik & Romanowska-Duda, 2015). Bitkilerin artan büyümesinin; mikroalglerin toprağın doğal besin döngülerini geri kazandırma, toprak organik maddesini oluşturma ve ayrıca bitkilerin gelişimine etkili olan çeşitli besinler, hormonlar ve ikincil metabolitlerce toprağı zenginleştirme yeteneğinden kaynaklanabileceği öne sürülmüştür (Abo-Shady ve ark., 2023). Siyanobakteriyel patlamalar, küresel ölçekte önemli bir çevresel sorun olarak ortaya çıkmış sucul ötrofikasyon ve iklim değişikliği alg patlamalarına neden olmuştur (Monchamp ve ark., 2018). Sularda oluşan alg patlamaları ve ilişkili doğal toksinlerin salınımı insan aktivitelerinden ve iklim değişikliğinden kaynaklanan aşırı besin yüklenmesi nedeniyle son yıllarda artış göstermiştir (Li ve ark., 2023). *Microcystis aeruginosa (*Kützing) Kützing 1846 (*M.aeruginosa*), *Microcystis* cinsine ait bir alg türü olup, düşük ışık koşullarında gelişmesini sağlayan benzersiz bir fikobiliprotein sistemine sahiptir ve bazı izolatları su kalitesinin bozulmasına neden olmaktadır (Li ve ark., 2023). Bu mavi-yeşil alglerin bazı izolatları çeşitli kirleticileri azaltma yeteneğine sahiptir ve potansiyel olarak biyolojik olarak parçalayıcı organizmalar olduğu tespit edilmiştir (Shashirekha ve ark., 1997). Ayrıca bitki büyümesi ve verimi arttırmada da kullanılmıştır (Grzesik ve ark., 2017). Siyanobakteriler, bitki büyümesini ve ürün verimini artırmak için biyogübre olarak çeşitli tarımsal ürünlere kullanılmıştır (Abo-Shady ve ark., 2023). Siyanobakteriler; bitkilerin azot eksikliği olan topraklarda büyümesine yardımcı olduğundan kirlilik kaynağı olan ve maliyeti yüksek azot gübreleri kullanma ihtiyacını ortadan kaldırdığı belirlenmiştir (Li ve ark. 2019). Osman ve ark. (2020) bakla tohumlarının *Nostoc muscorum* ile muamelesinin; kök uzunluğu (%30), bitki boyu (%44), kök yaş ağırlığı (2 kat), yeşil aksam yaş ağırlığı (1.5 kat), kök kuru ağırlığı (%67) ve yeşil aksam kuru ağırlığı (1.6 kat) gibi büyüme parametrelerini artırmıştır. Mutale-Joan ve ark. (2020), *Aphanothece* sp. uygulamasının bitkinin kök ve yeşil aksam uzunluklarını %112.65 ve %53.70 oranında önemli ölçüde artırğını tespit etmişlerdir. Benzer olarak, *Arthrospira platensis* ve *Nostoc muscorum*'un sıvı özütlerinin buğday tohumlarına uygulanmasıyla, buğday büyümesinin uyarılmasına ve çeşitli büyüme parametrelerinde iyileşmeye neden olduğu bildirilmiştir (Osman ve ark., 2021). Araştırıcılar ayrıca buğday fidelerinde pigmentlerin, karbonhidratlar ve protein içeriklerinin kontrole göre arttığını da saptamışlardır. *A.platensis*'in domates ve biberlere yaprak püskürtme yoluyla uygulanması ile her iki bitki türünde de yeşil aksam kuru ağırlığı 1.4 kat artmış, kök ağırlığı üzerindeki olumlu etkileri domateslerde 2.30 kat, biberlerde %67 oranında artmıştır (Elarroussi ve ark. 2016). Biyokömür ve mikroorganizmaların entegre uygulaması, toprağın organik karbon içeriğini artırmış, bitki büyümesini ve üretkenliğini destekleyen toprağın fizikokimyasal özelliklerini iyileştirmiştir (Zhang ve ark., 2019). Ağır metallerle kirlenmiş topraklarda biyokömür ve mikroorganizmaların birlikte uygulanması, ağır metallerin stabilitesini ve toprak alkalizasyonunu iyileştirmeye yardımcı olabilmiş, yonca (*Medicago sativa*) ve soya fasulyesinin (*Glycine max*) gelişimini desteklemiştir (Zhang ve ark., 2019; Haider ve ark., 2021). Bununla birlikte, bitki büyümesini ve toprak özelliklerini iyileştirmede biyokömür ve mikroorganizma uygulamasının kombinasyonu, biyokömür uygulama dozları ve bunların fizikokimyasal özellikleri ile de ilişkili olduğunu göstermiştir (Zhang ve ark., 2018; Yuan ve ark., 2019).

Toksik ve toksik olmayan *M.aeruginosa*'nın oranları göl, gölcük ve gölet sularında zamansal ve mekansal olarak değişmektedir (Cao ve ark., 2018). Tanabe ve ark. (2007), *M.aeruginosa* izolatlarını filogenetik analizle sınıflandırmış, yüksek intraspesifik genetik çeşitliliğe sahip olduğu belirlenmiştir (Tanabe ve ark., 2007; 2018). Bu yaklaşımla, *M.aeruginosa* izolatları 12 filogenetik gruba (A-K ve X) ayrılmış, A ve X gruplarındaki ve B grubundaki bazı izolatların mikrosistin ürettiği bildirilmiştir (Tanabe ve ark., 2007; 2018). *M.aeruginosa*'nın aşırı çoğaldığı göllerden toplanan izolatlarının ancak yarısı toksik çıkmıştır (Yamaguchi ve ark., 2020). Albay ve ark. (2024) yaptıkları çalışmalarında 25 adet göl veya barajda siyanotoksin tespit etmişlerdir. Araştırıcıların bu sonuçları,

Microcystis türlerinin büyük çoğunluğunun ya toksin salgılamadığını ya da suda bulunma oranının analiz edilemeyecek oranda toksin salgıladıklarını göstermektedir. *M.areroginosa* ilgili çalışmaların çoğunluğu üretilen mikrosistinler (MC'ler) gibi güçlü toksinlerin doğal yaşamın kirlenmesi ve insanların zehirlenmesiyle ilgilidir (Campos ve ark., 2021). Bazı *M. aeruginosa* izolatları tarafından salgılanan mikrosistinlerin bozunması ile ilgili laboratuvar ortamında 25 ^{o}C 'de yapılan çalışmada topraklardaki yarı ömürlerinin 6-8 gün arasında olduğu tahmin edilmekte, toprağa uygulanan mikrosistinlerin bir kısmı güneş ışığı veya bazı toprak bakterileri tarafından hızla parçalanabildiği, topraktaki kil ve organik madde içeriğinin mikrosistinlerin adsorpsiyonu ve bozunmasında önemli rol oynadığı bildirilmiştir (Corbel ve ark., 2014). Şanlıurfa'da gündüz hava sıcaklıkları yazın 40-50 ^{o}C arasında olmaktadır. Şanlıurfa Baraj göllerinde yaz aylarında aşırı çoğalan *M.aeruginosa* önceki çalışmada izole edilip tanımlanmıştır (Sezen & Küçük, 2021). Bu mikroalgi içeren sular ile etrafındaki tarlaların ve bahçelerin sulanması, çiftçilerin bu sular ile sulanan tarlalardan yüksek verim alması, baraj gölünde balık ve kuş ölümlerinin görülmemesi, bu yetiştirilen ürünleri yiyen ve tüketen hayvanlarda ve insanlarda da herhangi bir rahatsızlık ve ölüm olmaması mikroalgin toksik olmadığını göstermektedir. Farklı mikroorganizma türlerinin ve biyokömürün toprak ve bitki özelliklerini olumlu yönde etkilediği, kirli topraklardan ağır metallerin temizlenmesi üzerindeki etkileri de bilinmektedir (Haider ve ark., 2021), ancak biyokömür ve *Microcystis aeruginosa*'nın birlikte kullanımı ile ilgili yapılan çalışmalar oldukça sınırlıdır. Araştırmamız, *M. aeruginosa*'nın ve biyokömürün sera koşulları altında buğdayın (*Triticum aestivum* L.) gelişimi ve toprağın bazı biyolojik özelliklerine (dehidrogenaz, β-glukosidaz, alkalin fosfataz aktivitesi) olan etkilerini değerlendirmek amacıyla gerçekleştirilmiştir.

2. Materyal ve Metod

Çalışmamızda kullanılan buğday (*Triticum aestivum* L.) tohumu ticari olarak satın alınmıştır. Denemede kullanılan *Microcystis aeruginosa* Harran Üniversitesi Biyoloji Bölümü Hidrobiyoloji A.B.D.'dan temin edilmiştir. Denemede kullandığımız *M. areroginosa'*nın toplam fenolik içeriği 584.14 (µg PEs/mg ekstrakt), toplam flavonoid 617.52 içeriği (µg QEs/mg ekstrakt) olarak tespit edilmiştir (Ceylan & Sezen, 2024). Çalışmada kullanılan biyokömür; Biorfe marka olup, ticari olarak satın alınmış ve iki farklı dozda (%1, %2) kullanılmıştır. Kullanım talimatına göre (25 litre toprağa 250 g biyokömür olacak şekilde) biyokömür dozları ekim öncesi toprağa ayrı ayrı uygulanmıştır. Kullanılan biyokümür ince taneli olup, organik madde içeriği %80, nem %15, P %3, K %3, N %3'tür. Denemede kullanılan toprak, kampüs alanından daha önce herhangi bir ekim yapılmamış alandan 0-30 cm derinlikten alınarak, 2 mm elekten geçirilmiş, 3 kg'lık saksılara doldurulmuştur. Kullanılan toprağın pH'sı 8.17; organik madde (%) 1.35; kireç (%) 2.47; EC 0.2 mmhos/cm; N ise % 0.11 olup, killi bünyeye sahiptir. Kullanılan toprak; hafif alkalin, az kireçli ve organik madde içeriği düşüktür.

2.1. Denemenin kurulumu

Buğday tohumları 10 v/v sodyum hipoklorit'te (NaOCl) iki dakika bekletilmiş, ardından %70'lik etanol ve ardından steril distile su ile yıkanmış, fazla su filtre kağıdı üzerinde emdirilmiştir. Ekim öncesi biyokömür ile karıştırılan topraklara tohumlar ekilmiştir. Çimlenme sonrası saksılardaki bitki kök bölgesine *M.aeruginosa*'nın farklı dozları ayrı ayrı uygulanmıştır. Deneme doğal ışık alan serada 3 tekerrürlü olarak, tesadüf parselleri faktöryel deneme desenine göre yürütülmüştür. Her saksıya 10 tohum ekilmiş, çimlenme sonunda saksılarda 3 bitki kalacak şekilde seyreltilmiştir. *M. aeruginosa* çimlenme sonrası bitki kök bölgesine 0, % 0.5, %1, %1.5 dozlarda (Grzesik ve ark., 2017) ve saksılara ayrı ayrı 15 gün ara ile 3 kez uygulanmıştır (Sezen & Küçük, 2023). Deneme; hiçbir uygulamanın yapılmadığı kontrol grubu, biyokömür'ün farklı dozları (%1 ve %2) ve *M.aeruginosa*'nın farklı dozlarının ayrı ayrı ve kombinasyonları olarak kurulmuştur. Bitkiler 15 gün ara ile çeşme suyu ile sulanmıştır. Deneme üç tekerrürlü olarak doğal ışık alan serada yürütülmüştür. Bitkiler ekimden 60 gün sonra hasat edilmiştir.

2.2. Bitki parametreleri

Hasat sonunda temel bitki parametrelerinden bitki boyu, yeşil aksam ve kök yaş ağırlığı, kök uzunluğu belirlenmiştir. Her bir uygulamadaki yeşil aksam ve kök kuru ağırlığı için örnekler 70 ^{o}C'de sabit ağırlığa gelinceye kadar etüvde kurutulmuş, tartılmıştır (Yıldız & Özgen, 2004).

2.3. Buğday yapraklarının klorofil içeriğinin belirlenmesi

Yaprakların klorofil içeriği Arnon (1949)'a göre incelenmiştir. Her bir uygulamaya ait yaprak örnekleri aseton: su karışımı ile homojenize edilerek 5000 x g'de santrifüjlenmiştir. Filtratın absorbansı spektrofotometrede 645 nm ve 663 nm dalga boyunda 3 tekrarlı ölçülmüştür. Sonuçlar mg/g olarak Arnon (1949)'a göre hesaplanmıştır.

2.4. Rizosferin bazı enzim aktivitelerinin belirlenmesi

Hasat sonunda köklere yapışan toprak örnekleri alınıp, bekletilmeden laboratuvara getirilmiş ve analizler yapılmıştır. Topraktaki alkalin fosfataz aktivitesi için, toprak örneği (1g) üzerine eklenen toluen, fosfat tamponu (pH 8), p-nitrofenilfosfat iyice karıştırılmış, 1 saat 37^{o}C de inkübe edilmiştir. Süre sonunda açığa çıkan p-nitrofenol, standart (PNPP'den hazırlanan) kullanılarak, 410 nm'de spektrofotometrede (Shimadzu, Japonya) belirlenmiştir (Küçük ve ark., 2024). β-glukosidaz aktivitesi, substrat olarak p-nitrofenil-β-D-glukopiranosid kullanılarak ölçülmüştür. Toprak örneğine (1 g) toluen ilave edilmiş, 15 dakika çalkalandıktan sonra tampon çözelti ve p-nitrofenil-β-D-glukozit çözeltisi ilave edilerek 37°C'de 1 saat süreyle inkübe edilmiştir. Daha sonra kalsiyum klorür çözeltisi ve tris çözeltisi (pH 12) eklenmiş, santrifüj sonrası süpernatant 410 nm'de spektrofotometrik olarak ölçülmüştür (Küçük & Şinşek, 2020). Rizosfer toprağın dehidrogenaz aktivitesi Küçük & Cevheri (2019)'e göre yapılmıştır. Toprak örneğine eklenen glukoz ve %3'lük TTC (2,3,5-trifenil tetrazolium klorür) iyice çalkalanmış, 25 ^{o}C'de 24 saat inkübe edilmiştir. Süre sonunda oluşan 1,3,5 trifenil formazan 485 nm dalga boyunda UV- spektrofotometrede (Shimadzu, Japonya) okunmuştur. Sonuç mg TPF/kg toprak olarak hesaplanmıştır (Küçük & Cevheri, 2019).

2.5. İstatistiksel analiz

Deneme sonunda elde edilen veriler JMP 11 istatistik paketi kullanılarak değerlendirilmiştir. Elde edilen ortalama değerler arasındaki farklılıklar $p<0.05$ önem seviyesinde karşılaştırılmıştır.

3. Araştırma Bulguları ve Tartışma

Çalışmamızda; kontrolle karşılaştırıldığında uygulamalar, buğdayın kök uzunluğu, yeşil aksam boyu ve kuru ağırlığı üzerinde etkili bulunmuştur (Çizelge 1). En yüksek yeşil aksam ağırlığı biyokömürün %2 dozunda alınırken, en yüksek kök kuru ağırlık *M. aeruginosa*'nın %0.5 ve biyokömür %2 interaksiyonu ile elde edilmiştir (Çizelge 1). Biyokömürün %2'lik dozunun uygulanması ile yeşil aksam ağırlığı kontrolle karşılaştırıldığında % 45 oranında artış göstermiştir. *M. aeruginosa*'nın %1'lik dozu kontrole göre bitki boyunu %17 oranında artırmıştır. *M. aeruginosa*'nın %1'lik ve %2 biyokömür interaksiyonu ise bitki boyunu kontrole göre %81.2 oranında artırmıştır. Uygulamalar kök uzunluğu üzerinde de etkili olmuş, en yüksek kök uzunluğu biyokömür %2 ve *M. aeruginosa*'nın %1.5'luk dozunun birlikte uygulanması ile alınmış, bunu sırası ile biyokömür %1 ve *M. aeruginosa*'nın %1.5 dozunun beraber uygulanması ve sadece *M. aeruginosa*'nın %1.5'lik doz uygulaması izlemiştir. Bu uygulamalar, kontrolle karşılaştırıldığında artış, sırası ile %64.9, %61.3 ve %53.3 olarak belirlenmiştir (Çizelge 1). Uygulamaların yeşil aksam ve kök kuru ağırlığı, bitki boyu, kök uzunluğu üzerindeki etkileri Çizelge 1'de verilmiştir.

Çizelge 1. Uygulamaların buğday bitkisinin gelişim parametreleri üzerine etkileri

Parametreler	**Biyokömür (%)**	***M. aeruginosa* (%)**			
		0 (kontrol)	**0.5**	**1**	**1.5**
Yeşil aksam kuru ağırlık (g/bitki)	**0 (kontrol)**	0.02 g*	0.10 c-f	0.17 b	0.16 bc
(LSD 0.05: 0.06)	**1**	0.10 cde	0.13 bcd	0.04 efg	0.10 b-e
CV (%):4.30	**2**	0.24 a	0.03 g	0.07 d-g	0.15 bc
Bitki boyu (cm)	**0**	12.70 f	34.00 de	45.70 c	38.50 d
(LSD 0.05: 5.30)	**1**	32.50 e	36.90 de	48.50 c	48.40 c
CV(%): 8.97	**2**	37.90 de	37.60 de	67.90 a	56.90 d
Kök kuru ağırlık (g/bitki)	**0**	0.04 d	0.07 bcd	0.06 cd	0.16 abc
(LSD 0.05: 0.10)	**1**	0.05 cd	0.06 cd	0.06 cd	0.15 a-d
CV(%): 5.91	**2**	0.11 a-d	0.19 a	0.18 ab	0.16 abc
Kök uzunluğu (cm)	**0**	6.07 f	10.20 d	12.30 bc	13.00 b
(LSD 0.05: 1.87)	**1**	7.80 ef	11.00 cd	12.40 bc	15.70 a
CV(%):9.41	**2**	9.60 de	12.70 bc	13.70 b	17.30 a

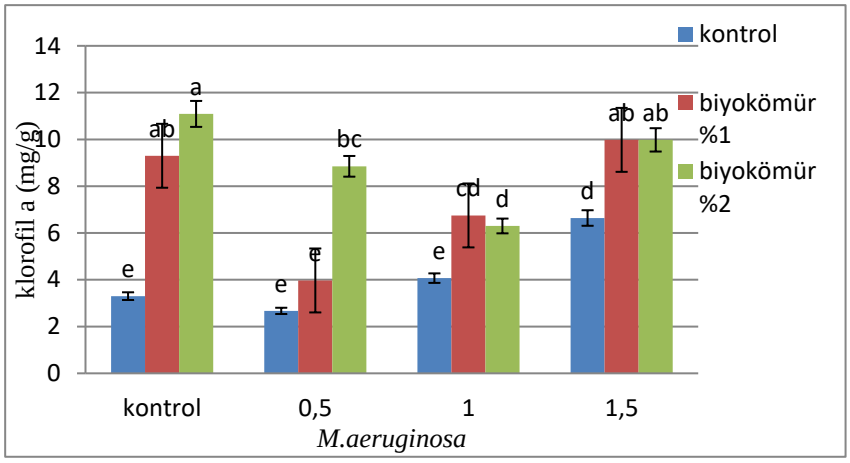
* Farklı harfler birbirinden farklı olan değerleri göstermektedir ($p < 0.05$)

Çizelge 1'de görüldüğü gibi uygulamaların dozları kendi aralarında karşılaştırıldığında dozlar arasında da farklılık belirlenmiştir ($p<0.05$). *M.aeruginosa*'ın farklı dozları kendi aralarında karşılaştırıldığında %1.5'luk doz ile kök uzunluğu, bitki boyu, kök kuru ağırlığı önemli oranda artmış, bu artış istatistiksel olarak önemli bulunmuştur ($p<0.05$). Yeşil aksam kuru ağırlığı üzerine *M. aeruginosa*'ın uygulanan dozları arasında ise farklılık önemsiz bulunmuştur. Biyokömürün %2'lık dozu incelenen özellikler üzerinde önemli bulunmuştur. Toprak özellikleri (fiziksel, kimyasal ve biyolojik) biyokömür uygulamasıyla iyileştikçe, bu da ürün verimini artırmıştır (Zhang ve ark., 2019). Biyokömür uygulamasının artan dozu bitki temel parametrelerini artırmıştır (Çizelge 1). Biyokömür uygulaması tohum çimlenmesini, kök yoğunluğunu iyileştirmiştir. Rondon ve ark. (2007) fasulyedeki biyokütle veriminin 60 t ha^{-1} kadar biyokömür uygulamasıyla arttığını, ancak doz 90 t ha^{-1}'a çıkarıldığında kontrol parselleriyle aynı değere ulaştığını bulmuştur. Bizim çalışmamızda ise artan dozlardaki biyokömür ve *M.aeruginosa*'nın uygulanması kök uzunluğu, yeşil aksam boyu ve yeşil aksam ağırlığında kontrole göre önemli iyileşmeye neden olmuştur (Çizelge 1). Yapılan çalışmalarda, buğdaya biyokömür uygulamalarının bitkinin vejetatif gelişimini ve toplam verimini artırdığı bildirilmiştir (Şener & Erdal, 2022; Erdal ve ark., 2024). Erdal ve ark. (2024) biyokömür uygulamalarının vejetatif büyümeyi ve saman verimini artırdığı, tane verimini azaltığını saptamışlardır. Ayrıca, biyokömür uygulamalarının toprakların fiziksel özellikleri üzerindeki önemli bir farklılık yaratmadığını tespit etmişlerdir. Araştırıcılar, biyokömürün toprağa besin sağlayarak veya alınabilir besin miktarını artırarak doğrudan bitki büyümesini etkilemediğini; ancak bazı toprak özelliklerini iyileştirerek bitki büyümesini uyarabileceğini tespit etmişlerdir. Yapılan bir çalışmada da, biyokömür uygulamalarının buğdayın vejetatif gelişmesini artırdığı, buna karşılık tane verimini azalttığını, hasat indeksi, başak boyu, bitki tane sayısı, kardeşlenme ve tane protein içeriklerini olumsuz etkilediği belirlenmiştir (Şener & Erdal, 2022).

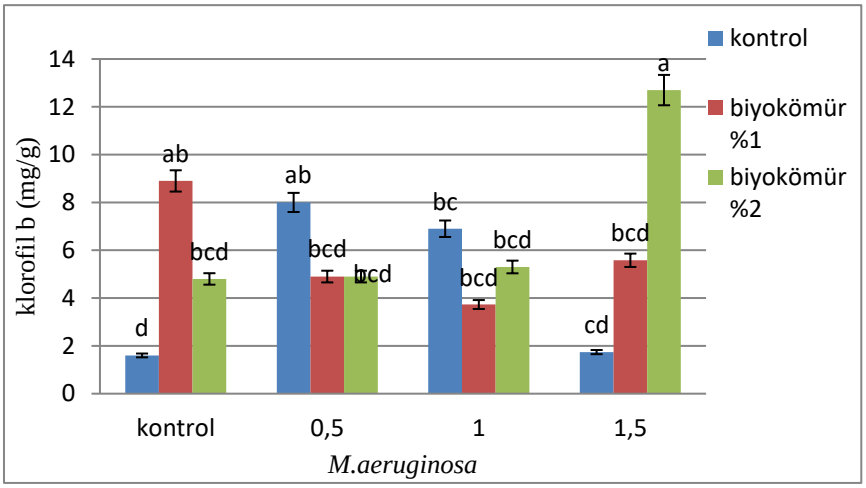
Yapılan bir araştırmada toksin üretici *M.aeruginosa* ile kirlenmiş göl suyu ile sulanan marul ve çeltik fidelerinin gelişimini ve verimlerini olumsuz etkilemediği saptanmıştır (Cao ve ark., 2018). *M.aeruginosa* 'nın farklı dozları ile yapılan sulama suyunun marul ve çeltiğin yeşil aksam ağırlığı, kök

ağırlığı, bitki boyu, yaprak alanı, başak sayısı ve tane verimi gibi parametrelerin olumsuz olarak etkilenmediği araştırıcılar tarafından bildirilmiştir (Cao ve ark., 2018). Zhu ve ark. (2018) tarafından yapılan bir çalışmada; *M.aeruginosa* içeren sulama suyuna maruz kalan hıyar büyümesi önemli ölçüde etkilenmiş, hıyarda organik asit, çözünür şeker ve C vitamini içeriğinin azaldığı bildirilmiştir. Ayrıca, *M.aeruginosa* içeren sulama suyu ıspanağın bitki biyokütlesini ve toplam yaprak alanını önemli ölçüde azaltmıştır (Tsoumalakou ve ark., 2021). Machado ve ark. (2017), *M.aeruginosa* uygulamasının, havuçlarda kök büyümesinde ve besin değerinde bir azalmaya yol açtığını belirlemişlerdir. Buna karşın yapılan başka bir araştırmada ise *M.aeruginosa* uygulanan marul, çeltik, domates, maydanoz ve kişnişin büyümesinde kontrole göre artışın önemli olduğu bildirilmiştir (Cao ve ark., 2018). Araştırıcılar *M.aeruginosa*'nın toksin üreten suşlarının bitki gelişimi ve veriminde azalmaya neden olduğunu, toksin üretmeyen suşların ise bitki gelişimini arttırdığını açıklamışlardır. Bizim çalışmamızda da *M.aeruginosa*'nın %1.5'lik dozu buğdayın kök uzunluğu, kök kuru ağırlığını artırmış, sonuçlarımız Cao ve ark. (2018) tarafından yapılan çalışma ile desteklenmiştir. Bitki boyu, kök ağırlığı, kök uzunluğunun kontrole göre daha fazla olması mikroalg uygulamaları sonucunda fazla miktarda aktif bileşiğin toprağa aktarılması ve bitki tarafından kullanılmasından kaynaklanabilir (Cao ve ark., 2018). Sezen & Küçük (2021; 2023), sera koşullarında *Microcystis viridis* ve *Aphanizomenon gracile* siyanobakterilerinin fiğ, nohut, arpa, mısır ve mercimek bitkilerinin büyümesi üzerine etkilerini araştırmışlar, siyanobakteri uygulamalarının işlem görmemiş kontrol bitkilerine kıyasla bitki boyunu, kök kuru ve yaş ağırlığını, kök uzunluğunu ve yeşil aksam ağırlığını önemli oranda artırdığını tespit etmişlerdir. Rey ve ark. (2024) vermikompost, deniz yosunu ve algal gübrelerin toprak verimliliği ve kenevir üzerindeki etkilerini araştırdıkları çalışmalarında Okeechobee Gölü'nden toplanan ve ekim sırasında uygulanan kurutulmuş algleri (*M. aeruginosa*) tarla koşullarında 1 ton ha^{-1} oranı ile uygulamışlar, *M.aeruginosa* uygulaması ile en yüksek biyokütle elde edildiği, yüksek azot ve organik madde içeriği nedeniyle vermikompost ve deniz yosunu uygulamalarına göre önemli besin içeriği sağladığı, bu nedenle zengin bir organik katkı maddesi olarak kullanılabileceğini belirtmişlerdir. Bu sonuçlar, toksik olarak bilinen bazı siyanobakter uygulamalarının kontrol gruplarına göre bitki büyümesi ve gelişimi üzerindeki olumlu etkilerini göstermektedir.

Yapılan bir çalışmada, *Spirulina platensis*, turp (*Raphanus sativus*) tohumuna ve yapraktan spreyleme olarak uygulanmıştır. *S. platensis'in* her iki şekildeki uygulamalarında farklılık bulunmamış, uygulamalar turp fidelerinin kontrole göre büyümesini, klorofil ve element içeriğini artırmıştır (Godlewska ve ark., 2019). Mutale-Joan ve ark. (2020) ise 18 siyanobakteri ve mikroalg türünden elde edilen ham biyo-ekstraktları, domates bitkisinin bitki büyümesi, besin alımı, klorofil içeriği ve metabolit profilleri için biyostimülant olarak önermiştir. Uygulamaların artan dozları bitki yapraklarındaki klorofil içeriklerini artırmıştır (Şekil 1 ve Şekil 2). Diğer uygulamalara göre klorofil a içeriğini (Şekil 1) sadece biyokömürün %2'lik dozu artırırken diğer taraftan, *M. aeruginosa* %1.5 ve biyokömürün %2'nin birlikte uygulanması klorofil b'yi (Şekil 2) artırmıştır. Söğüt fidelerine mikroalg uygulamasının fide gelişimini etkilediği, mikroalg uygulanmayanlara göre yaprak klorofil içeriğinin arttığı saptanmıştır (Grzesik ve ark., 2017). Benzer sonuçlar mısır bitkilerinde de gözlemlenmiştir (Grzesik & Romanowska-Duba, 2015). Deniz yosunu özütünün uygulanması 'Fuji' elmasının yapraklarında klorofil içeriğine, fotosentez ve solunum oranlarında %12'lik bir artışa neden olmuştur (Spinelli ve ark., 2009). Yapraklardaki klorofil içeriğinin artması, siyanobakteriler tarafından atmosferden asimile edilen ve bitki dokularına iletilen daha yüksek miktardaki azottan kaynaklanabileceği araştırıcılar tarafından açıklanmıştır (Parmar ve ark., 2023; Spinelli ve ark., 2009).



Şekil 1. Uygulamaların yapraklarda klorofil-a içeriğine etkileri.



Şekil 2. Uygulamaların yapraklarda klorofil-b içeriğine etkileri.

Bitkinin oksin (IAA), gibberellik asit (GA), sitokin, amino asit, makro (N, P, K, Ca, Mg) ve mikro element (S, Zn, Fe, Mn, Cu, Mo, Co), poliamin içeriğindeki artış, siyanobakteriler ve yeşil algler tarafından üretilebilen bazı ikincil metabolitlerce zenginleştirilmesiyle oluşabilir (Abo-Shady ve ark., 2023; Ashour ve ark., 2023). Grzesik ve ark. (2017) *M. aeruginosa*, *Anabaena* sp. (siyanobakteri) ve *Chlorella* sp.'nin (yeşil alg), sentetik gübrelerin sınırlı kullanıldığı koşullarda, söğüt (*Salix viminalis* L.) fidelerinin fizyolojik performansını, kimyasal bileşimini, büyümesini ve verimini iyileştirmek, kimyasal gübrelemenin kullanımını ve çevre kirliliğini azaltmak için biyogübre olarak kullanılabileceğini önermişlerdir. *M. arereginosa* tarafından üretilen metabolitler, fitohormonlar (IAA, sideroforlar, gibberellinler, oksinler, sitokinin), peptitler (poliaminler/amino asitler) ve fenoliklerin (gallik asit, kafeik asit, flavonoidler, terpenoidler, steroidler, saponinler vb.) bitki büyüme düzenlemesi ve gelişimi (hücre bölünmesi, uzama), besin elementlerin biyoyararlanımını iyileştirme, bitkilerin savunması, antioksidan, lignin sentezi, ozmotik dengenin korunması, sinyal moleküller gibi bitkiler üzerindeki olumlu etkileri bulunmaktadır (Bibi ve ark., 2024).

Enzimlerin, bitki kökleri veya toprak mikroorganizmaları tarafından salgılanan ve besin maddelerinin biyoyararlanımını etkilediği rapor edilmiştir (Rahmanian & Khadem, 2024). Biyokömür ilavesi toprağın mikrobiyal yanıtını (aktivite, bolluk ve topluluk yapısı) etkilediği gibi, enzimatik aktiviteyi de etkilemektedir. Biyokömürün substrat ve enzimle etkileşiminin, toprak enzimatik aktivitesini güçlü bir şekilde etkilediği açıklanmıştır (Rahmanian & Khadem, 2024). Substrat ve enzimler biyokömürde bulunan fonksiyonel gruplara bağlandığında, enzimatik aktivite ya teşvik edilebilir ya da sınırlanabilir (Rahmanian & Khadem, 2024). Enzimlerin, toprakların biyokimyasal sürecinde kritik roller oynadığı ve toprak sağlığının korunmasında önemli oldukları bilinmektedir. Toprakların enzim aktivitesi çevresel şartlara hızlı bir şekilde yanıt vermiş, bu nedenle toprak

sağlığındaki değişikliklerin belirlenmesinde önemli bulunmuştur (Wojewdzki ve ark., 2022). Bu çalışmada, dehidrogenaz, β-glukosidaz, alkalin fosfataz enzim aktivitelerinin uygulamalar tarafından etkilenip etkilenmediği değerlendirilmiştir. Çalışmamızda biyokömürün uygulanması toprağın dehidrogenaz, β-glukosidaz, alkalin fosfataz aktivitesini arttırmıştır (Çizelge 2). Biyokömür %2 ve *M. aeruginosa* %1.5'in birlikte uygulanması ile alkalin fosfataz aktivitesi, dehidrogenaz ve β-glukosidaz aktivitesinde en yüksek değerler elde edilmiştir. Çizelge 2 incelendiğinde Biyokömür % 2 ve *M. aeruginosa* %1.5'in birlikte uygulanması kontrolle karşılaştırıldığında alkalin fosfataz aktivitesi %88.9, dehidrogenaz aktivitesi %92.5 ve β-glukosidaz aktivitesi ise %92.7 oranında artmıştır. Topraklara uygulanan %0.4 ve %2 dozlarındaki biyokömürün toprak enzim aktivitesini arttırdığı Wojewdzki ve ark. (2022) tarafından da bildirilmiştir, araştırıcıların bulguları sonuçlarımızı desteklemektedir. Dehidrogenaz aktivitesi, metabolik aktivitenin bir endeksi olarak kullanılır ve mikrobiyal solunumla ilişkili bulunmuştur (Dick, 1997). Bu çalışmada, *M. aeruginosa*'nın artan dozları dehidrogenaz enzim aktivitesini önemli ölçüde artırmıştır ($p< 0.05$). Yüksek dozun dehidrogenaz enzim aktivitesi üzerindeki uyarıcı etkisi; *M. aeruginosa*'nın uygulanmasından topraktaki mikrobiyal aktivitenin artması ve toprağa uygulamalar sonunda giren organik maddeyi parçalayan mikroorganizmaların artan aktivitelerinden; toprağa uygulanan *M. aeruginosa* ve biyokömürün mineralize olan karbon nedeniyle dehidrogenaz enzim aktivitesinin uyarılmasından kaynaklanmış olabilir.

Çizelge 2. Uygulamaların rizosfer toprağın bazı enzim aktiviteleri üzerine etkileri

Enzim aktiviteleri	**Biyokömür (%)**	***M. aeruginosa* (%)**			
		0 (kontrol)	**0.5**	**1**	**1.5**
Alkalin fosfataz aktivitesi (mg PNP/kg toprak)	**0 (kontrol)**	2.83 f*	5.36 e	9.30 d	8.90 d
(LSD 0.05: 0.57)	**1**	10.08 d	9.90 d	13.20 c	12.60 c
CV(%): 4.69	**2**	13.00 c	12.90 c	18.10 b	25.50 a
Dehidrogenaz aktivitesi (mg TPF/kg toprak)	**0**	8.53 j	41.80 h	50.10 f	65.70 c
(LSD 0.05: 0.3.41)	**1**	33.80 ı	46.40 fg	60.50 de	88.70 b
CV(%): 4.26	**2**	44.50 h	57.40 e	63.70 cd	115.20 a
β-glukosidaz aktivitesi (mg-p nitrofenol/kg toprak)	**0**	1.31 ı	1.59 hı	1.64 hı	3.12 e
(LSD 0.05: 0.64)	**1**	1.86 gh	5.16 d	2.43 f	9.12 b
CV(%):14.1	**2**	2.20 fg	6.35 c	5.42 d	17.90 a

* Farklı harfler birbirinden farklı olan değerleri göstermektedir ($p < 0.05$)

Ayrıca denemenin kısa süreli olması da uygulamalar ve enzim aktiviteleri arasındaki etkiyi tam olarak gözlemleme fırsatını sınırlamış olabilir. Sonuçta toprağa uygulanan biyokömür uygulaması enzim aktivitelerini artırmıştır (Çizelge 2). Biyokömür ilavesiyle enzimatik aktivitelerdeki bu artışın, bu tür enzimler için organik substrat görevi gören yüksek miktardaki toprak organik karbonu, mikrobiyal biyokütle karbonu ve azot içeriği tarafından indüklendiği bildirilmiştir (Oladele ve ark., 2019). Çeltik kabuğu biyokömürü uygulaması, toprağın üreaz, katalaz, alkali fosfataz ve invertaz enzim aktivitelerini önemli ölçüde iyileştirmiştir (Oladele ve ark., 2019). Wojewodzki ve ark. (2022), biyokömür ilavesiyle fosfataz aktivitesinin arttığını bildirmişlerdir; bu artış yüksek oranda biyolojik olarak kullanılabilir fosfor anlamına gelmektedir. Biyokömür ilavesiyle enzimatik aktivitedeki artışın, bitkilerin bu enzimleri salgılamak üzere kök büyümesinin uyarılmasından kaynaklanmış olabileceği düşünülmektedir. Garbuz ve ark. (2021), alkalin fosfataz aktivitesindeki artışın, biyokömür eklenen topraklarda fosforun bulunabilirliğindeki artıştan kaynaklandığını bildirmişlerdir. Glukosidazlar,

topraktaki bitki ve hayvan artıkları gibi organik bileşiklerin ayrışmasını kontrol ettiği gibi, toprak organik maddesindeki hızlı değişiklikleri incelemek için ve toprak kalitesinin değerlendirilmesinde de kullanılmıştır (Rahmanian & Khadem, 2024). Toprağın biyolojik ve biyokimyasal özellikleri, özellikle enzimatik aktivite, topraklara eklenen organik maddenin mineralizasyonu, humik maddelerin üretimi, organik bileşiklerin ayrışması, bitki zararlılarının biyolojik kontrolünde yer alan mekanizmalar gibi birçok toprak sürecinde önemli bir rol oynar (Frene ve ark., 2021). Toprakta gerçekleşen tüm biyokimyasal değişikliklerin enzimlerin varlığına bağlı olduğu, toprağa eklenen biyokömürün toprağın mikrobiyal popülasyonunu ve enzim aktivitesini arttırdığı açıklanmıştır (Frene ve ark., 2021). *M. aeruginosa* ve biyokömürün toprağa uygulanan yüksek dozlarının toprağa karbonhidrat kazandırdığı ve dolayısıyla kolayca erişilebilir bileşiklerinin eklenmesi, toprağın heterotrofik popülasyonunu uyarmış, mikrobiyal aktivite ve enzim üretimini arttırmış olduğu düşünülmektedir.

4. Sonuç

Siyanobakteriler farklı ekosistemlerde azot, fosfor ve karbon döngüsünde önemli bir rol oynayan prokaryotik organizmalardır. Bu organizmalar toprakta azot, fosfor, demir, potasyum, magnezyum gibi besin elementlerinin içeriğini doğrudan ve dolaylı olarak iyileştirerek bitki büyümesini ve bitki verimini arttıran ve agroekosistem için muazzam yetenekleri olan alg grubudur. Toksik olmayan siyanobakteriyel kültürleri toksik kimyasal gübre ve pestisit kullanma ihtiyacını azaltarak çevre korumayı kolaylaştırabilir. Çalışmamızda biyokömürün %2'lik uygulama dozu yeşil aksam ağırlığını, Biyokömürün %2 ve %1 *M.aeruginosa*'nın birlikte uygulanması bitki boyunu, Biyokömürün %2 ve %1'lik dozları ile %1.5 *M.aeruginosa*'nın birlikte uygulanmaları kök uzunluğunu, Biyokömürün %2 ve %0.5 *M.aeruginosa*'nın birlikte uygulanması kök kuru ağırlığını diğer uygulamalara göre artırmıştır. Ayrıca *M.aeruginosa*'nınuygulanan %1.5'lik dozu diğer uygulama dozları ile karşılaştırıldığında toprakların test edilen enzim aktivitelerini artırmıştır. Ancak, mevcut veriler sınırlı olduğundan ve bu alana olan ilginin artması nedeniyle, *M. aeruginosa* tarafından salgılanan aktif bileşikleri ve bunların bitki türleri üzerindeki etkilerini belirlemek için daha fazla araştırmaya ihtiyaç vardır.

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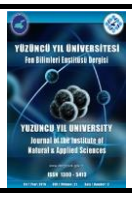
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Araştırma Makalesi

Çilek Yetiştiriciliğinde Bitkisel ve Hayvansal Kaynaklı Organik Gübrelerin Etkileri

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Öz: Çilek, farklı iklim koşullarında yetişebilmesi, taze ve işlenmiş olarak tüketilebilmesi, sağlık açısından faydaları nedeniyle Türkiye'de en çok yetiştirilen ticari değeri yüksek meyvelerden birisidir. Bu çalışma, pelet tavuk gübresi, pelet çiftlik gübresi ve bitkisel menşeili organik sıvı gübrelerin çilekte bitki gelişimi, verim, meyve kalitesi ve yaprak besin element içerikleri üzerine etkilerini belirlemek amacıyla yapılmıştır. Araştırmada, Monterey çilek çeşidi kullanılmıştır. Çalışmada bitki büyüme parametreleri, bitki başına verim (g/bitki), meyve ağırlığı (g), meyvede pH, SÇKM, titre edilir asit, SÇKM/asit oranı, toplam şeker, toplam antosiyanin ve yaprak besin element içerikleri incelenmiştir. Sonuç olarak, organik gübrelerin çilek bitkisinin büyümesi, verimi, meyve kalitesi ve yapraklardaki besin elementi içeriği üzerinde olumlu etkileri olduğu belirlenmiştir. Uygulamalar içerisinde bitki başına en yüksek verim (346.57 g/bitki), en iri meyveler (17.96 g), SÇKM, toplam antosiyanin, en uzun kök, en kalın gövde ve yaprakta en iyi azot, fosfor, potasyum, magnezyum ve çinko içerikleri T_4 uygulamasında "Tavuk gübresi (taban)+Sıvı gübre (üstten)" elde edilmiştir. Sonuçlar, tavuk gübresinin diğer organik gübrelere göre daha etkili olduğunu göstermiştir.

Anahtar Kelimeler: Besin elementleri, Çilek, Meyve kalitesi, Organik gübre, Verim

Effects of Plant and Animal-Derived Organic Fertilizers in Strawberry Cultivation

Abstract: Strawberry is one of the fruits with high commercial value that is mostly grown in Turkey due to its adaptability to different climatic conditions, its versatility in being consumed fresh or processed, and its health benefits. This study was conducted to determine the effects of pelletized chicken manure, pelletized farm manure, and plant-based organic liquid fertilizers on plant growth, yield, fruit quality and leaf nutrient element contents in strawberries. The experiment utilized the Monterey variety of strawberries. The study examined plant growth parameters, strawberry yield, fruit weight, pH, total soluble solids (TSS), titrable acidity, TSS/Acidity, total sugar, and total anthocyanin in fruit and leaf nutrient element contents. In conclusion, it was determined that organic fertilizers in the study have positive effects on the growth, yield, fruit quality, and leaf nutrient content of strawberry plants. Among the treatments the highest yield per plant (346.57 g plant^{-1}) the largest fruits (17.96 g), TSS, total anthocyanin, the longest root, the thickest stem and the best nitrogen, phosphorus, potassium, magnesium and zinc contents in the leaf were obtained in the T_4 application "Chicken manure (base) + Liquid fertilizer (top)" These findings indicated that chicken manure was more effective compared to other organic fertilizers.

Keywords: Fruit quality, Nutrients, Organic manure, Strawberry, Yield

1. Giriş

Çilek (*Fragaria x ananassa* Duch.), dünya genelinde taze veya işlenmiş olarak yaygın tüketilen ve üretimi her yıl artan ticari değeri yüksek bir meyvedir. 2022 yılı FAO verilerine göre dünyada çilek üretimi 9 569 864 ton olarak gerçekleşmiştir. Üretiminde Çin (3 354 803 ton) ilk sırada, Amerika (1 261 890 ton) ikinci sırada ve Türkiye 728 112 ton ile üçüncü sırada yer almıştır (FAO, 2024). Tüketiciler tarafından özellikle aroma, lezzet ve renk gibi çekici duyusal özellikleri nedeniyle severek

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tüketilmektedir (Kovačević ve ark., 2015; Kobi ve ark., 2018). Çilek (*Fragaria X ananassa* Duch.), şekerler, vitaminler ve mineraller gibi çok çeşitli besleyici bileşiklerin zengin bir kaynağıdır (Giampieri ve ark., 2015). Çilek üretimindeki artış, yalnızca duyusal ve besinsel özelliklerinden kaynaklanan yüksek talep nedeniyle değil, aynı zamanda antioksidan ve anti-inflamatuar bileşikler gibi tüketici sağlığına faydalı olduğu bilinen biyoaktif bileşenlerin varlığıyla da ilişkilendirilmektedir (Nunes ve ark., 2020).

Bitkisel üretimde kullanılan kimyasal gübreler zamanla toprağın fiziksel, kimyasal ve biyolojik özelliklerini değiştirmekte ve çevre için sorun yaratmaktadır (Apu ve ark., 2022; Sultana ve ark., 2022). Bilinçsizce kullanılan kimyasal gübreler hem üretim maliyetini artırmakta hem de toprak yapısının bozulması nedeniyle yetiştirilen ürünün verimini olumsuz etkilemektedir. Bu sorunların giderilmesinde organik tarım etkili bir alternatif olarak öne çıkmaktadır.

Organik tarım sadece toprağa ve çevre sağlığına destek olmakla kalmaz, meyvelerin kalitesini iyileştirerek aynı zamanda uzun vadede üretimde sürdürülebilirlik sağlamaktadır (Kumar ve ark., 2018; Hernández-Martínez ve ark., 2023). Bitkilerden veya hayvanlardan elde edilen organik gübreler yüksek miktarda besin maddesi içermekte ve toprağın organik maddesini artırmaktadır. Toprağın fiziksel özellikleri ile (su tutma kapasitesi, toprak havalandırması, toprak agregasyonu vb.), toprak pH'sını iyileştirmektedir. Ayrıca, toprak bozulmasını önlemekte ve yararlı toprak mikroorganizmalarının popülasyonunu artırmaktadır (Demirkıran, 2020; Sahana ve ark., 2020; Negi ve ark., 2021; Zha ve ark., 2024).

Çilek yetiştiriciliğinde solucan gübresi (Mehraj ve ark., 2014; Develi ve ark., 2021), organik sıvı gübre (Ginandjar ve ark., 2019), çiftlik gübresi, solucan gübresi ve biyogübre (Bhat & Hussain, 2023), koyun gübresi (Zha ve ark., 2024) gibi organik gübre uygulamalarının bitki büyümesi, verim ve meyve kalitesi üzerinde olumlu etkileri olduğu bildirilmiştir. Bu çalışmalar, ayrıca gübrelerin toprağı etkili bir şekilde iyileştirebileceğini göstermiştir. Çiftlik gübresi ve tavuk gübresi hem uygun maliyetli hem de kullanımı kolay organik gübrelerdendir. Çiftlik gübresi, toprağın fiziksel, kimyasal ve biyolojik özelliklerini iyileştirmektedir (Khan ve ark., 2010). Toprağın organik maddesini ve mevcut su tutma kapasitesini önemli ölçüde artırmakta, bitkinin büyümesi ve gelişmesi için iyi bir ortam yaratmaktadır (Tadesse ve ark., 2013).

Tavuk gübresi, önemli miktarda azot, fosfor ve potasyum içeren besin açısından zengin bir organik atıktır (Manogaran ve ark., 2022). Toprağın organik madde miktarını ve su tutma kapasitesini artırarak toprak sağlığını iyileştirirken, aynı zamanda topraktaki besin elementlerinin bitkiler tarafından alımını kolaylaştırmaktadır (Hoover ve ark., 2019). Organik sıvı gübreler ise toprağın organik maddesini artırır, toprak yapısını düzenler ve bitkinin besin elementini alımına yardımcı olur (Ginandjar ve ark., 2019; Mooy ve ark., 2019).

Çiftlik gübresi, tavuk gübresi gibi hayvansal atıklar ile bitkisel atıkların katı ya da sıvı formların tarımda değerlendirilmesi, çevreye olan doğal faydalarının yanı sıra bitki ve toprak yapısını iyileştirmektedir. Çilek bitkisinde verim ve meyve kalitesinin artması, ihtiyacı olan besin elementlerini büyüme ve gelişim süreci boyunca alabilmesiyle mümkün olabilir. Bu nedenle bitkinin ihtiyacı olan besin elementlerinin uygun yöntem ve miktarda verilmesi gerekmektedir. Pelet formundaki organik gübrelerin, besin elementlerini yavaş salarak bitkilere uzun süreli ve devamlı besin elementi sağladığı, ayrıca daha doğru dozajlama (daha az uygulama) gibi avantajlar sunduğu belirtilmiştir (Brunerová ve ark., 2020). Bununla birlikte, pelet formundaki organik gübre uygulamaları üzerine yapılan çalışmaların sayısı sınırlıdır. Ülkemizde tarımın sürdürülebilirliğini sağlamak için, çevre ve insan sağlığını koruyan organik üretimin yaygınlaştırılması büyük önem taşımaktadır. Bu da verim ve meyve kalitesini artırmaya yönelik organik uygulamalara dair çalışmaların artırılmasıyla mümkün olabilir.

Bu çalışmada, Monterey çilek çeşidinde, pelet çiftlik gübresi, pelet tavuk gübresi ve bitkisel menşeili sıvı organik gübre uygulamalarının bitki büyümesi, verim ve meyve kalite parametreleri üzerine etkisi incelenmiştir.

2. Materyal ve Yöntem

2.1. Materyal

Deneme 2022-2023 yılı yetiştiricilik sezonunda Osmaniye Korkut Ata Üniversitesi deneme arazisinde gerçekleştirilmiştir. Bu bölge, Akdeniz iklimi özelliklerine sahip olup, deniz seviyesinden

121 metre yüksekliktedir. Denemede, Monterey çilek çeşidi kullanılmıştır. Monterey çilek çeşidinin taze fideleri Çiltar firmasından (Adana) temin edilmiştir. Orta derecede nötr gün bir çeşit olan Monterey, belirgin aromaya ve iyi bir tada sahiptir. Bitki yapısı güçlü ve erkenci bir çeşittir. Monterey çeşidi mildiyö hastalığına karşı hassastır (Türemiş & Ağaoğlu, 2013). Çalışmada uygulama materyali olarak organik katı pelet çiftlik gübresi, katı pelet tavuk gübresi, bitkisel manşeili sıvı organik gübre kullanılmıştır. Ticari adı Nif organik katı çiftlik gübresi (Aydınlar madencilik, İzmir) sertifikalı, büyükbaş hayvan gübresidir. İçerisinde %40 organik madde, %2 azot, %1.5 fosfor, %1.5 potasyum, %5 hümik ve fulvik asit bulunmaktadır (Anonim, 2024a). Ticari adı Batısel kanatlı katı hayvan gübresinin (Yükseller zirai ürünler pazarlama Ltd.Şti, Manisa) içerisinde %50 organik madde, %2 azot, %3 fosfor, %1 potasyum, %28 hümik ve fulvik asit bulunmaktadır (Anonim, 2024b). Ticari adı Biobacti olan (Merkez Anadolu kimya, Antalya) bitkisel manşeili sıvı organik gübre içerisinde ise %35 organik madde, %3 azot, %5 potasyum bulunmaktadır (Anonim, 2024c).

Denemede yapılan uygulamalar

T_1: Gübresiz (kontrol) sadece su verilmiştir.

T_2: Sıvı gübre uygulaması

T_3: Tabana katı çiftlik gübresi, üstten sıvı gübre uygulaması

T_4: Tabana katı tavuk gübresi, üstten sıvı gübre uygulaması

2.2. Yöntem

Yapılan toprak analizinde deneme alanı topraklarının killi-tınlı bünyeye sahip ve organik maddesinin düşük olduğu saptanmıştır (Çizelge 1).

Çizelge 1. Deneme alanına ait toprak özellikleri

Toprak özellikleri	Değerleri
Bünye	Killi Tınlı
pH	7.30
Kireç (%)	38.68
Organik madde (%)	1.26
P (mg/kg)	9.50
K (mg/kg)	202.00
Ca (mg/kg)	6554.00
Mg (mg/kg)	162.00
Fe (mg/kg)	4.62
Cu (mg/kg)	0.82
Mn (mg/kg)	1.90
Zn (mg/kg)	0.31

Deneme alanında seddeler oluşturulduktan sonra pelet tavuk ve pelet çiftlik gübresi en az 10 cm derinlikte olacak şekilde toprakla karıştırılmıştır. Pelet tavuk ve çiftlik gübresi 300 kg/da olacak şekilde verilmiştir. Seddelere damlama sulama sistemleri kurulduktan sonra üzerleri siyah polietilen malçla örtülmüştür. Haftada 1 kez olmak üzere toplam 2 kez pelet gübrelerin toprakla karışmasını sağlamak amacıyla damlama sulama ile seddeler sulanmıştır. Taze çilek fideleri, çift sıra olarak 30 cm aralıklarla üçgen şeklinde 3 Kasım 2022 tarihinde dikilmiştir. Üretim süreci boyunca iki haftada 1 kez olmak üzere kontrol dışındaki seddelere eşit oranda organik sıvı gübre verilmiştir. Organik sıvı gübre 9 L/da olacak şekilde damlama sulama ile verilmiştir. Kontrole sadece su verilmiştir. Bitkiler, kışın soğuktan zarar görmemesi için alçak tünel içerisine alınmıştır.

Denemede bitki başına verim, meyve ağırlığı, meyve suyu pH, suda çözünebilir kuru madde (SÇKM) ve titre edilebilir asitlik (TA) analizleri yapılmıştır. Analizlere nisan ayında başlanmış haziran ayı sonun kadar devam edilmiştir. Denemede, hasat edilen meyveler 0.1 g duyarlı terazide tartılarak parsel verimleri belirlenmiş ve buradan bitki başına verim gram olarak hesaplanmıştır. Ortalama meyve ağırlığı, hasat dönemi boyunca elde dilen meyve ağırlıklarının toplam meyve sayısına bölünmesiyle elde edilmiştir. Meyve suyu pH analizi, uygulamaların her tekerrüründen rastgele seçilen 20 meyveden elde

edilen meyve suyunda pH metre ile 15 günde bir olmak üzere yapılmıştır. Suda çözünebilir kuru madde (SÇKM) analizi uygulamaların her tekerrürden rastgele seçilen 20 meyveden elde edilen meyve suyunda el refraktometresi ile 15 gün aralıklarla yapılmıştır. Titre edilebilir asitlik (TA) analizinde, meyve suyundan 1 ml alınmış ve saf su ile 50 ml'ye tamamlanmıştır. Örneğin pH değeri 8.1 oluncaya kadar 0.1 N sodyum hidroksitle (NaOH) titre edilmiştir. Hesaplamalar sitrik asit cinsinden % olarak 15 gün aralıklarla belirlenmiştir (Kafkas ve ark., 2007; Sarıdaş ve ark., 2017; Şener & Türemiş, 2017; Sayğı, 2023). Toplam şeker ve antosiyanin analizi ise meyvelerin en yoğun olduğu mayıs ayında yapılmıştır. Toplam şeker miktarı, AOAC 923.09 (Lane-Eynon yöntemi) esas alınarak belirlenmiştir (AOAC, 2000). Toplam antosiyanin analizi AOAC 2005.02 pH diferansiyel metotuna göre yapılmıştır (Lee ve ark., 2005).

Nisan ayında, her parselden gelişimini tamamlamış 15 genç yaprak, besin elementleri analizi amacıyla seçilmiştir. Yapraklarda azot, fosfor, potasyum, kalsiyum, magnezyum, çinko ve demir analizi yapılmıştır. Yapraklar önce çeşme suyu ardından 2 kez saf su ile yıkanmış, etüvde 65 ^{o}C'de sabit ağırlığa gelinceye kadar kurutulmuştur. Kurutulan örnekler öğütüldükten sonra 550 ^{o}C'de 5 saat süreyle yakılmıştır. Oluşan kül %3.3'lük (hacim/hacim) HCI asitte çözülerek atomik absorpsiyon spektrometrede K, Ca, Mg, Fe ve Zn konsantrasyonları belirlenmiştir (Jones, 2001). Çilek yapraklarında azot konsantrasyonları ise Kjeldahl yöntemine göre yaş yakma ile belirlenmiştir. Fosfor seviyelerini belirlemek için Barton yöntemi kullanılmıştır (Jones, 2001; Dasgan ve ark.,2023).

Deneme, yedi ay süreyle devam etmiş olup 30 Haziran 2023 tarihinde sonlandırılmıştır. Deneme sonunda uygulamaların her tekerrüründen tesadüfi seçilen 5 bitkide kök uzunluğu, kök kalınlığı, gövde çapı, kök ve gövde kuru madde miktarı belirlenmiştir. Gövde çapı, kök ile gövdesinin birleşme noktasından dijital kumpasla ölçülmüştür. Kök kalınlığı ölçümleri dijital kumpasla yapılmıştır. Kök ve gövde kuru madde miktarında taze ağırlıkları alındıktan sonra 65^{o} C etüvde sabit ağırlığa ulaşıncaya kadar kurutulmuş ve yüzde kuru madde oranları hesaplanmıştır (Türemiş & Kaşka, 1995).

Araştırma, tesadüf blokları deneme desenine göre 3 tekerrürlü ve her tekerrürde 20 bitki olacak şekilde kurulmuştur. Deneme sonucunda elde edilen verilerin istatistik analizinde MSTAT_C paket programı kullanılmış ve ortalamalar arası farklılık LSD'e göre belirlenmiştir.

3. Bulgular ve Tartışma

3.1. Vejetatif büyüme

Farklı organik gübre uygulamalarının çilek bitkisinin vejetatif gelişimi üzerine önemli düzeyde etki etmiştir (Çizelge 2). Organik gübre uygulamalarının kök uzunluğu değerleri kontrole (T_1) göre daha yüksek çıkmış, en uzun kök ise T_4 (25.89 cm) uygulamasında tespit edilmiştir. Khalid ve ark. (2013), Chandler çilek çeşidinde yapılan organik uygulamaların kök uzunluğunu artırdığını, en uzun köklerin 20.11 cm olduğunu, Ateş ve ark. (2019) çilek bitkisine uyguladıkları tavuk gübresinin kök boyunu önemli derece arttırdığını, Apu ve ark. (2022), çilekte farklı dozda (solucan gübresi, bioçar ve mikoriza) organik uygulamalarının etkilerini araştırdıkları çalışmada en uzun köklerin 24.50 cm ile solucan gübresi+mikoriza uygulamasında, en kısa köklerin ise kontrol (gübresiz) uygulamasında elde edildiğini bildirmişlerdir.

Kök kalınlığında en yüksek değer T_4 (1.38 mm) uygulamasında, en düşük değer ise 1.03 mm ile kontrolde (T_1) belirlenmiştir (Çizelge 2). Bitki büyüme ve gelişiminde önemli bir kriter olan gövde çapı açısından, organik uygulamaların kontrole kıyasla daha etkili olduğu belirlenmiştir. Uygulamalar arasında en etkili olan ise 17.59 mm gövde çapı ile T_4 uygulaması olmuştur (Çizelge 2). Köklerdeki en yüksek kuru madde miktarı %35.20 ile T_4 uygulamasında belirlenirken, en düşük miktar %27.13 ile kontrolde (T_1) saptanmıştır. Gövdede %kuru madde miktarları incelendiğinde, T_4 uygulamasının (%27.20) diğer uygulamalara göre en iyi sonucu verdiği tespit edilmiştir (Çizelge 2).

T_4 uygulaması diğer uygulamalara göre çilek bitkisinin büyüme parametrelerini iyileştirmiştir. Bu uygulamanın daha etkili olması, tabandan verilen tavuk gübresinin zengin besin elementi içeriğinden kaynaklanmış olabilir. Makinde & Ayoola (2012), bamyada tavuk ve inek gübresi uygulamalarının etkisinin araştırıldığı çalışmada tavuk gübresinin bitkinin vejetatif büyümesini daha fazla desteklediğini, Khalid ve ark. (2013), çilekte çiftlik gübresi ve solucan gübresi bazlı organik gübrelerin vejetatif büyümeyi artırdığını bildirmişlerdir. Yousry & El-Goud (2020), Karpuz bitkilerinin büyümesi üzerinde organik gübrelerin olumlu etkisini, büyüme aşamasında bitkilerin ihtiyaç duyduğu besin maddelerinin

toprakta yeterli miktarda bulunmasından kaynaklanmış olabileceği ve en iyi uygulamanın tavuk gübresi uygulamasında elde edildiğini bildirmişlerdir. Apu ve ark. (2022) organik katkı maddelerinin hücre bölünmesi ve enzim aktivitesi gibi bitki metabolik süreçlerini etkileyerek kök hacmi, gövde ve kök üzerinde iyileştirici etki yapabileceği, Rashid (2018), organik gübre uygulamalarının toprağın biyolojik işlevlerini iyileştirerek bitki gelişimini olumlu yönde etkileyebileceğini bildirmiştir.

Çizelge 2. Uygulamaların kök uzunluğu, kök kalınlığı, gövde çapı, kök ve gövde kuru madde miktarına etkileri

Uygulamalar	Kök uzunluğu (cm)	Kök kalınlığı (mm)	Gövde çapı (mm)	Kök kuru madde miktarı (%)	Gövde kuru madde miktarı (%)
T_1	20.83 c	1.03 c	12.98 c	27.13 c	19.02 c
T_2	22.22 bc	1.16 b	14.75 bc	31.08 b	22.40 b
T_3	24.22 ab	1.24 b	15.52 b	33.69 ab	24.17 b
T_4	25.89 a	1.38 a	17.59 a	35.20 a	27.20 a
Ortalama	23.29	1.20	15.21	31.78	23.20
LSD	2.56	0.13	1.99	3.105	1.87

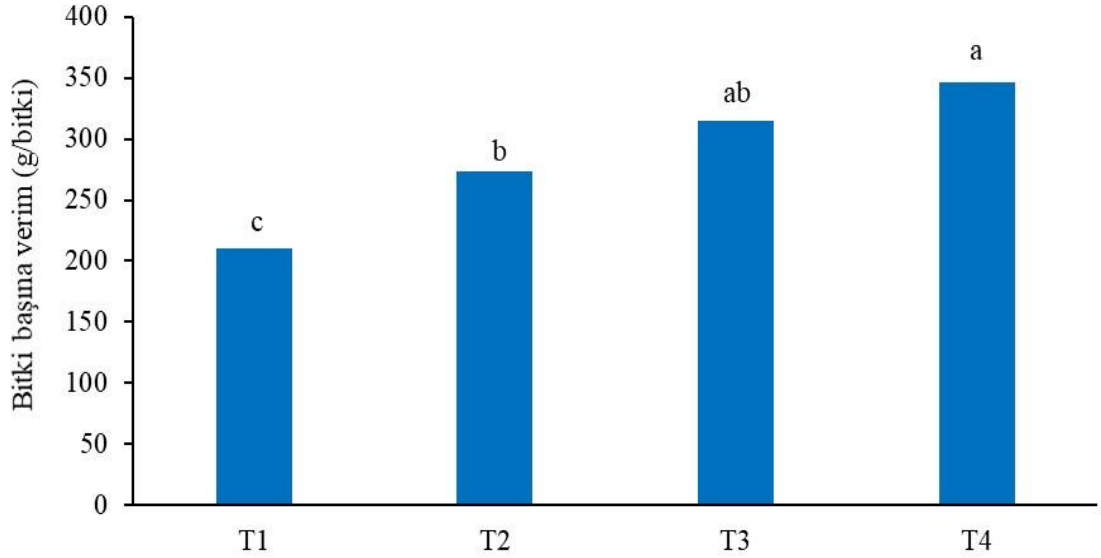
Ortamalar arasındaki önemli farklılıklar farklı harfler ile gösterilmiştir ($P<0.05$).
T_1: Gübresiz (kontrol); T_2: Sıvı gübre (üstten); T_3: Katı çiftlik gübresi (taban) + Sıvı gübre (üstten); T_4: Katı tavuk gübresi (taban) + Sıvı gübre (üstten)

3.2. Bitki başına toplam verim ve ortalama meyve ağırlığı

Bitki başına toplam çilek verimi ve ortalama meyve ağırlığı bakımından uygulamalar arasında önemli farklılıklar tespit edilmiştir. Bitki başına verim açısından en yüksek değer 346.57 g/bitki ile T_4 uygulamasında alınırken, ikinci en yüksek verim 314.84 g/bitki ile T_3 uygulamasında elde edilmiştir. En düşük verim ise 210.45 g/bitki ile kontrolde (T_1) tespit edilmiştir. T_4 uygulaması, T_3 uygulamasına göre %10.07, T_2 uygulamasına göre %26.89 ve kontrole (T_1) göre %64 daha fazla verim artışı sağlamıştır (Şekil 1). Tavuk gübresinin azot içeriği yönünden diğer çiftlik gübrelerine oranla daha değerli olduğu, nem içeriğinin az ve kuru madde miktarının yüksek olduğu bildirilmiştir (Soyergin, 2003).

Mehraj ve ark. (2014), çilekte yaptıkları çalışmada saksıda organik gübre uygulamalarında (inek gübresi, solucan gübresi ve tavuk) en yüksek verimin 282.8 g/bitki solucan gübresi, ardından 223.7 g/bitki ile tavuk gübresi uygulamasında elde edildiğini bildirmişlerdir. Rashid (2018), çilek yetiştiriciliğinde farklı organik gübre uygulamalarının etkilerini araştırmıştır. Çalışmada, en yüksek verimin 319.20 g/bitki ile inek gübresi, hardal küspesi ve kümes hayvanı gübresinin birlikte uygulanmasında elde edildiğini, en düşük verimin ise 115.20 g/bitki ile organik gübre uygulanmayan kontrolde olduğunu bildirmiştir. Negi ve ark. (2021), Chandler çilek çeşidinde tarla koşullarında organik gübre (çiftlik gübresi, solucan gübresi ve orman atıkları) ve biyogübrelerin etkilerinin araştırıldığı çalışmada, en yüksek verimin organik ve biogübrenin birlikte uygulamasında (185.08 g/bitki) elde ettiklerini bildirmişlerdir. Yapılan bir başka çalışmada, Chandler çilek çeşidinde organik (çiftlik gübresi, tavuk gübresi) ve inorganik gübre uygulamalarının etkileri araştırılmıştır. En yüksek verimin 313.44 g ile tavuk ve çiftlik gübresinin birlikte uygulamasında elde edildiği, gübrelerin etkinliğinin, deneme yapılan alana, iklim koşullarına ve çeşitlere bağlı olarak değişebileceği bildirilmiştir (Zahid ve ark., 2022).

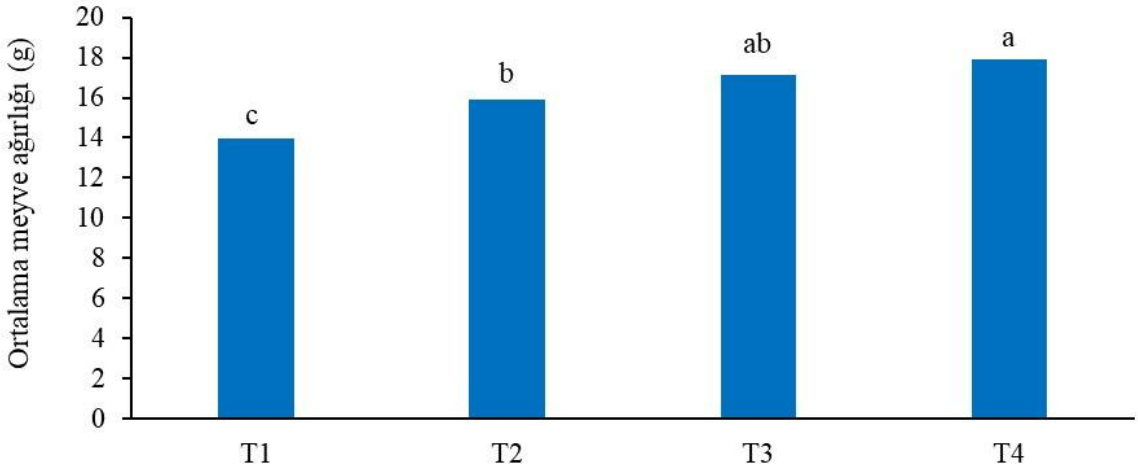
Ayrıca Enujeke (2013), Karpuzda farklı dozda tavuk gübresi uygulamalarının kontrole göre bitki büyümesi ve verimi olumlu etkilediğini, tavuk gübresinin toprak koşullarını iyileştirmekle kalmayıp aynı zamanda verim artışı için yeterli besin elementlerini serbest bıraktığını bildirmişlerdir. Sahin ve ark. (2014) biber bitkisine pelet formda tavuk gübresini, 0 (kontrol), 10, 20 ve 40 g/kg dozları uygulanmış ve temel gübreleme amacıyla bu uygulamalara amonyum nitrat ile monopotasyum fosfat gübresi eklemişlerdir. Yapılan çalışma sonucunda tavuk gübresinin biber bitkisinin gelişimini artırdığı ve meyve verimini önemli ölçüde iyileştirdiğini bildirmişlerdir.



Şekil 1. Uygulamaların bitki başına verim üzerine etkisi.

Ortamalar arasındaki önemli farklılıklar farklı harfler ile gösterilmiştir ($P<0.05$). T_1: Gübresiz (kontrol); T_2: Sıvı gübre (üstten); T_3: Katı çiftlik gübresi (taban) + Sıvı gübre (üstten); T_4: Katı tavuk gübresi (taban) + Sıvı gübre (üstten)

En yüksek meyve ağırlığı 17.96 g ile T_4 uygulamasında en düşük ise 14.06 g ile T_1 uygulamasında belirlenmiştir (Şekil 2). T_4 uygulaması ile meyve ağırlığı, T_3 uygulamasına göre %4.30, T_2 uygulamasına göre %12.39 ve kontrole (T_1) göre % 27.74 artmıştır. Mehraj ve ark. (2014) Saksıda çilek yetiştiriciliğinde farklı organik gübre uygulamaları arasında en yüksek meyve ağırlığının 14.4 g ile solucan gübresi, ardından 13.4 g ile tavuk gübresi uygulamasında elde edildiğini bildirmişlerdir. Rashid (2018) yaptığı çalışmada, çeşitler arasında en yüksek meyve ağırlığının 15.07 g ile Festival çeşidinde, inek gübresi, hardal küspesi ve kümes hayvanı gübresinin birlikte uygulamasıyla elde edildiğini bildirmiştir. Meyve ağırlığındaki artışın, organik gübre uygulamaları ile bitkinin topraktan yeterli besin elementi almasını sağlayarak meyve sayısının ve ağırlığının artmasına katkıda bulunabileceğini belirtmiştir. Meyve iriliğinde, bitkinin genetik yapısının yanı sıra çevresel faktörler ve kültürel işlemlerin (sulama, gübreleme vb.) etkili olduğu bildirilmiştir (Scott & Lawrance, 1975).



Şekil 2. Uygulamaların ortalama meyve ağırlığı üzerine etkisi.

Ortamalar arasındaki önemli farklılıklar farklı harfler ile gösterilmiştir ($P<0.05$). T_1: Gübresiz (kontrol); T_2: Sıvı gübre (üstten); T_3: Katı çiftlik gübresi (taban) + Sıvı gübre (üstten); T_4: Katı tavuk gübresi (taban) + Sıvı gübre (üstten)

3.3. Meyve suyu pH, SÇKM, asitlik, SÇKM/Asit, toplam şeker ve antosiyanin

Çilek meyvelerinde pH, suda çözünür kuru madde (SÇKM), titre edilir asitlik, SÇKM/Asitlik oranı, toplam şeker ve antosiyanin içeriği önemli meyve kalite parametreleridir (Di Vittori ve ark., 2018). Uygulamalar arasında meyve suyu pH değeri 3.44 ile 3.61 arasında değişmekte olup en yüksek pH değeri 3.61 ile T_3 ve T_4 uygulamalarında tespit edilmiştir. Uygulamalar arasında en yüksek SÇKM değeri %10.54 ile T_4 uygulamasında, en düşük değer ise %9.30 ile T_1 uygulamasında belirlenmiştir (Çizelge 3). Mehraj ve ark. (2014), Saksıda çilek yetiştiriciliğinde organik gübre uygulamalarının SÇKM değerinin kontrolden yüksek olduğunu, solucan gübresi uygulamasında SÇKM değerinin %10.2, sıvı tavuk gübresi uygulamasında ise %8.7 çıktığını bildirmişlerdir. Yapılan bir başka çalışmada, Chandler çilek çeşidinde % 10.00 ile en yüksek SÇKM değerinin tavuk ve çiftlik gübresinin birlikte uygulamasında elde edildiği bildirilmiştir (Zahid ve ark., 2022).

Asit değerleri uygulamalara bağlı olarak %0.57-0.63 arasında değişmiştir (Çizelge 3). Elzopy ve ark. (2023) dört farklı organik gübrenin Festival çilek çeşidinde etkilerini araştırmışlardır. Çalışmada çilek meyvelerinin asit değerlerinin 2020/2021 yılında %0.269-0.618 arasında, 2021/2022 yılında %0.299-0.692 arasında ve en yüksek değerin ise kontrolde çıktığını bildirmişlerdir. Organik uygulamaların SÇKM/Asit oranı (T_3:17.93; T_4:17.61 ve T_2:17.14) kontrolden (T_1:14.88) daha yüksek çıkmıştır (Çizelge 3). Kumar ve ark. (2015), Sweet Charlie çilek çeşidinde solucan gübresi ve biyogübrenin tek ve birlikte uygulamalarıyla SÇKM/Asit oranının 12.84-17.05 arasında değiştiğini bildirmişlerdir.

Organik gübrelerin toplam şeker değerleri kontrolden daha yüksek çıkmıştır. En yüksek toplam şekerin T_4 (7.85 g/100 gr) ve T_3 (7.67 g/100 gr) uygulamalarında ve en düşük ise T_1 (6.46 g/100 gr) uygulamasında olduğu belirlenmiştir (Çizelge 3). Sahana ve ark. (2020), saksıda çilek yetiştiriciliğinde farklı organik gübre uygulamalarında, toplam şeker değerlerinin %5.501-7.568 arasında çıktığını bildirmişlerdir. Bhat & Hussain (2023) Chandler çilek çeşidinde farklı oranlarda çiftlik gübresi, solucan gübresi tek ve biyogübre ile birlikte uygulamalarında, çilek meyvelerinin toplam şeker değerlerinin 2020 yılında %6.60-7.67 arasında; 2021 yılında %6.62-7.69 arasında çıktığını ve organik uygulamaların şeker değerlerinin kontrolden yüksek olduğunu bildirmişlerdir. Çilek meyvelerinde şeker artışının, organik gübre uygulamalarının nişasta ve pektinin çözünür bileşiklere metabolik dönüşümünü hızlandırması ve şekerlerin yapraklardan gelişmekte olan meyvelere hızlı taşınmasından kaynaklanıyor olabileceği, ayrıca, gübrelerin içindeki potasyumun (K) meyvelerde şeker birikimini teşvik edeceği bildirilmiştir (Sahana ve ark., 2020).

En yüksek toplam antosiyanin miktarı 48.04 mg siyanidin-3-glikozit/100g ile T_4 uygulamasında, en düşük T_1 (30.41 mg siyanidin-3-glikozit/100g) uygulamasında belirlenmiştir (Çizelge 3). Bhat & Hussain (2023) Chandler çilek çeşidinde farklı oranlarda çiftlik gübresi, solucan gübresi tek ve biyogübre ile birlikte uygulamaların etkileri araştırılmıştır. Yapılan çalışmada, çilek meyvelerinin antosiyanin değerlerini 2020 yılında 39.71-52.67 mg/100g; 2021 yılında 39.73-52.69 mg/100g arasında çıktığını ve en düşük değerin kontrolde olduğunu bildirmişlerdir. Zahid ve ark. (2022) yaptıkları çalışmada, Chandler çilek çeşidinin meyvelerinde en yüksek toplam antosiyanin değerinin tavuk ve çiftlik gübresinin birlikte uygulamasında elde edildiğini bildirmişlerdir. Antosiyaninlerin sentezinde çeşit, ışıklanma, sıcaklık ve gübre uygulamaları etkili olmaktadır (Da Silva ve ark., 2007). Antosiyaninler, meyvelerin renginde önemli bir rol oynamakta, ayrıca insanların kardiyovasküler, kanser gibi hastalıklara yakalanma riskini de azaltmaktadır (Dai ve ark., 2007). Bu uygulamalarda antosiyanin miktarının yüksek olması, organik gübrelerin meyve kalitesini iyileştirmesinin yanı sıra sağlık açısından önemli olduğunu göstermektedir.

Çizelge 3. Uygulamaların pH, SÇKM, Asit ve SÇKM/Asitlik oranı, toplam şeker ve antosiyanin üzerine etkileri

Uygulamalar	pH	SÇKM (%)	TEA (%)	SÇKM/Asit	Toplam Şeker (g/100 g)	Toplam Antosiyanin (mg siyanidin-3-glikozit/100g)
T_1	3.44 c	9.30 c	0.63 a	14.88 b	6.46 c	30.41 c
T_2	3.53 b	10.04 b	0.59 b	17.14 a	7.01 b	31.35 bc
T_3	3.61 a	10.25 b	0.57 b	17.93 a	7.67 a	33.50 b
T_4	3.61 a	10.54 a	0.60 b	17.61 a	7.85 a	48.04 a
Ortalama	3.55	10.03	0.60	16.89	7.25	35.82
LSD	0.06	0.26	0.03	0.90	0.46	2.53

Ortamalar arasındaki önemli farklılıklar farklı harfler ile gösterilmiştir ($P<0.05$).
T_1: Gübresiz (kontrol); T_2: Sıvı gübre (üstten); T_3: Katı çiftlik gübresi (taban) + Sıvı gübre (üstten); T_4: Katı tavuk gübresi (taban) + Sıvı gübre (üstten)

3.4. Yaprakta bitki besin elementi içerikleri

Yapraktaki toplam azot (N), fosfor (P), potasyum (K), kalsiyum (Ca), magnezyum (Mg), demir (Fe) ve çinko (Zn) içeriği açısından uygulamalar arasında önemli farklılıklar belirlenmiştir (Çizelge 4). Uygulamaların yaprak N içeriği %1.60-2.40 arasında değişmekte olup T_4 uygulamasının N içeriği (%2.40) diğer uygulamalara göre daha yüksek çıkmıştır. Mills & Jones (1996), yaprak N içeriğinin %2.10-4.00 arasında yeterli olduğunu bildirmişlerdir. Bu çalışmada organik uygulamaların yaprak N içeriği yeterlilik sınırları içerisinde olup kontrolde (T_1) yetersiz olduğu belirlenmiştir. Demir ve ark. (2010) domateste farklı dozlarda (0,10, 20 ve 40 g kg^{-1}) pelet formunda tavuk gübresi uygulamasının yapraklardaki N içeriğini artırdığını, Negi ve ark. (2021) Chandler çilek çeşidinde yaprak N içeriğinin %0.81 ile %2.67 arasında çıktığını bildirmişlerdir. Elzopy ve ark. (2023), organik gübre uygulamalarını N içeriğinin kontrolden daha yüksek çıktığı, en yüksek azot içeriğinin ise tavuk gübresi uygulamalarında elde edildiğini bildirmişlerdir.

Çilek bitkisinin yaprak P içeriği, uygulamalara bağlı olarak %0.13 (T_1) ile %0.23 (T_4) arasında değişmiştir (Çizelge 4). Mills & Jones (1996), yapraktaki fosfor yeterlilik düzeyinin %0.20-0.45 arasında olduğunu bildirmişlerdir. Uygulamaların yaprak P içeriği yeterlilik sınırları içerisinde olup kontrolde (T_1) yetersiz çıkmıştır. Demir ve ark. (2010) domateste ve Sahin ve ark. (2014) biberde farklı dozlarda pelet formunda tavuk gübresi uygulamasının, yapraklardaki P içeriğini artırdığını bildirmişlerdir. Zydlik & Zydlik (2023) Rumba çilek çeşidinde yapraktan humik asitin, yaprak fosfor değerini %0.24 ile %0.28 arasında olduğunu bildirmişlerdir

Uygulamalar arasında en yüksek yaprak K içeriği %1.67 ile T_4 ve %1.55 ile T_3 uygulamalarında iken, en düşük K içeriği ise %1.11 ile kontrolde (T_1) belirlenmiştir (Çizelge 4). Mills & Jones (1996), yapraktaki K yeterlilik düzeyinin %1.10-2.50 arasında olduğunu bildirmişlerdir. Bu değerler çalışmada elde ettiğimiz yaprak K içeriğinin yeterlilik sınırı içinde olduğunu göstermektedir. Hassan (2015) organik, inorganik ve biogübrenin farklı oranlarının Sweet Charlie çilek çeşidinde etkisinin araştırıldığı çalışmada %100 kompost uygulamasının K içeriğini 2011/2012 yılında %1.59 ve 2012/2013 yılında %1.62 olarak bulduğunu bildirmiştir.

Uygulamaların yaprak Ca içeriği % 0.95 (T_1) ile %1.22 (T_4) arasında değişmiştir (Çizelge 4). Mills & Jones (1996), yapraktaki Ca yeterlilik düzeyinin % 0.60-2.50 arasında olduğunu bildirmişlerdir. Bu çalışmada, tüm uygulamalarda yaprak Ca içeriğinin yeterli olduğu tespit edilmiştir. T_4 uygulamasında en yüksek yaprak Mg içeriği (%0.30) elde edilirken, kontrolde (T_1) en düşük Mg içeriği (%0.18) elde edilmiştir (Çizelge 4). Mills & Jones (1996), yaprak Mg içeriğinin %0.25-0.70 arasında yeterli olduğunu bildirmişlerdir. Uygulamaların yaprak Mg içeriği yeterlilik sınırları içerisinde olup kontrolde (T_1) yetersiz çıkmıştır. En yüksek yaprak Fe içeriği T_4 (68.75 mg/kg), T_3 (66.75 mg/kg) ve T_2 (62.13 mg/kg) uygulamalarında iken, en düşük Fe içeriği 54.13 mg/kg ile kontrolde (T_1) belirlenmiştir (Çizelge 4). Mills & Jones (1996), yapraktaki Fe yeterlilik düzeyinin 50-250 mg/kg arasında olduğunu bildirmişlerdir. Tüm uygulamaların yaprak Fe içeriği yeterli düzeyde çıkmıştır. Uygulamaların yaprak Zn içeriği 15.13 mg/kg (T_1) ile 30.38 mg/kg (T_4) arasında değişmiştir (Çizelge 4). Yaprakta çinko

yeterlilik düzeyini Mills & Jones (1996), 20-50 mg/kg arasında olduğunu bildirmişlerdir. Uygulamaların (T_2, T_3 ve T_4) yaprak Zn içeriği yeterlilik sınırları içerisinde yer alırken, kontrol (T_1) yetersiz bulunmuştur. Sahin ve ark. (2014) biberde farklı dozlarda pelet formunda tavuk gübresi uygulamasının, yapraklardaki Zn içeriğini artırdığını bildirmişlerdir.

Bu çalışmada T_4 uygulamasının yapraktaki besin element içeriği diğer uygulamalara göre daha yüksek çıkmıştır. Tabandan uygulanan tavuk gübresinin, bitkinin ihtiyacı olan besin elementlerini uzun süreli ve dengeli almasını sağlamış olabilir. Cayci ve ark. (2017) tavuk gübresinin toprak organik karbon ve toplam azot miktarını artırdığını, Dróżdż ve ark. (2020) Tavuk gübresinin azot bakımından zengin olduğunu ancak aynı zamanda önemli miktarda fosfor, potasyum içerdiğini ve toprak iyileştirici olarak etkili olabileceğini bildirmişlerdir.

Çizelge 4. Uygulamaların çilek yapraklarının azot, fosfor, potasyum, kalsiyum, magnezyum, demir ve çinko içerikleri üzerine etkileri

Uygulamalar	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg/kg)	Zn (mg/kg)
T_1	1.60 c	0.13 c	1.11 c	0.95 c	0.18 c	54.13 b	15.13 d
T_2	2.22 b	0.20 b	1.29 b	1.15 b	0.25 b	62.13 a	20.38 c
T_3	2.31 b	0.21 ab	1.55 a	1.15 b	0.25 b	66.75 a	24.25 b
T_4	2.40 a	0.23 a	1.67 a	1.22 a	0.30 a	68.75 a	30.38 a
Ortalama	2.13	0.19	1.40	1.12	0.24	62.94	22.53
LSD	0.09	0.02	0.14	0.06	0.02	7.73	1.70

Ortamalar arasındaki önemli farklılıklar farklı harfler ile gösterilmiştir ($P<0.05$).
T_1: Gübresiz (kontrol); T_2: Sıvı gübre (üstten); T_3: Katı çiftlik gübresi (taban) + Sıvı gübre (üstten); T_4: Katı tavuk gübresi (taban) + Sıvı gübre (üstten) mg/kg = ppm

4. Sonuç

Bu çalışmada Monterey çilek çeşidinde, pelet çiftlik gübresi, pelet tavuk gübresi ve bitkisel menşeili sıvı organik gübre uygulamalarının bitki büyümesi, verim ve meyve kalite parametreleri üzerine etkisi araştırılmıştır. Yapılan çalışmada, Monterey çilek çeşidinde organik gübrelerin bitki gelişimi, verim, meyve kalite özellikleri ve yaprak besin element içerikleri kontrole kıyasla daha yüksek çıkmıştır. Toplam verim, meyve ağırlığı, SÇKM, SÇKM/asitlik, toplam şeker, antosiyanin, yaprak besin elementi değerleri ve vejetatif gelişim bakımından en iyi sonucun T_4 uygulamasında "Tavuk gübresi (taban)+Sıvı gübre (üstten)" olduğu tespit edilmiştir. Sonuçlar, çilek bitkisinde tavuk gübresinin bitki büyüme ve verimliliği açısından diğer organik gübrelere göre daha etkili olduğunu göstermiştir. Tavuk gübresinin besin element içeriğinin zengin olması ve pelet formu ile toprağa sağladığı besin elementlerini bitkinin büyüme ve gelişimi boyunca bulabilmesini sağlayarak dengeli beslenmesinde etkili olduğu düşünülmektedir. Çilek üretiminde toprak, bitki ve çevre üzerinde olumlu etkileri olan tavuk gübresinin kullanımının yaygınlaştırılması, sürdürülebilir tarımın gelişimine katkı sağlayabilir.

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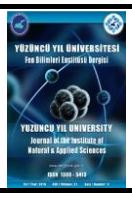
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Araştırma Makalesi

Arbusküler Mikoriza, Polimer ve Osmoprotektanın Yapraklı Tür Ağaçlandırmasının Başarısız Olduğu Koşullarda İğde (*Elaeagnus angustifolia* L.) Fidanlarının Büyüme ve Yaşam Süresine Etkisi

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Öz: Su açığı bulunan sahalarda iklim değişikliği ile birlikte var olan stres faktörleri daha da şiddetli hale gelmektedir. Bu çalışmanın amacı büyüme döneminde şiddetli su açığı gerçekleşen alanda bitkilerin kuraklığa karşı direncini arttıracak bitki destekleyici işlemlerin (mikoriza, polimer, osmoprotektan, polimer + osmoprotektan) fidanların arazi performansına olan etkilerinin belirlenmesidir. İzmir Kâtip Çelebi Üniversitesi kampüs alanında yer alan çalışma sahasına sulama yapılmaksızın 1+1 yaşlı iğde (*Elaeagnus angustifolia* L.) fidanları dikilmiştir. Çalışmada fidanların yaşama oranları, çap ve boy değerleri, nispi çap ve boy artımları ve toprak nemindeki değişimler tespit edilmiştir. Mikoriza, polimer, osmoprotektan uygulamaları, fidanların sıcaklık rekorlarının kırıldığı dönemi atlatmasını sağlayamasa da hayatta kalma sürelerini iki ay uzatılabilmiştir. Toprak neminin en düşük olduğu Temmuz ayında polimer ve mikoriza ünitesindeki nem değerleri kontrol ünitesindekine göre %73 daha fazla ölçülmüştür. Mikoriza, polimer, osmoprotektan ve polimer+osmoprotektan ünitelerindeki fidanların kontrole göre yaklaşık %23 daha kalın çapa sahip oldukları ve %73 daha fazla çap artışı gerçekleştirdikleri tespit edilmiştir. Polimer ve osmoprotektan ünitelerindeki fidanların boyunun kontrol, mikoriza ve polimer+osmoprotektan ünitelerine göre yaklaşık %47 daha uzun olduğu belirlenmiştir. Kontrole göre diğer ünitelerdeki fidanlar iki kat fazla nispi boy artımı gerçekleştirmiştir.

Anahtar Kelimeler: Glisin-Betain, Mikorizal funguslar, Nispi büyüme oranları, Su tutucu polimer, Toprak nemi

Effects of Arbuscular Mycorrhiza, Polymer and Osmoprotectant on Growth and Survival of Russian Olive (*Elaeagnus angustifolia* L.) Seedlings Under Conditions Where Broadleaf Species Afforestation Fails

Abstract: In water deficit areas, existing stressors are becoming more severe with climate change. Therefore, the aim of this study was to determine the effects of plant supportive treatments (mycorrhiza, polymer, osmoprotectant, polymer + osmoprotectant) on the water stress of seedlings to increase the drought resistance of plants in an area with severe water deficit during the growth period. 1 + 1 Russian olive (*Elaeagnus angustifolia* L.) seedlings were planted without irrigation in the study area located in the campus area of Izmir Kâtip Çelebi University. In the study, survival rates, diameter and height values, relative growth rates of root collar diameter and shoot height and changes in soil moisture were determined. Although mycorrhiza, polymer and osmoprotectant treatments did not help the seedlings to survive the period of record-breaking temperatures, they were able to extend their survival by two months. In July, when soil moisture levels were the lowest, the polymer and mycorrhiza treatments were 73% higher than the control. Seedlings in mycorrhiza, polymer, osmoprotectant and polymer+osmoprotectant units had about 23% thicker diameter and 73% more relative growth rates of root collar diameter than the control. Seedlings in polymer and osmoprotectant units were about 47% taller than the control, mycorrhiza and polymer+osmoprotectant units. Compared to the control, the seedlings in the other units realized two times more relative growth rates of shoot height.

Keywords: Glycine-betaine, Mycorrhizal fungi, Relative growth rates, Soil moisture, Super-absorbent polymer

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1. Giriş

Kurak sahalar, karasal düzeyde dünyamızın %40'ından fazla alanı kaplamaktadır (Bastin ve ark., 2019; Schimel, 2010). Ülkemizin alansal dağılımı göz önüne alındığında ise yaklaşık olarak %37'si yarı kurak iklim koşulları etkisi altında kalmaktadır. Kurak ve yarı kurak alanların miktarı 51 milyon hektarı kapsamaktadır. Gelecekte ülkemizin kurak ve yarı kurak alan dağılımının değişebileceği öngörülmektedir (Anonim, 2014). İklim değişikliği senaryolarına göre Türkiye'nin Ege bölgesinde var olan kuraklık durumu ileriki yıllarda daha da şiddetlenecektir. Su açığının olduğu alanlarda bitkilerin faydalanabileceği su kaynaklarının yetersiz olması ve bozulan toprak yapısının yeterince su depolayamaması sebebiyle bu alanlarda yapılan mevcut ağaçlandırma çalışmalarının başarıya ulaşması oldukça zordur. Küresel düzeyde son zamanlarda daha da bariz şekilde ortaya çıkan yüksek sıcaklık ve düşük yağış unsurlarının sebep olduğu ağaç kuruma oranlarının ve orman alanlarının azalmasındaki artışa (Liu ve ark., 2022) karşı bahse konu sorunlu sahaların ağaçlandırmasında fidanların su stresini azaltıcı işlemlerin (mikoriza, polimer, osmoprotektan) uygulanması önem arz etmektedir.

Mikoriza bitkilerin su streslerini azaltmada yardımcı olduğu için kurak ve yarı kurak sahalarda yapılan ağaçlandırma çalışmalarında başarıyı destekleyebilecek özelliktedir. Toprak (2020a), su stresine karşı dayanıklı fidanların yetiştirilmesi ve mikorizanın bitkilerin su stresine olan etkilerinin belirlenmesi amacıyla İç Anadolu'daki ağaçlandırma sahalarından toplanan mikorizal sporları üreterek steril yetişme ortamındaki Yalancı akasya (*Robinia pseudoacacia* L.) tohumlarına aşılamıştır. Elde ettiği mikorizal fidanların tüplerindeki toprak nemi değişimlerine göre yaprak su potansiyellerindeki farklılığı Basınç Çemberi cihazı (PMS Instruments Company, 1505D-EXP) ile gün ortası ölçümleri yaparak ortaya koymuştur. Mikorizalı olmayan fidanların yetişme ortamındaki nemin %4 seviyelerine geldiğinde kuruduklarını, mikorizalı olanların ise hayatiyetlerini devam ettirebildiklerini tespit etmiştir. Çalışmada mikoriza, fidanların su stresine olan dayanıklılığını arttırarak fidanların çektiği su stresini azaltmıştır. Ortaya çıkan sonuçlar ele alındığında, su açığının olan sahalarda yapılacak olan ağaçlandırma çalışmalarında mikoriza kullanımının önemi ortaya çıkmaktadır.

Toprağa ilave edilen bazı maddeler de fidanların yetişmesine katkı sağlamak için kullanılmaktadır. Bu maddeler arasında fidanın kurak dönemi atlatmasına destek sağlayan su tutucu polimerler dikkat çekmektedir. Bitkilerin hayatiyetini devam ettirmekte zorlandığı özellikle su açığının fazla olduğu sahalarda polimerler yağış ile birlikte gelen suları toprak içerisinde daha fazla adsorbe ederek su açığının fazla olduğu aylarda bitkilerin suya ulaşmasına yardımcı olmaktadır. Aynı zamanda polimer vb. uygulamaların yapıldığı topraklarda bitkilerin daha iyi büyüme ve kök gelişimi sağladığı ortaya konmuştur (Sharma, 2004; Arbona ve ark., 2005; Viero & Little, 2006; Shi ve ark., 2010). Toprağın su tutma kapasitesini arttırdığı; bitkinin su stresini azalttığı, bitki büyümesine, beslenmesine ve yaşama oranına olumlu etkileri olduğu belirtilen polimerlere (Raju ve ark., 2003; Han ve ark., 2005; Yu ve ark., 2012; Madakbaş ve ark., 2014; Darini ve ark., 2015; Akat, 2020) ilişkin farklı araştırmalarda polimerlerin önemli bir faydasının olmadığı da (Tu ve ark., 1985; Ingram & Yeager, 1987) rapor edilmiştir. Bu çelişkinin sebebinin ise superabsorbant materyallerinin çeşitli çevresel ve iklimsel koşullarda değişik bitki türlerinde denenmemiş olmasından kaynaklandığı düşünülmektedir. Bu bakımdan projeye konu olan farklı şiddetlerde su açığı oluşan sahalarda belirli miktarda polimerin denenmesi sonucunda elde edilen veriler bu konudaki bilgi eksikliğine katkıda bulunacaktır.

Osmoprotektan olan Glisin ve Betain kuraklığa, ekstrem sıcaklıklara, tuzluluğa karşı dayanıklılığı arttırdığından ve osmotik dengeyi ayarlamaya yardımcı olduğundan (Roussos ve ark., 2010; Denaxa ve ark., 2012) dolayı kuraklığın hüküm sürdüğü alanların ağaçlandırma çalışmalarında denenmesi büyük önem arz etmektedir.

İklim değişikliği ve kuraklığının tehdit olduğu sahalarda toprak, bitki ve su kaynaklarının sürdürülebilirliğinin sağlanabilmesine katkı sunacak verilerin üretilmesi gerekmektedir. Dolayısıyla yukarıda belirtilen bilgilere ilişkin boşlukların giderilmesine dair özgün değer içeren bu çalışmanın amacı vejetasyon döneminde su açığı bulunan ve sulama yapılmaksızın yapraklı tür ağaçlandırmasında başarı sağlanamayan sahaların rehabilitasyonuna yönelik uygulamalar için altlık oluşturmaktır.

2. Materyal ve Yöntem

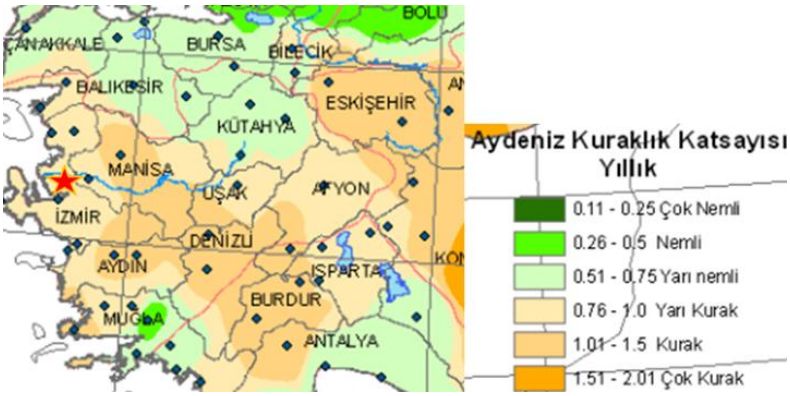
2.1. Çalışma sahası

Çalışma, su kıtlığı, sıcaklık ve rüzgâr gibi faktörlerden bitki büyümesinin olumsuz etkilendiği Çiğli/İzmir'deki İzmir Kâtip Çelebi Üniversitesi'nin kampüs alanı içerisinde gerçekleştirilmiştir (Şekil 1). Bu çalışmanın yapıldığı yıldan önce kampüse dikilen 2 bin yapraklı tür fidanı, yoğun stres karşısında hayatiyetlerini sürdüremeyerek kurumuşlardır.



Şekil 1. Çalışma sahasının konumu (a) ve görünümü (b,c).

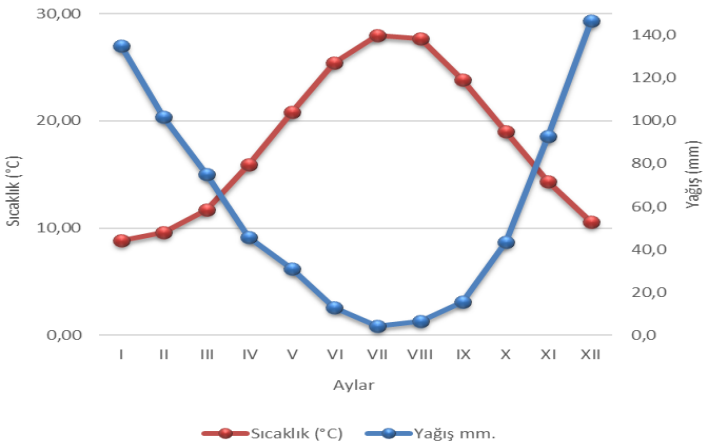
Çalışma sahasının bulunduğu bölgede yılın yedi ayında yaz, beş ayında ise kış koşullarının olduğu Akdeniz iklimi hâkimdir (Atalay, 2014). Sahada yaz aylarında yetersiz olan yağış miktarı ile birlikte yüksek sıcaklık ve buharlaşma bitkinin rizosferinde şiddetli su kıtlığına sebep olmaktadır. Aydeniz iklim sınıflandırmasına (1981-2016) göre sahaların yer aldığı İzmir yarı kurak olarak belirtilmektedir (Şekil 2) (Anonim, 2016).



Şekil 2. Aydeniz Kuraklık Katsayısına göre oluşturulan haritada sahanın konumu (Anonim, 2016).

Cebeci ve ark. (2019) Türkiye'nin 81 ilindeki meteoroloji istasyonlarından ortalama olarak aylık toplam yağış miktarları ve aylık ortalama sıcaklık verilerini elde ederek Bagnouls-Gaussen kuraklık indislerini hesaplamışlardır. Söz konusu çalışmadaki 1981-2016 yıllarını kapsayan Bagnouls-Gaussen kuraklık indisine göre çalışma sahasının yer aldığı İzmir çok kurak olarak sınıflandırılmıştır.

Deneme sahasına ait iklimin Copernicus/ ECMWF- ERA5 (Hersbach ve ark., 2020) verileri incelendiğinde yıllık yağış rejiminin düzensizleştiği ve hem yağış hem de sıcaklık anomalilerinin arttığı gözlemlenmektedir. İzmir'e ait (1938-2023) verilere göre oluşturulan Walter iklim diyagramı Nisan ayından Ekim ayının ortalarına kadar bölgede su açığı olduğunu göstermektedir (Şekil 3).



Şekil 3. Walter iklim diyagramı (İzmir).

2.2. Bitkisel materyal

Çalışmada 2x2 m aralıklarla TTS-2120 Menderes OİM-Torbalı OİŞ orijinli, tüplü 1+1 yaşlı iğde (*Elaeagnus angustifolia* L.) fidanları 2023 Mart ayında sahaya dikilmiştir. Tüp hacmi 1.3 L olup harc ortamı %60 toprak, %20 torf, %10 cüruf ve %10 leonarditten oluşturulmuştur. İğde kurak ve yarı kurak arazilerin ağaçlandırılmasında kullanılan iğde su stresine karşı oldukça dayanıklı bir tür olarak nitelendirilmektedir (Toprak, 2020b). Ayrıca iğde, yenilebilir meyveleri hem ekonomik açıdan hem de yapılacak olan ağaçlandırma çalışmalarında kırsal alanda yaşayan yöre halkının kalkınmasını ve bölgedeki yaban hayvanlarını çekerek bölgenin biyoçeşitliliğin zenginleşmesine katkı sağlayabilecek niteliktedir. İğde azot bağlaması sebebiyle besin bakımından sahayı zenginleştiren ve saha verimliliğinin artmasıyla bitki örtüsü gelişiminin hızlanmasını sağlayabilen bir türdür (Evans & Turnbull, 2004).

2.3. İşlemler

2.3.1. Arbusküler mikorizal fungus işlemi

Arbüsküler mikorizal mantarları içeren ticari mikorizal ürün (RhizoMyx®[Novozymes]) çalışmada fidanlara uygulanmıştır (Çizelge 1). Mikorizal işlem uygulanmış ünitelerde dikilen her fidanın kök bölgesine bir gram mikorizal ürünün 500 ml suda karıştırılmasıyla oluşan çözelti uygulanmıştır.

Çizelge 1. Mikorizal karışımın içeriği (RhizoMyx ® [Novozymes])

Arbusküler mikorizal mantarlar	**(propagule/g)**	**Ek Bileşenler**	**%**
Rhizophagus irregularis	21	Humik asitler	28.7
Funneliformis mosseae	20	Su yosunu ekstraktları	18
Glomus aggregatum	20	Askorbik asit	12
Rhizophagus clarus	1	Amino asitler	6
Glomus monosporum	1	Myo-inositol	2.5
Glomus deserticola	1	Surfactant	2.5
Glomus brasilianum	1	Tiamin (Vitamin B_1)	1.75
Glomus etunicatum	1	Aplha-tocopherol	1
Gigaspora margarita	1		

2.3.2. Osmoprotektan işlemi

Fidanlarda osmoprotektan etkisinin tespit edilmesi için osmotik koruyucu olarak glisin betain etken maddeli "Greenstim" adlı ürün kullanılmıştır. Çalışmada %0.5'lik glisin betain uygulaması tek vejetasyon döneminde Haziran, Temmuz, Ağustos ve Eylül aylarında bir kez olmak üzere yılda toplam 4 kez sırt pulverizatörü ile yapraktan uygulanmıştır. Uygulanmış olan glisin- betain dozu ve zamanlaması Küçük (2013) ve Hozman (2016) tarafından uygulanan dozlar dikkate alınarak kararlaştırılmıştır.

2.3.4. Polimer işlemi

Çalışmada, bileşiminde saman bulunan, hacminin 200-300 katı su ile birlikte besini de tutabilen ve bitkinin ihtiyacı olduğu kadarını köklere verebilen, Bozok Teknopark çatısı altında yürütülen Ar-Ge çalışmaları sonucunda samanın modifikasyonu ve akrilik polimerizasyonuyla hazırlanmış yerli malı olan samanlı süper absorban polimer (Natural Aquatic®) kullanılmıştır. Fidan başına bu superabsorbentten üretici tarafından tavsiye edilen doz olan 50 g uygulanmıştır.

2.4. Deneme deseni

Çalışma için beş deneme ünitesi oluşturulmuştur. 1-Mikoriza (M), 2- Polimer (P), 3-Osmoprotektan (O), 4- Polimer+ Osmoprotektan (P+O) şeklinde 4 farklı işlem uygulanmıştır. Ayrıca sahada bir adet kontrol ünitesi (Kn) işlemlerin etkisinin karşılaştırmak için oluşturulmuştur. Bir deneme ünitesinde 20 tane fidan yer almıştır. Deneme ünitelerinin dört bir tarafında kenar etkisini en aza indirebilmek amacıyla 5'er metrelik tampon bölgeler bırakılmıştır.

2.5. Ölçüm ve analizler

Dikimden önce rasgele belirlenen beş noktadan ve ilk 20 cm derinliğinden ikişer set toprak örneği alınmıştır. Birinci set toprak örneği hacim ağırlığı için 100 cm^3'lük silindirlerle örneklenmiştir. İkinci set toprak örneği fiziksel ve kimyasal analizler için kullanılmıştır. İkinci set toprak örneği için alınan örnekler birleştirilerek bir kompozit örnek oluşturulmuştur.

Silindirlerle alınan toprak örnekleri 105 ºC sıcaklığa sahip etüvde sabit ağırlığa gelene kadar kurutulduktan sonra tartılarak hacim ağırlıkları hesaplanmıştır. İkinci set toprak örneği ise hava kurusu hale getirilip porselen havanlarda keseklerin parçalanmasının ardından iki mm gözenekli eleklerden elenerek fiziksel ve kimyasal analizler için hazır hale getirilmiştir. Bouyoucos hidrometre yöntemiyle elde edilen tanecik bileşimiyle toprak bünyesi belirlenmiştir (Gee & Bauder, 1986). Toprak tepkimesi cam elektrotlu pH metre ile tespit edilmiştir (Hanna-HI 221; Thomas, 1996). Tuzluluk seviyesinin dolaylı olarak belirlenmesi için elektrik iletkenliği (EC) µS cm^{-1} olarak ölçülmüştür (WTW InoLab Cond Level 1; Rhoades, 1996). Toplam kireç miktarı Scheibler kalsimetresi ile belirlenmiştir (Loeppert & Suarez, 1996). Toprakta bulunan N kuru yakma yöntemi ile tespit edilmiştir (Elementar vario MAX CNS analyzer, Elementar Analysensysteme, Hanau, Germany). Değiştirilebilir katyonlar (P, K) ICP/OES (Perkin Elmer) ile belirlenmiştir.

Ayrıca arazideki anlık nem miktarındaki değişim için her ünitede 5 adet fidanın gövdesinden dışa doğru 20 cm mesafedeki toprağın ilk 20 cm'sindeki nem miktarları TDR (TRIME-PICO64, IMKO GmbH) yöntemiyle anlık ölçümler yapılarak belirlenmiştir. Nem ölçümleri Mayıs, Haziran, Temmuz, Ağustos ve Eylül aylarında yapılmıştır.

Fidanların büyüme dönemi içerisinde her ay yaşama oranları belirlenmiş; kök boğazı çapları (KBÇ) dijital çap ölçer ve boyları (FB) metre yardımıyla ölçülmüştür. Vejetasyon döneminin başında sahalara dikilen tüm fidanlara numara verilerek çap ve boy değerleri kaydedilmiştir. Hunt (1990) tarafından belirtilen hesaplamalar doğrultusunda yaşayan fidanlar esas alınarak nispi çap (NÇA, mm mm^{-1} $yıl^{-1}$) ve boy (NBA, cm cm^{-1} $yıl^{-1}$) artımları, ikinci yılsonundaki logaritmik olarak kök boğazı çapı ($lnKBÇ_2$) ve boyu ($lnFB_2$) ile dikim anındaki logaritmik kök boğazı çapı ($lnKBÇ_1$) ve boyu ($lnFB_2$) arasındaki farkın ölçümler arasındaki geçen süreye (t) oranlanmasıyla belirlenmiştir (Denklem 1 ve 2).

$$\text{NÇA} = (\text{In KBÇ}_2 - \text{In KBÇ}_1)/\text{t} \quad (1)$$

$$\text{NBA} = (\text{In F}B_2 - \text{In F}B_1)/\text{t} \quad (2)$$

2.6. İstatistiki analizler

Tesadüfi parseller deneme desenine göre analizler SAS (Statistical Analysis Software, 1996) programında gerçekleştirilmiştir. Sonuçlar $p<0.05$ düzeyinde farklı kabul edilmiştir. İşlemlerin istatistiki olarak önemli farklılıklar oluşturduğu değişkenler için ortalamaları ayırma işlemi olarak Tukey HSD testi $\alpha=0.05$ düzeyinde uygulanmıştır.

3. Bulgular

3.1. Toprak özellikleri

Çalışma sahasının toprağı USDA toprak tekstür üçgenine göre killi balçık bünyelidir. OGM (2024)'teki sınır değerleri göz önüne alındığında; toprakların reaksiyonu orta alkali, tuzsuz, orta kireçli, organik madde bakımından düşük düzeydedir. Besin elementleri açısından topraklarda azot düzeyi çok düşük; mangan ve bor düşük; çinko orta; bakır yeterli; fosfor, potasyum, kalsiyum, magnezyum ve demir yüksek düzeyde bulunmuştur (Çizelge 2-3).

Çizelge 2. Toprağın bazı özellikleri

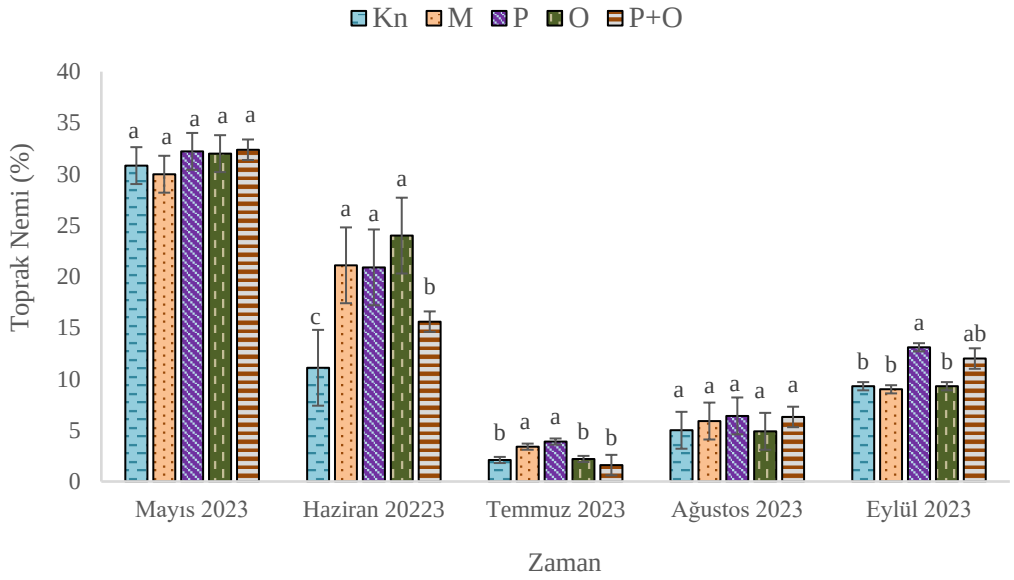
Toprak türü	**Hacim ağırlığı (g/cm^3)**	**Organik madde (%)**	**Toplam kireç (%)**	**pH**	**EC (dS/m)**
Killi balçık	0.9	0.5	12.03	7.6	0.63

Çizelge 3. Toprağın besin elementleri

N	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Zn**	**Cu**	**B**
%					mg/kg				
0.03	17	633	4885	523.5	6.1	9.1	1.3	2	0.89

3.2. Toprak nemi

Haziran, Temmuz ve Eylül 2023'de fidanların kök bölgesindeki toprak nemi bakımından işlemler arasında farklılıkların olduğu belirlenmiştir (P-değeri sırasıyla <0.0001; 0.0006; 0.0051). Haziran ayında M, P ve O ünitelerindeki toprak nemi Kn ünitesindekine göre yaklaşık iki kat daha fazla olduğu tespit edilmiştir. Temmuz ayında P ve M ünitesindeki toprak nemi kontrol ünitesindekine göre %73 daha fazla olduğu belirlenmiştir. Eylül ayında P ünitesindeki toprak nemi Kn, M ve O ünitesindekilerden %42 daha fazla ölçülmüştür. Mayıs ve Ağustos 2023 tarihlerinde fidanların kök bölgesindeki toprak nemi işlem farkı olmaksızın sırasıyla ortalama %31 ve 6 olarak tespit edilmiştir (Şekil 4).



Şekil 4. İğde fidanlarının kök bölgesindeki toprak nem yüzdelerinin ortalamaları ± standart hataları (Aynı harflerle takip edilen ortalamalar α=0.05 düzeyinde birbirlerinden farklı değildir. Kontrol (Kn), Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O)).

3.3. Fidanların hayatta kalma oranları

Mikoriza, polimer ve osmoprotektan uygulanan fidanların tamamı Mayıs ayında hayatta kalmalarına rağmen kontrol ünitesindeki fidanların yarısı hayatiyetlerini yitirmiştir. Temmuz ayında ise kontrol fidanlarının tamamı kuruduğu tespit edilmiştir. Diğer ünitelerdeki fidanların yaklaşık yarısı hayatiyetlerini korumuştur. Fakat hayata tutunan fidanların yarısı da sıcaklık rekoru kırılan ağustos ayında kurumuş olup Eylül ayında tüm fidanların hayatiyetlerini kaybettikleri tespit edilmiştir (Çizelge 4).

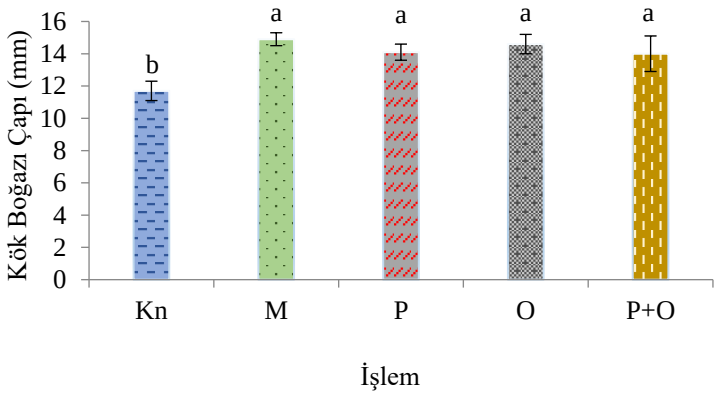
Çizelge 4. İğde fidanlarının yaşama oranları ortalamaları (%)

	M	**P**	**O**	**P+O**	**Kn**
Mayıs	100	100	100	100	50
Haziran	100	100	100	100	50
Temmuz	60	50	50	40	0
Ağustos	20	15	15	15	0
Eylül	0	0	0	0	0

Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O), Kontrol ünitesi (Kn)

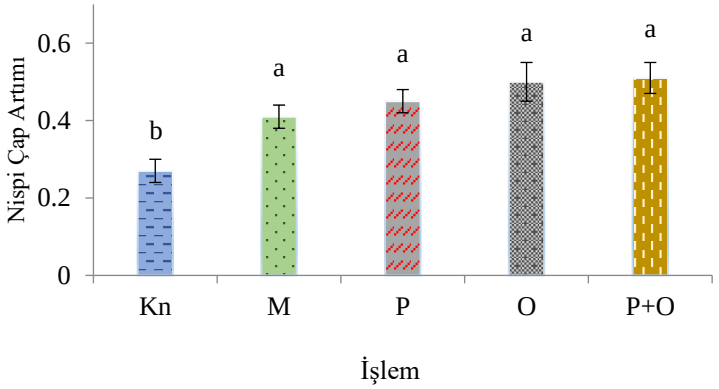
3.4. Çap artışı

Arazide dikimlerin gerçekleştirildiği büyüme dönemi sonunda M, P, O ve P+O ünitelerindeki fidanların KBÇ'sinin Kn ünitesindekinden yaklaşık %23 daha kalın olduğu belirlenmiştir (P-değeri 0.0160; Şekil 5).



Şekil 5. İğde fidanlarının büyüme dönemi sonundaki KBÇ ortalamaları ± standart hataları (Aynı harflerle takip edilen ortalamalar α=0.05 düzeyinde birbirlerinden farklı değildir. Kontrol (Kn), Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O)).

Fidanların nispi çap artımları bakımından büyüme dönemi sonunda işlemler arasında farklılıkların olduğu tespit edilmiştir (P-değeri 0.0026). M, P, O ve P+O ünitelerindeki fidanların NÇA'larının Kn ünitesindekinden yaklaşık %73 fazla olduğu tespit edilmiştir (Şekil 6).

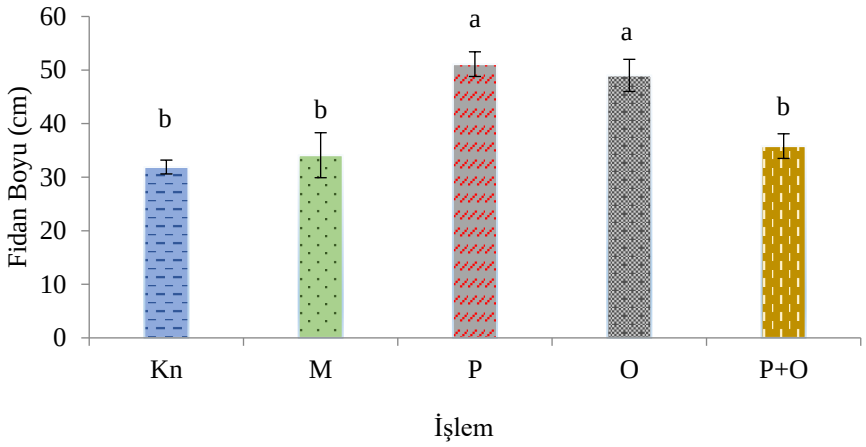


Şekil 6. İğde fidanlarının nispi çap artımı ortalamaları ± standart hataları (Aynı harflerle takip edilen ortalamalar α=0.05 düzeyinde birbirlerinden farklı değildir. Kontrol (Kn), Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O)).

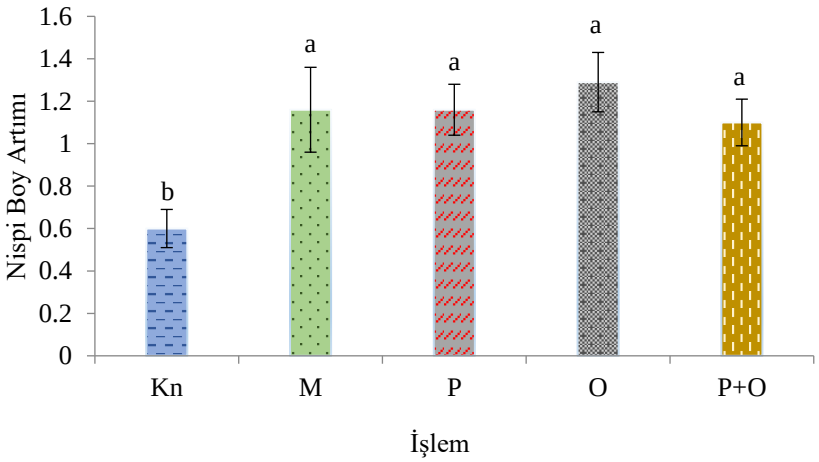
3.5. Boy artışı

Büyüme dönemi sonunda P ve O ünitelerindeki fidanların FB'sinin Kn, M ve P+O ünitelerindekinden yaklaşık %47 daha uzun olduğu belirlenmiştir (P-değeri <0.0001, Şekil 7).

Fidanların nispi boy artımları bakımından büyüme dönemi sonunda işlemler arasında farklılıkların olduğu tespit edilmiştir (P-değeri 0.0152). M, P, O ve P+O ünitelerindeki fidanların NBA'larının Kn ünitesindekinden yaklaşık iki kat fazla olduğu belirlenmiştir (Şekil 8).



Şekil 7. İğde fidanlarının büyüme dönemi sonundaki FB ortalamaları ± standart hataları (Aynı harflerle takip edilen ortalamalar α=0.05 düzeyinde birbirlerinden farklı değildir. Kontrol (Kn), Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O)).



Şekil 8. İğde fidanlarının nispi boy artımı ortalamaları ± standart hataları (Aynı harflerle takip edilen ortalamalar α=0.05 düzeyinde birbirlerinden farklı değildir. Kontrol (Kn), Mikoriza (M), Polimer (P), Osmoprotektan (O), Polimer+Osmoprotektan (P+O)).

4. Tartışma ve Sonuç

İklim değişikliğiyle birlikte ağaçlandırmaların başarısı üzerinde kritik öneme sahip olan güneş radyasyonu, sıcaklık ve yağış gibi faktörlerdeki değişimlere karşı erken büyüme döneminde fidanlar hassasiyet göstermektedir (Noulèkoun ve ark., 2018). Özellikle son yıllarda büyüme dönemi içerisinde gerçekleşen şiddetli kuraklık, bitkilerin büyümesini sınırlandırmakta ve ağaçlandırmaların başarısızlıkla sonuçlanmasına sebep olmaktadır. Su kıtlığının ağaçlandırmalar üzerinde olumsuz etki oluşturduğu sahalarda geleneksel yöntemlerin haricinde iklim değişikliği ile mücadele kapsamında alternatif yöntemlerin belirlenmesine ihtiyaç duyulmaktadır. Bu konuda kuraklığa karşı yapraklı tür ağaçlandırmalarında başarısızlık durumuna ilişkin bitki destekleyici unsurların kullanılarak fidanların arazi performansının ortaya konulması önem arz etmektedir. Bu çalışmada, 2022 yılında gerçekleştirilen ağaçlandırma çalışmalarında dikilen binlerce yapraklı türe ait fidanın kuruduğu sahada mikoriza, polimer ve osmoprotektan uygulamalarının bitki büyümesi, yaşam süresi ve toprak nemi üzerine etkileri ortaya konularak ağaçlandırmaların başarıya ulaştırılmasına yönelik atılabilecek adımlara dair veriler ortaya konulmuştur.

Mikoriza, polimer ve osmoprotektan uygulamalarının gerçekleştiği tüm ünitelerdeki fidanlar, nispi çap ve boy artımında kontrol ünitesindeki fidanlara göre üstünlük kurmuşlardır. En zayıf büyüme

performansının meydana geldiği kontrol ünitesindeki fidanlara kurulan bu üstünlüğün, diğer ünitelere uygulanan toprak nemine etki eden işlemler sayesinde ve bu işlemlerin yabani otlarla olan rekabette fidanları desteklemesinden kaynaklandığı düşünülmektedir. Abbey ve Rathier (2005) tarafından *Ilex crenata*, *Pyrus calleryana*, *Spiraea japonica*, *Thuja occidentalis* türlerine ait fidanlarda gerçekleştirilen çalışmada da mikorizal ürünler ve su tutucu hidrojel işlemlerinin kontrole kıyasla daha iyi büyüme performansı sergiledikleri ortaya konulmuştur. Su tutucu hidrojel ile mikoriza arasındaki kıyaslamada ise mikorizal mantar popülasyonun artabilme ve köklerde kolonizasyonu sağlama olasılığı göz önüne alınarak mikorizal mantar içeren uygulamaların öne çıkacağı vurgulanmıştır. Bunun yanında mikoriza gibi su tutucu polimerler de bitkilerin su stresinin azaltma, büyüme ve beslenmeyi destekleyici olumlu özelliklerinden dolayı ağaçlandırmalarda kullanım potansiyeline sahiptir (Shooshtarian ve ark., 2012; Yu ve ark., 2012; Madakbaş ve ark., 2014; Darini ve ark., 2015; Akat, 2020). Bitkilerin ihtiyacı olan suyu temin eden su tutucu polimerler, toprak-bitki-hava sistemi için ek bir su kaynağı niteliği taşıyarak (Bhardwaj ve ark., 2007) su stresine maruz kalan *Pinus halepensis* (Hüttermann ve ark., 1999), *Eucalyptus grandis* (Viero ve ark., 2002), *Quercus rubra* (Apostol ve ark., 2009), *Populus euphratica* (Chen ve ark., 2004), Populus popularis (Shi ve ark., 2010) türleri üzerinde iyileştirici etkiler sergilemiştir. Bu çalışma da toprak neminin en düşük olduğu Temmuz ayında kontrol ünitesine göre %73 daha fazla neme sahip olan polimer ve mikoriza ünitelerindeki fidanların en fazla nispi çap ve boy artımı yapmasıyla sonuçlanmıştır. Çalışmada ayrıca bu etkiyi ortaya koyan uygulamalardan biri de glisin-betain etken maddeli osmoprotektan işlemidir. Bu çalışmada uygulandığı şekliyle osmoprotektanlar bitkileri su stresinin zararlı etkilerinden koruyup toleransını arttırarak bitki büyümesini ve hayatta kalmasını desteklemektedir (Abbas ve ark., 2010; Korkmaz ve ark., 2015). Glisin ve betain sadece kuraklığa değil ekstrem sıcaklıklara, tuzluluğa karşı da dayanıklılığı arttırdığından ve osmotik dengeyi ayarlamaya yardımcı olduğundan (Roussos ve ark., 2010; Denaxa ve ark., 2012) dolayı kuraklığın hüküm sürdüğü alanların ağaçlandırma çalışmalarında denenmesi büyük önem arz etmektedir. Günümüzde osmoprotektanlar tarımsal üretimde kullanım alanı bulmasına ve bu konuda araştırmalar yapılmasına rağmen ormancılık faaliyetlerinde yer bulamamıştır.

Kuraklığa eğilimli yetişme ortamlarında toprakta tutulan suyu arttırarak bitkilerin kullanımına sunan su tutucu toprak düzenleyicileri (Supare & Mahanwar, 2022) ve mikorizal mantarlar (Janos, 1980; Menkis ve ark., 2007) bitkilerin hayatta kalması sağlayabilmektedir. Ayrıca osmoprotektanların osmotik düzenlemedeki katkısı ile enzim ve membran bütünlüğü üzerindeki olumlu etkileri sayesinde (Ashraf & Foolad, 2007) abiyotik stres koşullarında bitkilerin yaşama oranını arttırmada önemli etkileri bulunmaktadır (Allard ve ark., 1998; Zulfiqar ve ark., 2020). Bu çalışmada, sulama yapılmaksızın ağaçlandırmalarda başarının sağlanmasına yöneliklik iğde fidanlarında gerçekleştirilen bahse konu uygulamalar, fidanların sıcaklık rekorlarının kırıldığı dönemi atlatmasını sağlayamasa da, hayatta kalma sürelerini iki ay daha uzatılabilmiştir. Her ne kadar Eylül ayında fidanların tamamı kurumuş olsa dahi çalışmada kullanılan uygulamaların ağaçlandırmalarda sorun yaşanan alanlarda başarının elde edilmesi açısından kullanım potansiyeli olduğu ortaya konulmuştur. Bu bakımdan bitki büyüme ve hayatta kalmasını kısıtlayıcı koşulların olduğu alanlarda küresel ısınmanın olumsuz etkilerine karşı toprak-bitki-su kaynaklarının sürdürülebilirliği kapsamında sulama ve gübreleme ile birlikte mikoriza, osmoprotektan ve polimer uygulamalarının dozları arttırılarak ve kombinasyonları oluşturularak yeni çalışmalarda denenmesi alternatif uygulamaların ortaya konulması açısından araştırmacılara önerilmektedir.

Teşekkür

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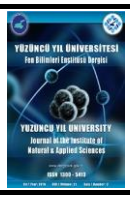
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Research Article

The Effect of Melatonin Applications on Quality Characteristics of Brussels Sprouts During Storage Period

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Abstract: The edible portion of Brussels sprouts, their sprouts, is recognized for its high nutritional value. These sprouts are rich in glucosinolate compounds, which play a crucial role in enzyme regulation, DNA protection against degradation, and cancer prevention. However, the storage life of Brussels sprouts is relatively short. Thus, this study targeted to investigate the impacts of different melatonin concentrations (50 µM, 100 µM, and 150 µM) on the postharvest quality of Brussels sprouts. Brussels sprouts were immersed in melatonin solutions at concentrations of 50 µM, 100 µM, and 150 µM for 5 minutes, with pure water serving as the control. Following immersion, the sprouts were stored at 1 ± 0.5 °C and 90 ± 5% relative humidity (RH) for 28 days. Key quality criteria, including weight loss, titratable acidity, soluble solids content, vitamin C, chlorophyll, total phenolic content, and total antioxidant capacity, were analyzed at every seven days (on days 7, 14, 21, and 28). Melatonin treatments significantly influenced the postharvest quality of Brussels sprouts. The highest chlorophyll content was noted in the 50 µM melatonin treatment, whereas the maximum vitamin C levels were recorded in both the control and 50 µM melatonin applications. The greatest total antioxidant capacity was achieved with the 100 µM melatonin treatment. Conversely, weight loss and total phenolic content were not significantly affected by melatonin applications. In conclusion, the application of 50 µM melatonin was found to effectively preserve the quality of Brussels sprouts, allowing for commercial storage of up to 28 days.

Keywords: Antioxidant, Chlorophyll, Melatonin, Post-harvest, Vegetable

Melatonin Uygulamalarının Depolama Süresince Brüksel Lahanalarının Kalite Özellikleri Üzerindeki Etkisi

Öz: Brüksel lahanasının yenilebilir kısmı olan filizleri, yüksek besin değeriyle tanınır. Bu filizler, enzim düzenlenmesinde, DNA'nın bozulmaya karşı korunmasında ve kanser önlenmesinde önemli rol oynayan glukozinolat bileşikleri açısından zengindir. Ancak, Brüksel lahanasının depolama ömrü nispeten kısadır. Bu nedenle, bu çalışma farklı melatonin konsantrasyonlarının (50 µM, 100 µM ve 150 µM) Brüksel lahanasının hasat sonrası kalitesi üzerindeki etkilerini araştırmayı hedeflemiştir. Brüksel lahanaları, kontrol olarak saf su kullanılarak 50 µM, 100 µM ve 150 µM konsantrasyonlarındaki melatonin solüsyonlarına 5 dakika daldırıldı. Daldırmanın ardından filizler 1 ± 0,5 °C ve %90 ± 5 bağıl nemde (RH) 28 gün boyunca saklandı. Ağırlık kaybı, titre edilebilir asitlik, çözünür katı madde içeriği, C vitamini, klorofil, toplam fenolik içerik ve toplam antioksidan kapasitesi dahil olmak üzere temel kalite kriterleri her yedi günde bir (7., 14., 21. ve 28. günlerde) analiz edildi. Melatonin uygulamaları Brüksel lahanalarının hasat sonrası kalitesini önemli ölçüde etkiledi. En yüksek klorofil içeriği 50 µM melatonin uygulamasında kaydedildi, maksimum C vitamini seviyeleri ise hem kontrol hem de 50 µM melatonin uygulamalarında kaydedildi. En büyük toplam antioksidan kapasiteye 100 µM melatonin uygulamasıyla ulaşıldı. Öte yandan, ağırlık kaybı ve toplam fenolik içerik melatonin uygulamalarından önemli ölçüde etkilenmedi. Sonuç olarak, 50 µM melatonin uygulamasının Brüksel lahanalarının kalitesini etkili bir şekilde koruduğu ve 28 güne kadar ticari depolamaya olanak sağladığı bulundu.

Anahtar Kelimeler: Antioxidan, Hasat sonrası, Klorofil, Melatonin, Sebze

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1. Introduction

Brussels sprouts (Brassica oleracea L. var. gemmifera), a Brassicaceae member, have been widely studied regarding sowing date, fertilization, plant density, planting time, cessation, and temperature-growth relationships (Kurtar, 2006). Brussels sprouts are a biennial vegetable that reproduces by seed and needs low temperatures for flowering. However, if it is exposed to temperatures below 10 ^{o}C for a few weeks, it blooms in the same year (Guvenc, 2016). The sprouts, which are the consumed part of Brussels sprouts, are rich in nutrients. The key nutritional components include fiber, vitamin C, niacin, and minerals. It also contains substantial amounts of glucosinolate compounds (glukorafanin, glukobrassisin), which regulate enzymes to protect against DNA degradation and may help prevent cancer (Verkerk et al., 2009; Yılmaz & Demirel, 2012; Sarvan et al., 2014; Kraśniewska et al., 2016). However, Brussels sprouts do not have a long shelf life. Beneficial compounds have been decreased at inappropriate conditions. Brussels sprouts can be preserved for up to one month at a temperature of 1-2°C and a relative humidity (RH) of 90-95% (Guvenc, 2016).

Discoloration is the biggest problem during storage (Kraśniewska et al., 2016). Loss of nutritional and commercial value are the problems (Hasperué et al., 2016; Bilgin & Aslantaş 2022). Tissue senescence is often accompanied by accumulation of reactive oxygen species. Researchers have recently begun to examine the impact of melatonin on green vegetables to alleviate this problem (Xin et al., 2017; Miao et al., 2020; Wu et al., 2021; Hu et al., 2022). Melatonin is an animal hormone that plays a role in many regulatory processes, especially sleep. In 1958, the hormone melatonin was first named by Lerner et al. (1960) (Demirsoy, 2018). It is called phyto-melatonin after discovered in plants, in 1995 (Arnao & Hernández-Ruiz, 2020). Studies indicate that melatonin plays a significant role in various physiological processes, such as supporting root regeneration by stimulating the formation of the root system in plants, acting as an antioxidant to increase plant tolerance to high and low temperatures, chemical pollutants, and other environmental stressors, protecting chlorophyll from oxidative stress, and accelerating the rate of photosynthesis in plants (Ahmad et al., 2023; Sharma et al., 2024; Khan et al., 2024; Cai et al., 2025). One of the most attractive properties of melatonin, distinguishing it from most antioxidants, is its potential to eliminate both reactive oxygen species (ROS) and reactive nitrogen species (RNS) (Hu et al., 2022). The benefits of melatonin in plants include scavenging free radicals and helping plants resist biotic and abiotic stresses (Arnao & Hernández-Ruiz, 2015). Post-harvest melatonin applications can improve the quality of tomatoes, strawberries, and apples (Sun et al., 2016; Aghdam & Fard, 2017; Liu et al., 2018; Onik et al., 2021). In addition, it has been reported that melatonin application in peaches delays senescence and reduces cold damage (Cao et al., 2016; Fu et al., 2017; Gao et al., 2018). There is also information in the literature that passion fruit preserves its physicochemical properties and delays senescence (Cai et al., 2024).

There are several studies investigating the effect of exogenous melatonin applications on broccoli (Miao et al., 2020; Wei et al., 2020a; Wei et al., 2020b; Hu et al., 2022). However, there is no study on the application of melatonin in Brussels sprouts. Thus, the objective of this study is to explore the impact of different doses of melatonin on the postharvest quality of Brussels sprouts.

2. Material and Methods

2.1. Plant material

Divino F$_1$ Brussels sprouts cultivar was used as a material. Same size sprouts were harvested and transferred to the bioactive laboratory. Brussels sprouts, free from mechanical damage, stains, and disease, were first subjected to pre-cooling at a temperature of 1±0.5 °C and a relative humidity (RH) of 95±5% for 24 hours. (Pre-Cooling: It is called bringing the harvested products to the transportation or storage temperature as soon as possible. It is done to maintain post-harvest quality and reduce quality losses). Each treatment used plastic boxes containing approximately 400 g of sprouts. Before storage, pre-storage analyses were conducted. The plastic boxes were then stored at a temperature of 1±0.5 °C and a relative humidity of 95±5%. For treatments, melatonin was applied in doses of 50 µM, 100 µM, and 150 µM. Brussels sprouts were soaked in melatonin solutions for 5 minutes, followed by drying at room temperature (23 °C) for 2 hours. Pure water was used as a control. Analyses were performed on

days 7, 14, 21, and 28 of cold storage. The experiment was conducted using a randomized plot design with three replications (Figure 1).

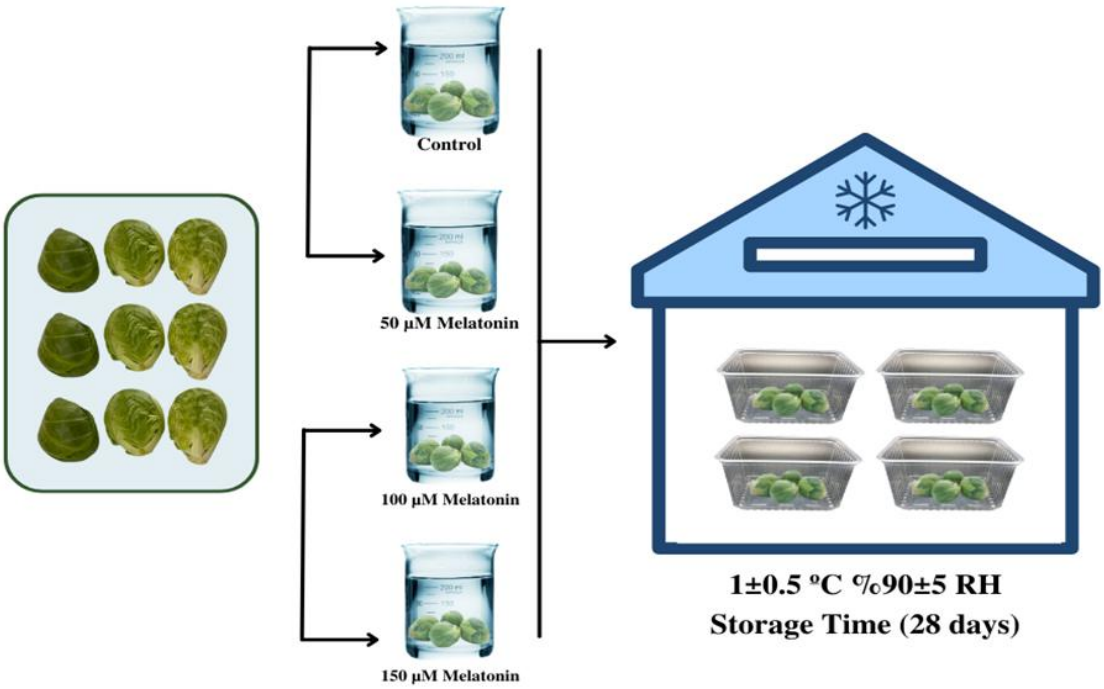


Figure 1. Schematic representation of harvested Brussels sprouts, postharvest melatonin treatments (50 µM, 100 µM, and 150 µM), and storage conditions.

2.2. Weight loss (WL)

At the beginning of storage, the initial weight of the sprouts was measured using a digital balance (Radwag, Poland) with an accuracy of 0.01 g. Subsequent measurements of the final weights were taken on the 7, 14, 21, and 28th days of storage. The weight loss was calculated as a percentage by taking the difference between the initial and final weights and dividing it by the initial weight.

2.3. Soluble solids content (SSC), titratable acidity (TA) and vitamin C

In every repetition, five sprouts were homogenized using a blender (Promix HR2653, Philips, Turkey), and the water content was subsequently removed. Soluble solids content (SSC) was assessed using a digital refractometer (Atago PAL-1, Japan, Brix = 0–53%) and recorded as a percentage (%). Titratable acidity (TA) was calculated as the percentage of citric acid, according to the volume of NaOH consumed during titration. For vitamin C content, ascorbic acid test strips (Catalog no: 116981, Merck, Germany) were used, and the resulting value was presented as mg L^{-1} (Aglar et al., 2017).

2.4. Chlorophyll content (Total, a and b)

A 0.1 g sample taken from the outer leaves of Brussels sprouts was weighed and crushed by adding 2-3 mL of 80% acetone. The samples were homogenized with 80% acetone until the total volume reached 10 mL, and then filtered through filter paper. The chlorophyll a, chlorophyll b, and total chlorophyll contents of the samples were then recorded at wavelengths of 645, 663, and 652 nm, respectively, with a UV-vis spectrophotometer (Model T60U, PG Instruments). The results were calculated using the formulas provided by Lichtenthaler & Wellburn (1983) and Sarac et al. (2022).

2.5. Total phenolic content (TPC)

Total phenolic content was determined using the method described by Singleton & Rossi (1965). 2 g of pureed samples were weighed and acetone buffer was added and the extraction process was applied for 24 hours. The next day, 0.5 mL of the samples were taken and 0.5 mL of Folin-Ci°Calteu's chemical was added, followed by 9 mL of pure water, and 2.5 mL of 7% sodium carbonate was added after 8 min. After two hours, the spectraphotometer was read at 750 nm wavelength. The results are expressed as micrograms (µg) of gallic acid equivalent (GAE) per gram fresh weight (fw).

2.6. Total antioxidant activity (TAA)

Total antioxidant activity was determined using the TEAC (Trolox equivalent antioxidant capacity) method as described by Ozgen et al. (2006). According to the method, 2.97 mL of the prepared TEAC solution was added to 30 µL of sample and the spectrophotometer was read at a wavelength of 734 nm after 10 minutes. The results were presented as Trolox equivalent (TE) micromoles (µmol) per gram fresh weight (fw).

2.7. Statistical analysis

Statistical analyses were carried out using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA). The means were compared using Tukey's range test, with the significance level set at 1% and 5%.

3. Results

3.1. Weight loss (%)

The weight loss was significantly influenced by storage time ($p < 0.01$), but was not influenced by melatonin applications ($p > 0.05$). Weight losses ranged from 2.89% to 2.99% on the 7th day, and from 11.27% to 11.90% on the final day of storage (28th day) (Figure 2).

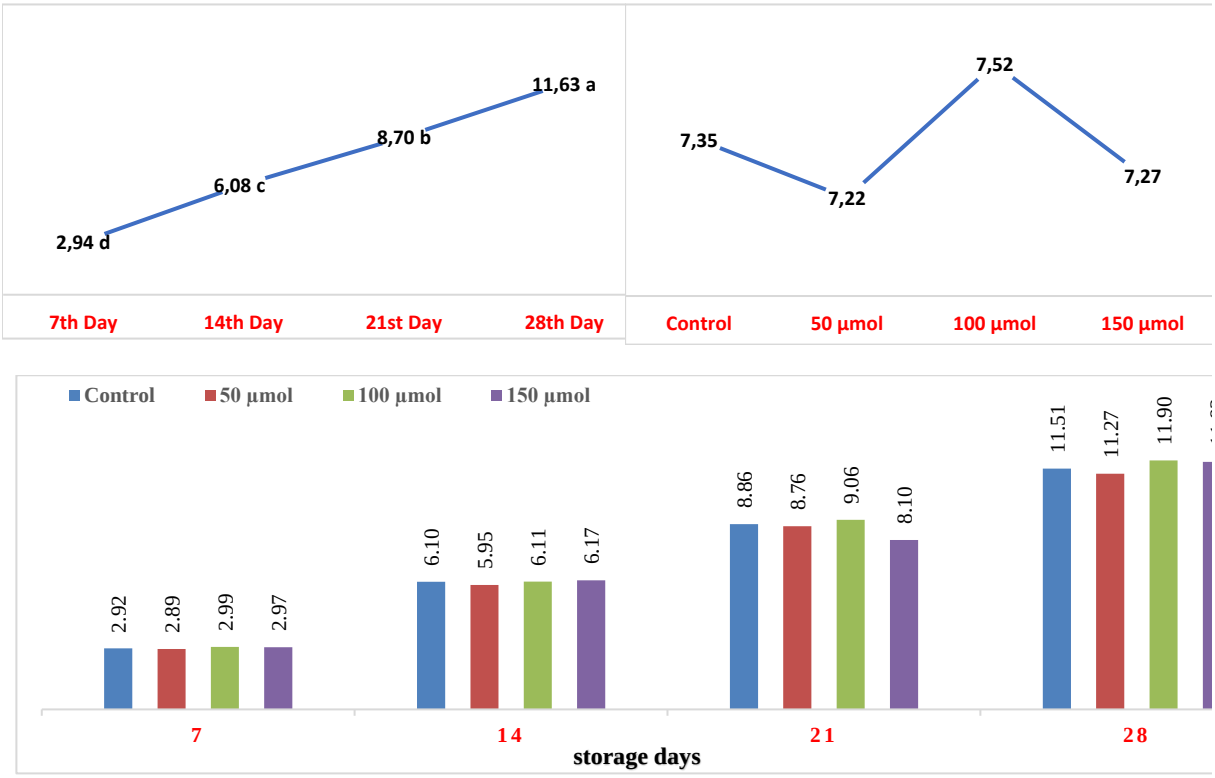


Figure 2. The impact of melatonin treatments on Brussels sprout weight loss throughout storage at 1±0.5 °C and a RH of 95±5%.

3.2. Soluble solids content (%), titratable acidity (%) and vitamin C (mg L^{-1})

Soluble solid content (SSC) was affected by the main factors (storage time ($p<0.01$) and applications ($p<0.05$)). It was observed that the SSC increased during storage, while the application of 50 µM melatonin throughout the storage period caused in a reduction in SSC compared to the control. SSC showed no notable effect from the treatments on day 7; however, significant changes were observed on the 14th, 21st, and 28th days. On the last day of the storage period, SSC was higher in the control and 50 µM melatonin treatments, while it was lower in the 150 µM melatonin treatment (Figure 3).

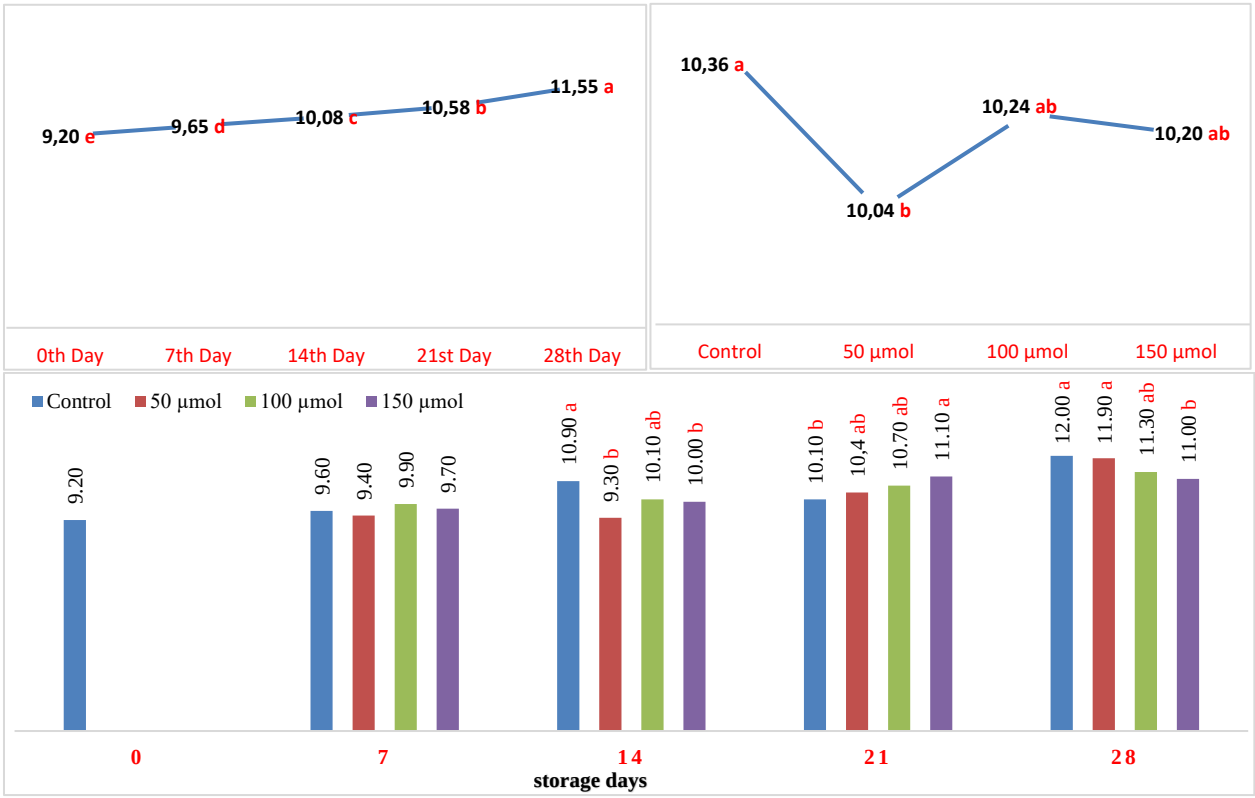


Figure 3. The impact of melatonin treatments on the soluble solid content of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

Titratable acidity (TA) was influenced by both main factors: storage time ($p < 0.01$) and treatments ($p < 0.05$). TA was found to increase throughout the storage period, with the most significant increase occurring on the 14th day. The applications of 50 and 150 µM melatonin during storage resulted in higher TA compared to the control. TA content of Brussels sprouts was significantly affected by the treatments at all storage periods, except on the 14th day. Melatonin applications on the 7th and 21st days significantly increased TA levels compared to the control. However, by the 28th day, the control treatment exhibited a higher TA content than the melatonin treatments (Figure 4).

Vitamin C content was influenced by the main factors (storage time and treatments, $p < 0.05$). It was noted that vitamin C increased during storage, but the applications of 100 and 150 µM melatonin throughout storage reduced vitamin C compared to the control. The treatments had a significant effect on vitamin C content on the 7th day of storage, but no notable effects were detected in the subsequent periods. On day 7, vitamin C content decreased with 100 µM and 150 µM melatonin treatments in comparison to the control, while the 50 µM melatonin treatment had a similar effect as the control (Figure 5).

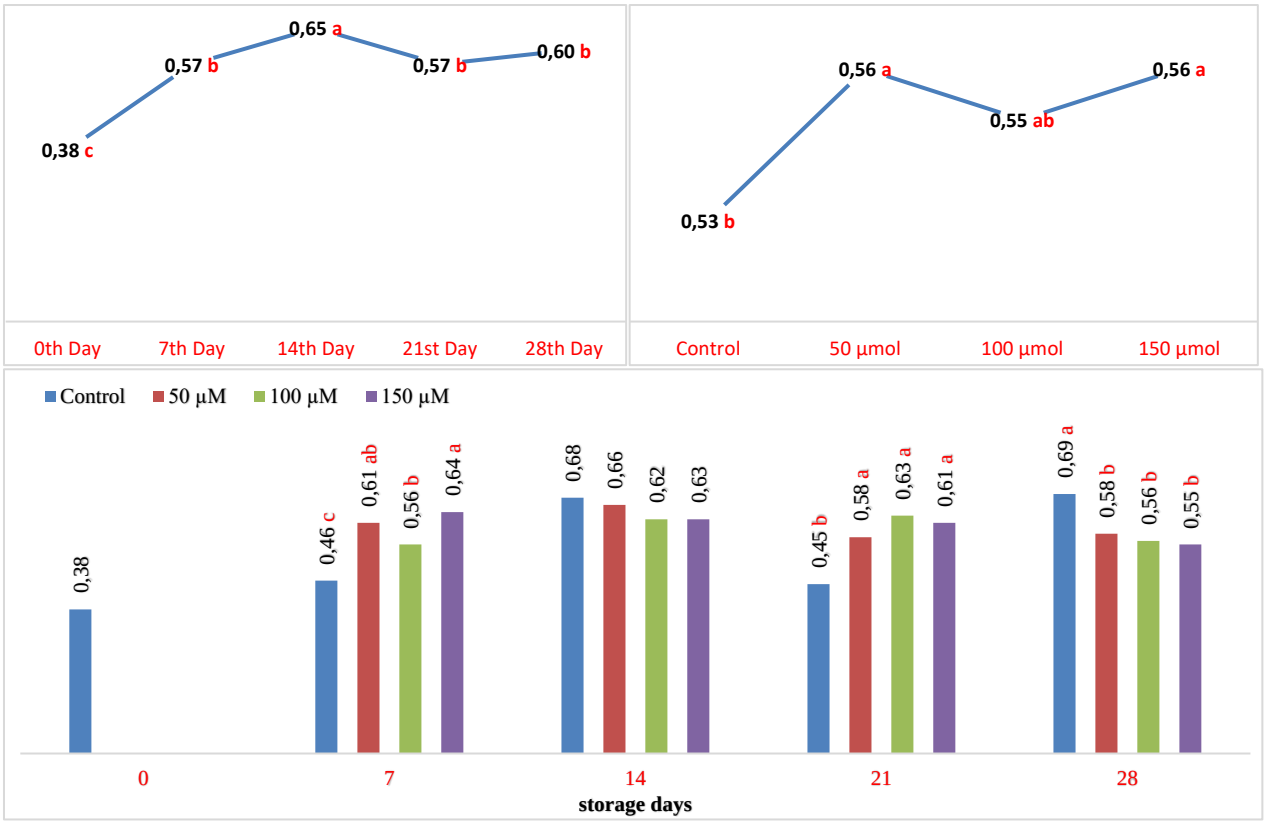


Figure 4. The impact of melatonin treatments on the titratable acidity of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

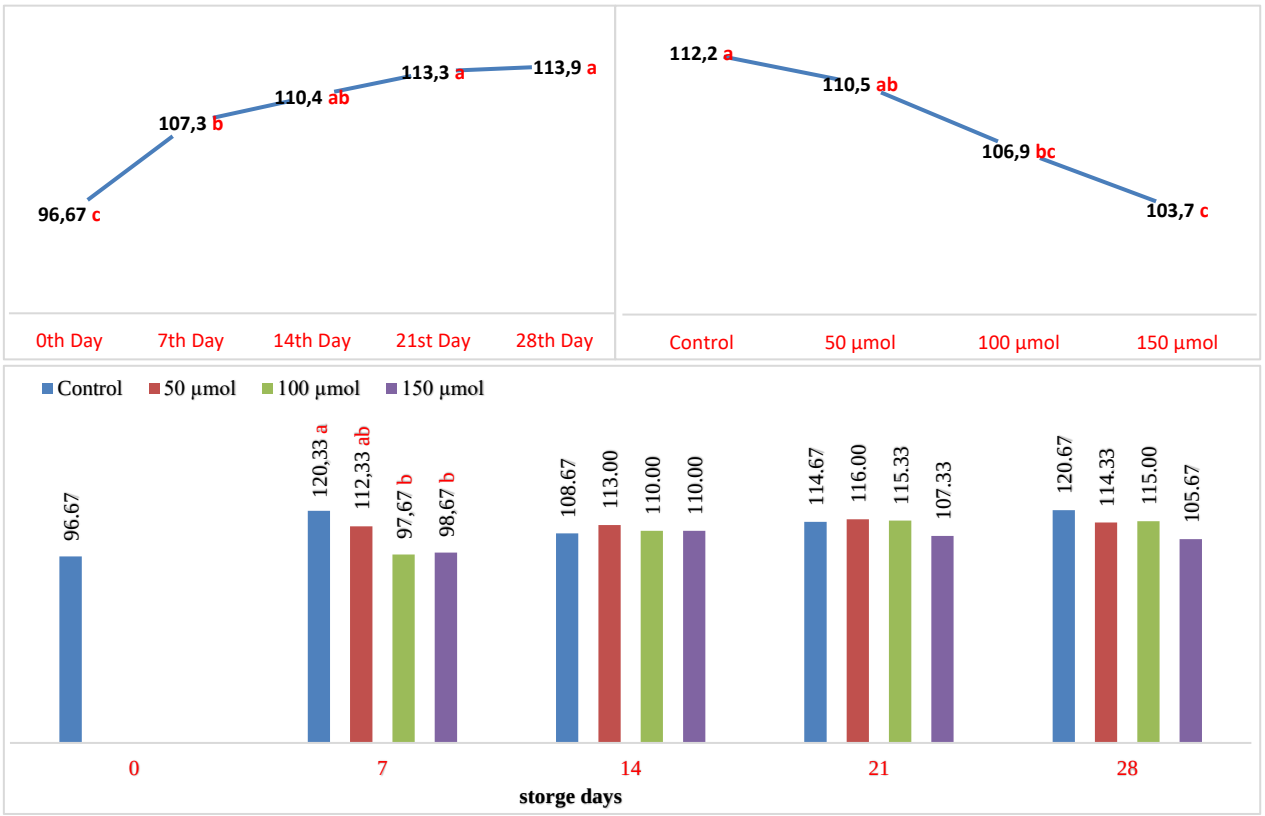


Figure 5. The impact of melatonin treatments on vitamin C of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

3.3. Chlorophyll content (mg g^{-1})

The chlorophyll content (total, a, and b) was influenced by the main factors (storage time and treatments, $p < 0.05$). It was determined that chlorophyll content (total, a, and b) increased during the storage period, with the most significant increase occurring on the 14th day. The applications of melatonin throughout storage resulted in higher chlorophyll content in comparison to the control, with the greatest rise monitored in the 50 µM melatonin treatment (Figures 6, 7, and 8).

Total chlorophyll content of Brussels sprouts was significantly affected by the treatments only during the final period of storage (Figure 6). Analysis conducted on the 28th day revealed that all melatonin applications (50, 100, and 150 µM) concluded in an increase in total chlorophyll content in comparison with the control.

When chlorophyll-a content was examined, it was found to be affected by the treatments on days 21 and 28 of storage (Figure 7). On the 21st day, the effect of melatonin applications was similar to the control, with the highest chlorophyll-a value monitored in the 50 µM melatonin treatment and the lowest in the 100 µM melatonin treatment. By the 28th day, chlorophyll-a values were higher in all melatonin treatments (50, 100, and 150 µM) compared to the control.

Chlorophyll-b values were affected by the treatments only on the 28th day of storage (Figure 8). On this day, the applications of 50 and 150 µM melatonin increased chlorophyll-b values compared with the control, while the 100 µM melatonin application showed a similar effect to the control.

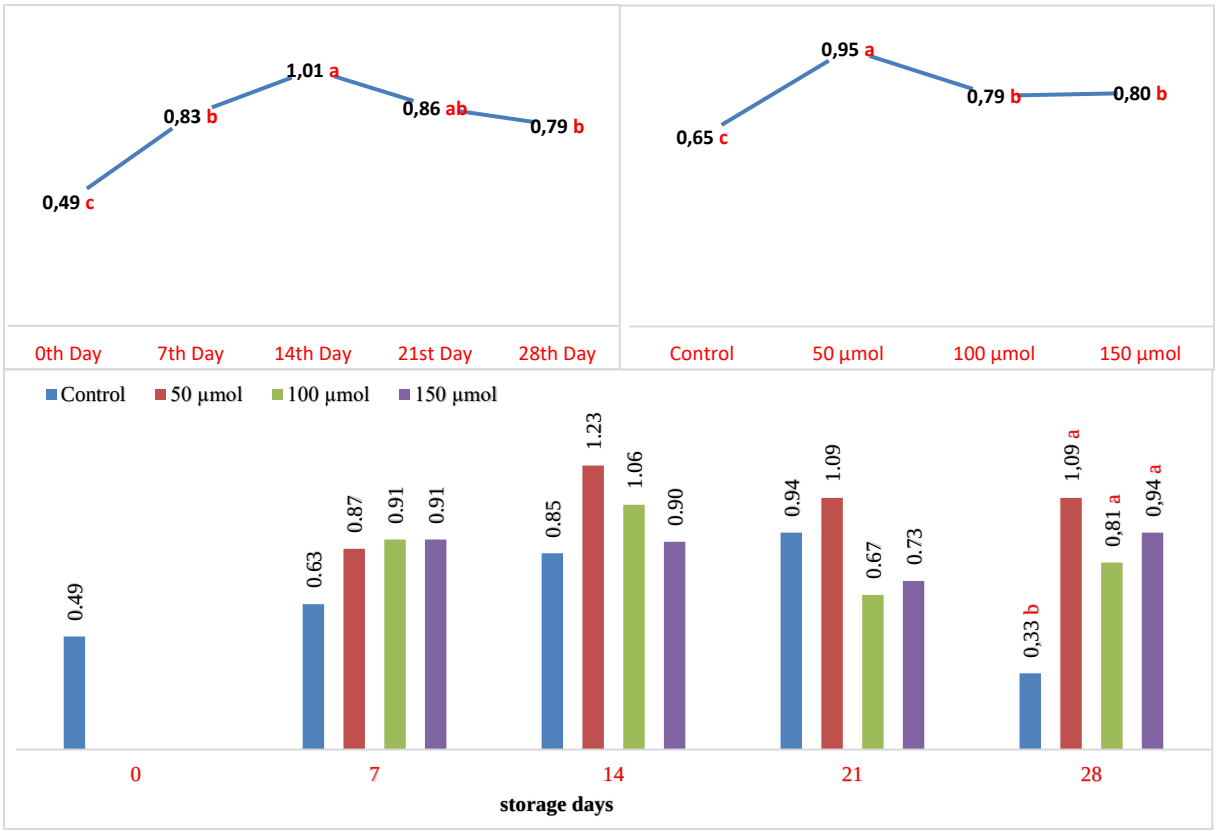


Figure 6. The impact of melatonin treatments on the total chlorophyll of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

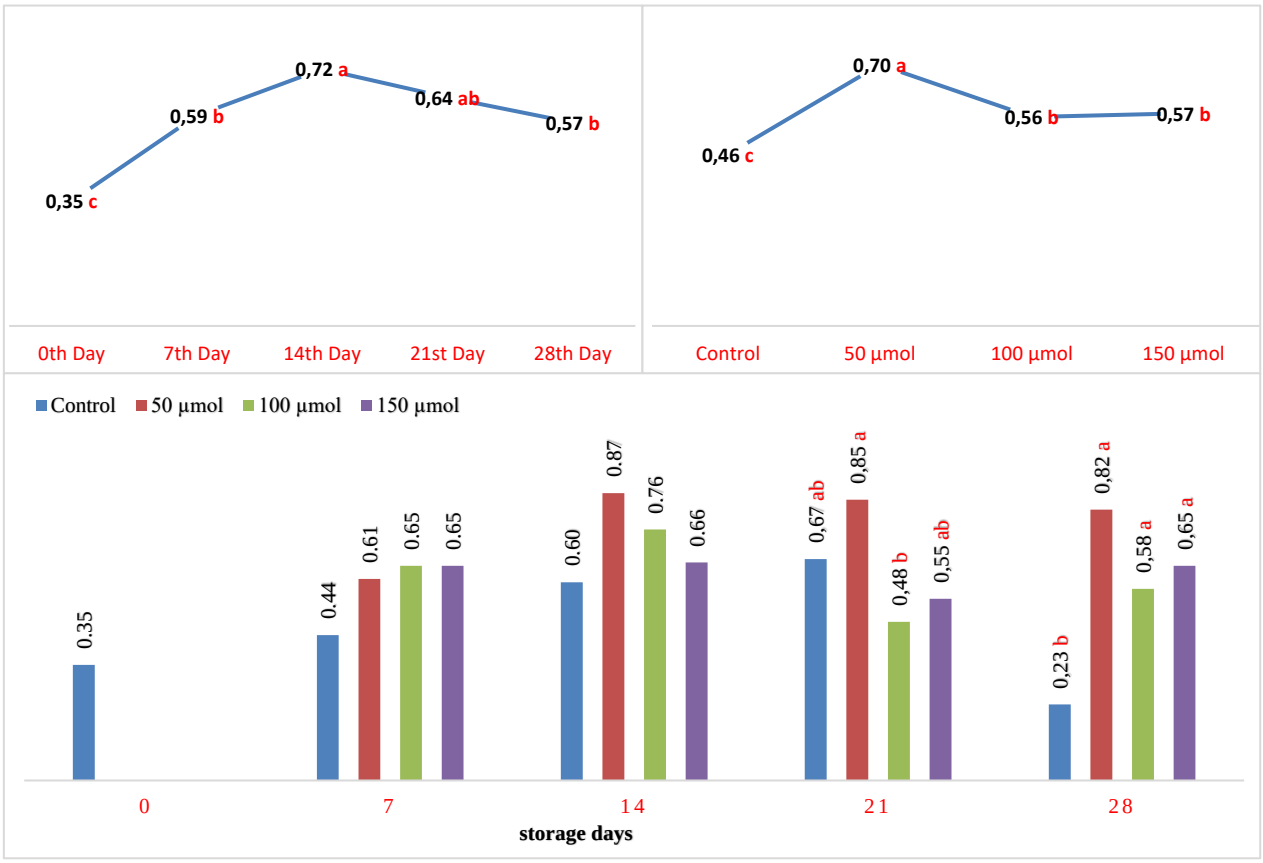


Figure 7. The impact of melatonin treatments on the chlorophyll-a content of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.



Figure 8. The impact of melatonin treatments on the chlorophyll-b of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

3.4. Total phenolic content (µg GAE g^{-1} fw)

The total phenolic content (TPC) was significantly influenced by storage time ($p < 0.05$) but was not influenced by melatonin applications ($p > 0.05$). It was observed that TPC increased during the storage period, with the most notable increase occurring on the 28th day. Analysis performed on the 28th day revealed that TPC was 2853.34 µg GAE g^{-1} in the control and 3215.84 µg GAE g^{-1} in the 150 µM melatonin treatment. However, this difference was found to be statistically insignificant (Figure 9).

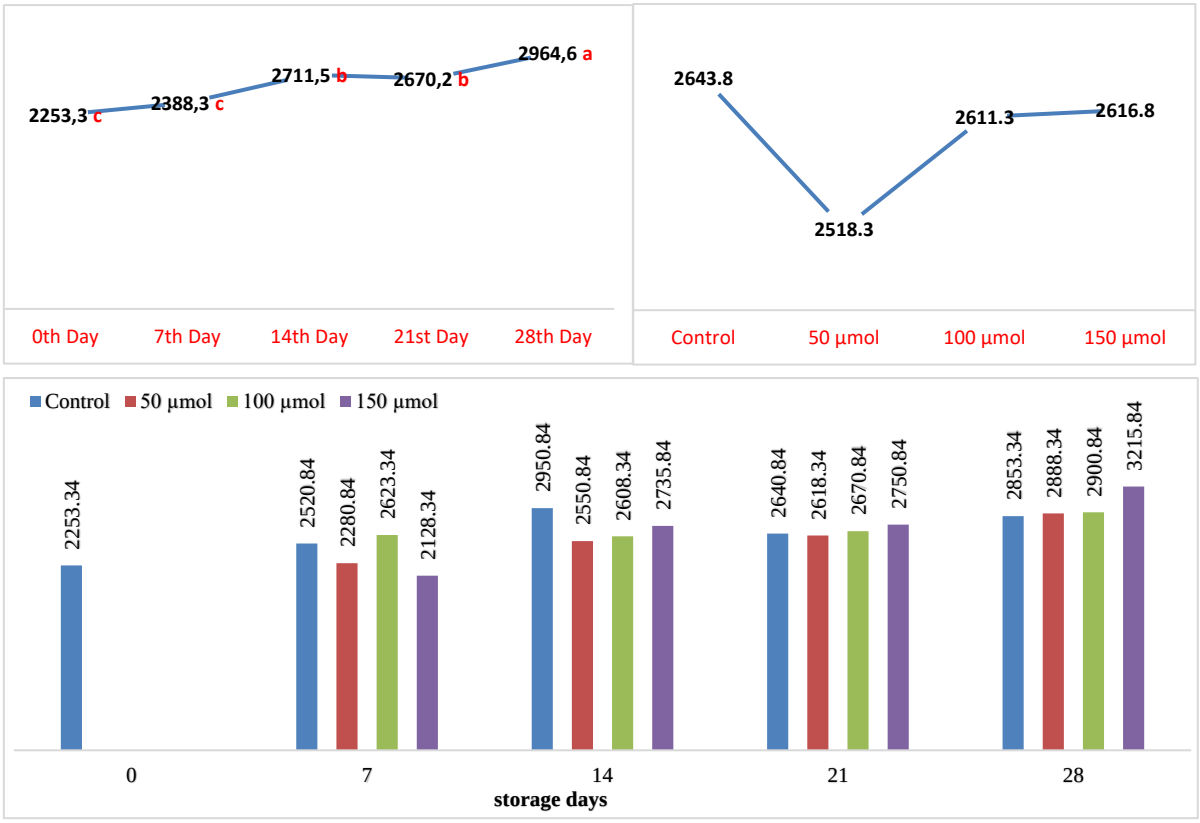


Figure 9. The impact of melatonin treatments on the total phenolic content of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

3.5. Total antioxidant activity (µmol TE g^{-1} fw)

Total antioxidant activity (TAA) was influenced by the main factors (storage time, $p < 0.01$, and treatments, $p < 0.05$). It was observed that TAA increased during the storage period, with the most significant increase occurring on the 28th day, similar to the trend seen in TPC. The applications of 100 and 150 µM melatonin throughout storage resulted in higher TAA compared to the control. TAA was significantly affected by the treatments only on the 7th day. The results from this period showed that all melatonin doses led to higher TAA values compared with the control. Among the melatonin treatments, the 100 µM dose exhibited the highest antioxidant activity (Figure 10).

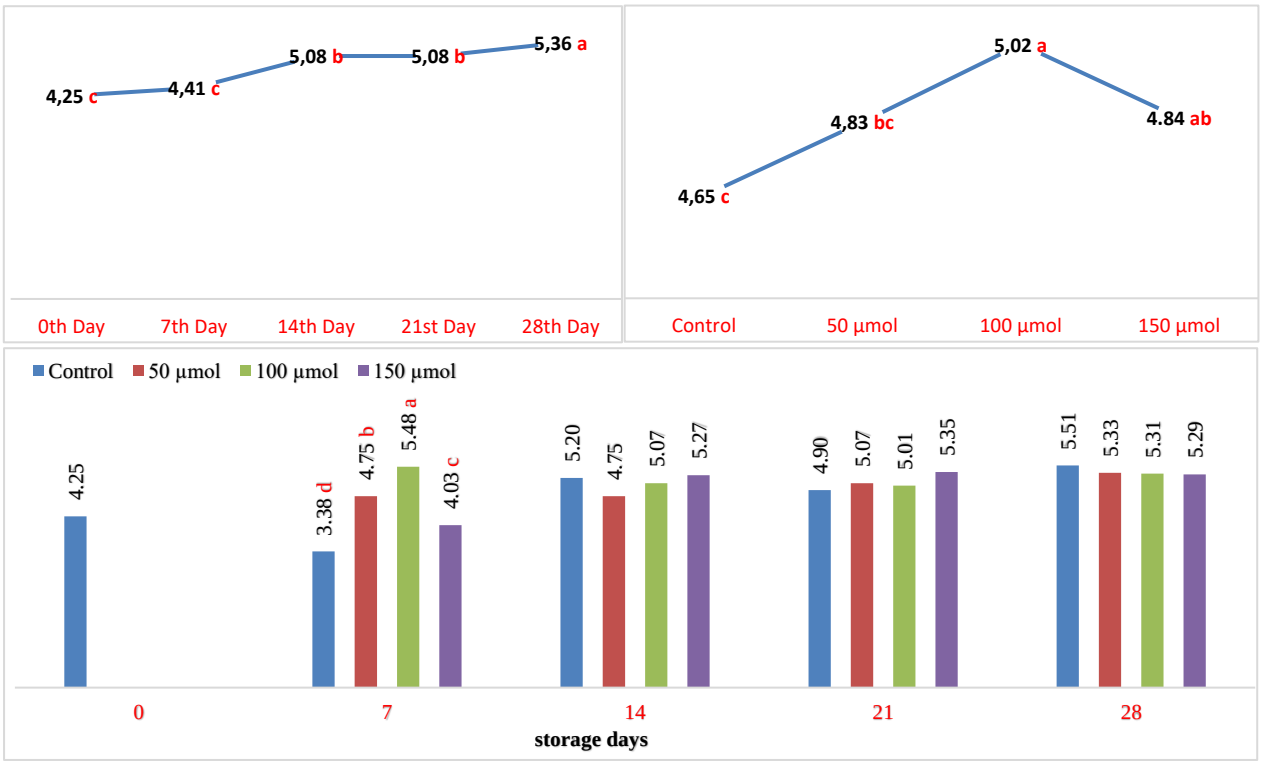


Figure 10. The impact of melatonin treatments on the total antioxidant activity of Brussels sprouts throughout storage at 1±0.5 °C and a RH of 95±5%.

4. Discussion

The quality of freshly consumed fruits and vegetables, influenced by pre-harvest factors, does not improve after harvesting. In this context, all post-harvest treatments are aimed at maintaining the existing quality. Minimizing water loss (wilting), loss of green color (yellowing), and senescence (accelerated metabolic processes) is crucial for preserving the quality of green vegetables after harvest. Water loss not only results in weight loss in quantitative terms but also leads to the softening of the product, the development of a spongy texture, fading, and wrinkling of the skin. Generally, the acceptable rate of water loss during storage ranges between 5-10%, depending on the species and cultivar of the product (Turk et al., 2017). In a study by Kasım & Kasım (2007), it was found that Brussels sprouts lost up to 10% of their weight after 21 days of storage. In this study, consistent with the literature, the weight loss of Brussels sprouts ranged from 11.27% to 11.90% after 4 weeks of storage (at 1±0.5 °C and a RH of 95±5%). Additionally, melatonin applications did not significantly impact weight loss (Figure 2).

An increase in the amount of soluble solids content (SSC) and titratable acidity (TA) was observed at the end of the storage period. However, melatonin applications limited the increase in SSC compared to the control group. In general, melatonin applications also preserved the TA content better. When both parameters were considered, the 50 µM dose of melatonin applications was the most effective. Similarly, in the study by Bilgin & Aslantaş (2022), it was observed that TA and SSC values of Brussels sprouts rose after a 28-day of storage. Kowalczyk et al. (2019) also reported an increase in TA content over time in their study with Brussels sprouts. However, in another study, contrary to our findings, it was reported that SSC decreased after 10-day storage of Brussels sprouts at 22°C (Hasperué et al. (2016). This discrepancy may be attributed to differences in storage conditions.

The most abundant and common vitamin in fruits and vegetables is ascorbic acid, commonly referred to as vitamin C. Besides its role as a cofactor in the synthesis of violaxanthin in chloroplasts within plant cells, ascorbic acid is an important antioxidant. It is particularly abundant in citrus fruits and horticultural products rich in citric acid. During storage, ascorbic acid content decreases due to degradation, which is influenced by the ambient temperature (Kasım & Kasım, 2007; Karaçalı, 2016; Turk et al., 2017; Kowalczyk et al., 2019). No reduction in vitamin C content was noted after cold

storage in this study (Figure 5). Consistent with our findings, Viña et al. (2007) stated that the vitamin C content of Brussels sprouts remained stable throughout storage, with no significant decrease. However, studies on broccoli have shown a decline in vitamin C levels, with melatonin helping to limit this decrease compared to the control (Lerner et al., 1960; Demirsoy, 2018; Arnao & Hernández-Ruiz, 2020; Miao et al., 2020; Wei et al., 2020a; Wu et al., 2021; Hu et al., 2022). In our study, no such effect of melatonin was observed. This discrepancy may be attributed to the fact that the vegetables used in the two studies belong to different species.

Chlorophylls are green pigments with a lipid-protein structure located in the chloroplasts of plant cells. Chlorophyll molecules are classified into four types: chlorophyll a, b, c, and d. In all highly organized plants, algae, and cyanobacteria, chlorophyll serves as the primary photosynthetic pigment. All highly organized plants and green algae contain chlorophyll b, except for mutant forms. Diatoms, dinoflagellates, and brown algae contain chlorophyll c. Red algae are the only organisms where chlorophyll d is found (Demirsoy, 2021). In fresh vegetables and fruits, chlorophyll a constitutes the majority of the chlorophyll composition, with chlorophyll b making up the remainder. Chlorophyll is rapidly broken down into small, colorless particles through enzymatic reactions, which are influenced by environmental factors and senescence. During this process, changes in pH, the action of chlorophyllase, and oxidation in the vacuole play key roles in the degradation of chlorophyll (Karaçalı, 2016). Tan et al. (2019) stated that abscisic acid (ABA) and melatonin play opposing roles in the regulation of leaf senescence in plants. Exogenous melatonin application was reported to reduce endogenous ABA levels by downregulating the expression of genes (BrABF1, BrABF4, BrABI5) associated with chlorophyll degradation and ABA biosynthesis. Consequently, melatonin postponed the senescence of Chinese flowering cabbage. Subsequent studies have documented that melatonin stimulates chlorophyll production in tomato seedlings (Siddiqui et al., 2020), pepper (Kaya et al., 2020), and corn leaves (Ahmad et al., 2020). In post-harvest studies, Hu et al. (2022) and Miao et al. (2020) stated that chlorophyll content in broccoli deteriorated throughout the storage, but these declines were largely prevented by the application of melatonin. Similarly, in our study, it was found that melatonin applications increased the chlorophyll levels in Brussels sprouts compared with the control.

Phenolic compounds and vitamin C, which are abundant in *Brassica* vegetables, are particularly notable for their high content and strong antioxidant activity. When consumed, these compounds can contribute to preventing chronic diseases such as cancer, heart disease, and diabetes by protecting cells from oxidative damage (Podsędek, 2007). The conservation of these compounds after harvest is crucial for maintaining their health benefits. Our study showed a trend of increasing both total phenolic content and antioxidant activity during storage. However, no effect of melatonin on phenolic content was observed. The effect of the applications on antioxidant activity was found to be significant only on the 7^{th} day. On this day, melatonin applications increased antioxidant capacity compared with the control group. The highest antioxidant activity was detected in the 100 µM melatonin treatment, followed by melatonin doses of 50 µM and 150 µM, respectively. Consistent with our findings, Miao et al. (2020) and Wei et al. (2020a) also stated that total phenolic content and antioxidant capacity in broccoli flowers increased by the deadline of the storage period. Miao et al. (2020) indicated that there was no notable difference between the control group and the 1 µM melatonin treatment after storage, whereas Wei et al. (2020a) observed that 100 µM melatonin treatment led to an increase in TPC and TAA contents in comparison to the control. In our study, melatonin did not exhibit such an effect. This discrepancy could be due to the varying responses of Brussels sprouts and broccoli flowers to melatonin treatment.

5. Conclusion

As a result, postharvest quality of Brussels sprouts was significantly affected by melatonin applications. Application of 50 µM melatonin limited the increase in SSC while promoting the increase in TA levels. All tested melatonin concentrations (50, 100 and 150 µM) resulted in an increase in total chlorophyll and chlorophyll a and b levels compared to the control group. During the first seven days of cold storage, 100, 50 and 150 µM melatonin applications showed the highest antioxidant activity, respectively. However, 50 µM melatonin application provided the highest vitamin C content. Melatonin application had no significant effect on weight loss or phenolic content. In general, melatonin did not adversely affect the quality of Brussels sprouts and preserved the external color and sugar/acid ratio of the product. The best quality results were obtained with the application of 50 µM melatonin. These

results indicate that melatonin can be effectively used in postharvest applications. Brussels sprouts can be stored commercially for up to 28 days, after which time weight loss exceeds 10%.

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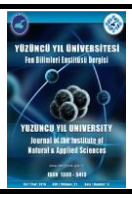
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Araştırma Makalesi

Van ilinde Kesilen Besi Sığırları ile Koyunların Rumen Fermentasyon Özellikleri ve Rumen Siliyatları Üzerine Bir Çalışma

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Öz: Bu çalışma, Van ilindeki bir kesimhaneye getirilen besi sığırları ve tokluların rumenlerinde yaşayan rumen siliyatlarının bulunuş yüzdelerini, mililitre başına toplam sayılarını ve rumen fermentasyon özelliklerini belirlemek amacıyla gerçekleştirilmiştir. Bu doğrultuda, 10 baş ortalama 24 aylık besi sığırı ile 10 baş ortalama 8 aylık toklu hayvan materyal olarak kullanılmıştır. Seçilen hayvanların postmortem muayenesi sırasında abdominal bölge açıldıktan hemen sonra ön mideler tamamen çıkarılmış; omasum ve abomasum bıçak yardımıyla ayrıldıktan sonra rumen içeriği ve rumen sıvısı örnekleri alınmıştır. Rumen NH_3-N konsantrasyonları, erkek kuzularda anlamlı derecede daha yüksek bulunmuştur ($P<0.05$). Rumen asetat konsantrasyonu, besi sığırlarında 67.72 mmol/L iken, erkek kuzularda 61.12 mmol/L olarak saptanmıştır ($P<0.05$). Her iki türde rumen propiyonat konsantrasyonu benzerlik gösterirken, rumen bütirat konsantrasyonu erkek kuzuların rumen sıvısında daha yüksek tespit edilmiştir ($P<0.05$). Besi sığırları ve erkek kuzuların rumenlerinde bulunan siliyatların sayısal yoğunluğu (x 10^4 mL^{-1}) ve Mann-Whitney U testi ile elde edilen istatistiksel sonuçlar incelendiğinde, kuzuların daha düşük siliyat yoğunluğuna sahip olduğu, sığırların ise bu konuda belirgin bir üstünlük sergilediği ortaya konulmuştur ($P<0.005$). Sonuç olarak, hayvan sahipleriyle yapılan görüşmeler sonucunda elde edilen bilgilere dayanarak, besi yapılan kuzu ve sığırların rumen fermentasyon özelliklerinden NH_3-N konsantrasyonu, asetik asit ve bütirik asit konsantrasyonlarının rasyon bileşimlerinden etkilendiği belirlenmiştir. Besi rasyonlarında dane yem oranının yüksek olması hem sığırlarda hem de kuzularda Entodiniomorphida familyasından *Entodinium sp.*'nin yoğun olarak bulunmasına neden olmuştur.

Anahtar Kelimeler: Koyun, Rumen fermentasyonu, Rumen siliyatları, Sığır

A Study on the Rumen Fermentation Characteristics and Rumen Ciliates of Fattened Cattle and Sheep Slaughtered in Van Province

Abstract: This study aimed to determine the occurrence percentages, total counts per milliliter, and rumen fermentation characteristics of rumen ciliates in the rumen of fattened cattle and lambs brought to a slaughterhouse in Van province. Accordingly, 10 fattened cattle with an average age of 24 months and 10 lambs with an average age of 8 months were used as animal material. During the postmortem examination of the selected animals, the abdominal region was opened, and the entire fore-stomachs were removed immediately. After separating the omasum and abomasum with a knife, rumen contents and rumen fluid samples were collected. Rumen NH_3-N concentrations were significantly higher in male lambs ($P<0.05$). The rumen acetate concentration was 67.72 mmol/L in fattened cattle and 61.12 mmol/L in male lambs ($P<0.05$). While the rumen propionate concentrations were similar in both species, the rumen butyrate concentration was higher in the rumen fluid of male lambs ($P<0.05$). Analyzing the numerical density of ciliates (x 10^4 mL^{-1}) in the rumens of fattened cattle and lambs and the statistical results obtained through the Mann-Whitney U test, lambs exhibited lower ciliate density, whereas cattle demonstrated a significant advantage in this regard ($P<0.005$). In conclusion, based on the information gathered from interviews with animal owners, it was determined that the rumen fermentation characteristics rumen NH_3-N, acetic acid, and butyric acid concentrations were influenced by the composition of the ration in fattened lambs and cattle. The high proportion of grains in the fattening rations led to a higher prevalence of Entodinium sp., a member of the Entodiniomorphida family, in both cattle and lamb rumen.

Keywords: Cattle, Rumen ciliates, Rumen fermentation, Sheep

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1. Giriş

Ruminantlar diğer tek midelilerden farklı bir mide yapısına sahiptir. Tek midelilerde kimyasal sindirimin olduğu tek odacıklı mideden bahsedilirken, ruminantlarda mide anatomik yapı itibariyle 4 odacıklı olup ilk 3 bölümü ön mide (rumen, retikulum ve omasum), son bölüm ise gerçek midedir (abomasum). Ön midede mikrobiyel sindirim, gerçek mide de ise kimyasal sindirim söz konusudur (Patterson, 1992). Organizmalar içerisinde doğada yapısal karbonhidratları (selüloz, hemiselüloz, sellebiyoz, pektin vb) sindirebilen tek hayvan türü ruminantlar olup bu özelliği ile kaba yem niteliği yüksek olan yem materyallerini en iyi şekilde sindirerek elde ettikleri enerjiyi yaşamlarını ve verimlerini devam etmek için kullanan ender canlılardır. Ruminantlar selülozun sindiriminden sorumlu olmayıp bitki hücre duvarı elamanları ruminant ile simbiyotik şekilde yaşayan rumen mikroorganizmaları tarafından sindirilmektedir (Church, 1993).

Mikroorganizmaların bulunma eğilimi biyolojik etkileşimlerin fazla olduğu alanlarda yoğunluk gösterir. Rumen mikroorganizma popülasyonu; 10^{10}- 0^{11} hücre/ml bakteri, 10^{7}-10^{9} hücre/ml arkea, 10^{4}-10^{6} hücre/ml protozoa, 10^{3}-10^{5} zoospor/ml mantar ve 10^{8}-10^{9} hücre/ml bakteriofajlardan oluşmaktadır (Kamra, 2005). Rumen ortamı mikroorganizmalar için en uygun mikro ekosistemlerden biridir. Rumende büyüyen ve kalıcı olan mikroorganizma türleri bu ekosistemin özel koşullarına en iyi uyum sağlamış olanlardır. Rumendeki düşük oksijen konsantrasyonu, -250 ile -450 milivolt arasında ölçülen negatif oksidasyon-redüksiyon potansiyeli ile gösterildiği üzere, yalnızca oksijenin tamamen yokluğunda veya çok düşük seviyelerde varlığında yaşayabilen zorunlu anaerobik mikroorganizmaların varlığına işaret etmektedir. Bu mikroorganizmalar, oksijenin olmadığı ortamlarda büyüme ve çoğalma yeteneğine sahiptir. Ancak aerobik koşullarda büyüyebilen fakültatif anaeroblar da bulunmaktadır. Rumen duvarından geçerek veya yemin bünyesine giren oksijen rumen duvarına yapışık durumda bulunan mikroorganizmalar veya rumendeki mantarlar tarafından kullanılarak karbondioksit üretirler ve bu şekilde rumendeki anaerobik ortamı hazırlarlar. Rumen gaz karışımın kompozisyonu %65 CO_2, %27 CH_4, %7 N, %0.6 O_2, %0.2 H_2 ve % 0.01 H_2S'dür. Rumen içeriği pH'sının ağızda üretilen salya tarafından tamponlanması sağlamaktadır. Rumenin normal pH aralığındaki en önemli tamponları, tükürük sayesinde gelen tamponlayıcı maddelerdir. Ruminantlarda tükürükle büyük miktarlarda bikarbonat (HCO_3-) ve fosfat (PO_4) tampon maddeleri salınımı ile rumen fermentasyon pH'sının 6-7 arasında gerçekleşmesini sağlar. Yapılan bir çalışmada sığır tükürük pH'sının 8.6, koyun tükürüğünün pH'sının ise 8.1 olduğu belirtilmiştir (Beal, 1974).

Ruminatlarda ön mide ve bölümleri ilgili çalışmaların yapılmaya başlamasından sonra 1920'li yıllarda rumende yaşayan mikroorganizmalar ve özellikle protozoonların tanımlanması, morfolojisi ve işlevleri konusunda önemli çalışmalar yapılmaya başlanmıştır (Patel ve Ambalam, 2018). Yapılan çalışmalarda protozoonların, mikrobiyal popülasyonun önemli bir bileşeni olduğu ve rumen ekosisteminin işlevselliğinde rol oynadığı belirlenmiştir (Williams ve ark., 1992). Rumende yaşayan protozoonlar kamçılılar (Mastigophora) ve siliyatlar (Ciliophora) olmak üzere iki grup halinde sınıflandırılmakla birlikte rumendeki protozoonların çoğunluğunu silayatlar oluşturmaktadır. Siliyat protozoonlar değişik ve sert bir pelikül, kalın bir ektoplazma ve peristom hariç diğer kısımlarda sillerin bulunmayışı ile karakterize olan Entodiniomorphida takımı ile çoğunlukla uniform olarak silli bir vücuda, türe göre değişen karakteristik yerleşimlerde bulunan bir ağıza ve bazen de bir konkresyon vakuolüne sahip "holotrich" siliyatlar olmak üzere 2 siliyat gruba ayrılır (Imai, 1998).

Siliyat protozoonların ruminantların beslenmesi üzerinde doğrudan veya dolaylı etkileri vardır. Siliyatların varlığı veya yokluğu durumunda rumen pH'sının, amonyak konsantrasyonunun, rumen substrat düzeyinin, bakteri sayısı ve tiplerinin değiştiği ve sonuç olarak sindirim hızının ve kapsamının etkilendiği bildirilmiştir (Veira, 1986).

Protozoonlar rumende yapısal karbonhidratların (selüloz, hemiselüloz, pektin, nişasta gibi) sindiriminde 1/3'lik kısmından sorumludur. Flagellatalı protozoonlar nişasta ve hemiselülozun yıkımında etkin bir şekilde görev alırken, selülozun yıkımında ise siliyatlı protozoonlar önemli rol oynamaktadır (Ünay ve ark., 2008). Kaba ve kesif yem içerikli rasyonların kullanımı durumunda rumendeki protozoonların değişimlerini inceleyen Ushida ve ark. (1988), kolay eriyebilir karbonhidrat içeriği yüksek kesif yemlerin kullanılması durumunda rumen sıvısında laktik asit konsantrasyonunun ve Holotrich tipi protozoonların sayısının arttığını tespit etmişlerdir. Bu sonuçlar, Holotrich tipi siliyatların genellikle eriyebilir karbonhidratların fermentasyonundan sorumlu olduğunu göstermektedir. Bu bağlamda, ruminantlara verilen rasyonun kalitesi ve miktarı ile rumendeki protozoon türleri ve sayıları

arasında doğrudan bir ilişki bulunmaktadır. Entodiniomorphid siliyatlar, yapısal olarak Holotrichlerden daha karmaşık bir yapıya sahiptir. Bu protozoonlar, nişastayı fagosite ederek sindirebilme yeteneğine sahiptir. Ayrıca, yapısal olmayan karbonhidratların fermentasyonundan sorumlu olan bu tür protozoonlar, dane yem ve nişasta oranı yüksek rasyonlarla beslenen hayvanların rumen sıvısında Entodinium ve Epidinium türlerinin sayısındaki artışla ilişkilendirilmektedir (Coleman, 1992). Ushida ve ark. (1990); koyunlarda protozoonların defaunasyonu (yok edilmesi) ile rumende protein yıkımın düştüğünü, protozoa varlığında ise rumende amonyak azotu konsantrasyonun arttığını bildirmişlerdir. Protozoonların olmadığı koyunlarda bakteriyel protein sentezi ve mikrobiyel protein etkinliği ile protozoonların varlığındaki duedonuma akan mikrobiyel protein sentez etkinliğinin farklı olduğu belirlenmiştir. Çalışma sonucunda elde edilen veriler ile protozoonların rumende proteinlerin yıkılımı üzerinde etkili olduğunu göstermiştir.

Rumen protozoonlarının lipid metabolizması üzerindeki rolleri hala tam olarak anlaşılamamıştır (Newbold ve ark., 2015). Ancak aktif olarak lipolize katkıda bulunduğu ve hatta siliyatların (özellikle Epidinium türleri) farklı mekanizmalarla rumen biyohidrojenizasyonunda etkin rol aldığı ifade edilmiştir (Harfoot ve Hazelwood, 1997; Jenkins ve ark., 2008; Nagaraja, 2016).

Protozoonlar ruminal içerikte rumen amonyak havuzunu dengelemede (nitrat- nitrit konsantrasyon) (Yoshida ve ark., 1982) ve bazı mikotoksinleri parçalamada (Kiessling ve ark., 1984) fonksiyonel oldukları için bu tür bir detoksifikasyonun, kontamine yemleri yiyen ruminantlar açısından da bir avantaj olacağı açıktır.

Bu gibi nedenlerden dolayı rumen protozoonlarının farklı türlerde popülasyonlarının ve türe özgü siliyat protozoonların tanımlanması gerekmektedir. Bazı siliyatlar muhtemelen konakçıya özgü olabilir (Ito ve Imai, 1990; Ito ve ark., 1995; Göçmen ve Öktem, 1996; Imai, 1998). Protozoonlar rumen biyokütlesinin büyük bir bölümünü oluşturmasına rağmen, rumen fermentasyonundaki rolleri ve konakçının metabolizmasına ve beslenmesine katkıları hala önemli bir tartışma konusudur (Williams ve ark., 1992). Rumen siliyat kompozisyonunun bilinmesi ve konakçılar arasındaki faunal benzerlik ve farklılıkların ortaya çıkarılarak karşılaştırılmasının, konağın ve söz konusu siliyatların coğrafik dağılımı, konakçının beslenme şekli ve fizyolojisi ile siliyat türlerinin spesifikliğine ilişkin veriler sağlayacağı açıktır. Bu çalışmada, Van ili kesimhanesine getirilen besi sığırları ile erkek kuzuların rumenlerinde yaşayan rumen siliyatlarının bulunuş yüzdeleri, mililitredeki toplam sayıları ile rumen fermentasyon özelliklerini belirlemek amacıyla yapılmıştır.

2. Materyal ve Yöntem

2.1. Hayvan materyali

10 baş ortalama 24 aylık erkek Simental sığırı ile 10 baş 2 aylık sütten kesilen ve 70 gün besiye alınan Karakaş erkek kuzuları hayvan materyali olarak kullanılmıştır. Hayvan materyalleri hakkında genel bilgiler (kulak numarası, beslenme şekli, yaşı, ırk ve besi süresi) hayvan sahipleri ile yüz yüze görüşülerek belirlenmiştir. Kesimhaneye gelen erkek kuzular Van Yüzüncü Yıl Üniversitesi Ziraat Fakültesi Zootekni Bölümü Koyunculuk Ünitesi'nde yürütülen bireysel araştırma projesinin kuzuları olup, proje sahibi ile yapılan görüşmeler neticesinde besi kuzularının 70 gün süreyle 12.60 mj/kg KM metabolik enerji ve 165 g/kg KM ham protein içerikli kesif yemle besiye alındıkları bilgisine ulaşılmıştır. Kuzulara verilen besi karma yemi arpa, mısır, kenevir tohumu küspesinden oluşturulmuştur ve canlı ağırlığın %4.5'ü kadar yem tükettikleri bildirilmiştir. Kesimhaneye gelen besi sığırları ise hayvan sahipleri ile görüşüldüğünde arpa (ezme), buğday samanı, çayır kuru otu ve şeker pancar posasından oluşan bir rasyon tükettiklerini beyan etmişlerdir.

Çalışmada kullanılacak olan hayvanlar belirlendikten sonra kesim sırasına alınırken numaralandırılmıştır. Postmortem olarak abdominal bölge açıldığında ön midelerin tamamı çıkarılır çıkarılmaz omasum ve abomasum bıçakla ayrıldıktan sonra rumen içeriği ve rumen sıvısı örneklemesi yapılmıştır.

2.2. Yöntem

2.2.1. Rumen fermentasyon özelliklerinin belirlenmesi

Rumen sıvısının pH'sı, 50 ml rumen sıvısı alınır alınmaz pH-metre ile ölçülmüştür. pH değeri ölçüldükten sonra rumen sıvısı 4 katlı gazlı bez ile süzülerek 10 ml rumen sıvısı NH_3-N için ve 10 ml rumen sıvısı da uçucu yağ asitleri (UYA) konsantrasyonu için örnekleme yapılmıştır. Rumen NH_3-N için alınan 10 ml rumen sıvısına rumen mikroorganizmaların aktivitesini durdurmak için %50'lik H_2SO4 0.2 ml çözelti ilave edilmiştir. UYA analizleri için behere alınan 10 ml rumen sıvısı örneklerine %25 metafosforik asit çözeltisinden 2 ml ilave edilmiştir. Alınan örnekler UYA ve NH_3 analizleri yapılıncaya kadar -20^{o}C'de depolanmıştır. UYA analizleri için alınan örnekler oda sıcaklığında çözdürüldükten sonra 12000 rpm 10 dakika santrifüjlenmiştir. Santrifüj sonrasında supernatanttan 2 ml'lik viallere örnekleme yapılarak 300x7.8mm HPX-87H kolonu ile mobil faz 0.015 N H_2SO_4 + 0.0034 M EDTA, akış oranı 0.7 ml/dk, kolon sıcaklığı 45^o C, dedektör PDA – DAD ve enjeksiyon hacmi 50µl olacak şekilde HPLC koşulları ayarlanmıştır (Vargas ve ark., 2020). Rumen NH_3-N analizi ise Markham (1942) tarafından geliştirilen distilasyon yöntemine göre yapılmıştır. Bunun için santrifüj edilmiş rumen sıvısından 2 ml Kjeldahl tüpüne alınarak üzerine %40 NaOH çözeltisinden 1 ml ilave edilip destilatın toplanacağı erlen mayere ise %2'lik H_3BO_3 çözeltisinden 5 ml, metilen kırmızısı indikatöründen ise 3 damla ilave ederek distilasyon düzeneği ortalama 3 dk süresince çalıştırılmıştır. Toplanan destilat N/70'lik H_2SO_4 çözeltisi ile titre edilerek rumen sıvısı NH_3-N'u konsantrasyonu belirlenmiştir.

2.2.2. Rumen siliyatların belirlenmesi

Protozoonların sayımı için kesimhanede hayvanların rumenleri çıkar çıkmaz 40^{o}C'lik sıcak suyun bulunduğu termoboksun suyu boşaltıldıktan hemen sonra rumen sıvısı doldurularak üzerine CO_2 gazı verilip hava almayacak şekilde kapatılıp laboratuvara getirilmiştir. Rumen siliyatlarını rumen içeriğinden ayırmak için rumen içeriği 150 rpm 5 dk santrifüj edilerek supernatant atılmış ve üzerine %30'luk sukroz çözeltisinden 40 ml ilave edilerek 3 dk daha 150 rpm santrifüjlenmiştir. Santrifüj sonrasında supernatant tekrar uzaklaştırılmış ve üzerine %0.9 NaCl solüsyonu ilave edilerek üç kez 150 rpm 5 dk santrifüj edilerek siliyatların ayrılması sağlanmıştır. Işık mikroskobu için siliyatların MFS solusyonu (metil-formalin-salin) boyaması ve sabitlemesi yapılmıştır (Ogimoto ve Imai, 1981). Bu yöntemde ayrılan siliyatların 5 katı ölçüsünde MFS solüsyonu (100 ml %35 formaldehit çözeltisi, 900 ml distile su, 0.6 g metil yeşili boyası çözeltisi ve 0.8 g NaCl) ilave edilmiş ve protozoonların boyanması için en az 30 dakika beklenmiştir. Dakikada 500 rpm'de santrifüj edilerek dipteki çökeltiden lam üzerine birkaç damla konulup yayılması sağlanarak lamel ile hava kabarcığı kalmayacak şekilde kapatılmış ve en çok görülen cinslerin fotoğrafları çekilmiştir.

2.2.3. İstatistik analizler

Rumen fermentasyon özelliklerinin incelenmesi için faktörler arasındaki farklılıkların belirlenmesinde t testi, rumen siliyatları sayısı için Mann Whitney U testi kullanılmıştır. Çalışmadan elde edilen verilerin istatistik analizinde SAS Versiyon 9.4 (2020) paket programı kullanılmıştır.

3. Bulgular

3.1. Koyunların ve besi sığırların rumen fermentasyon özellikleri

Araştırmada kullanılan besi sığırları ile erkek kuzuların rumen fermentasyon özellikleri saptanarak Çizelge 1'de verilmiştir. Çizelge 1 incelendiğinde her iki türün pH değeri 6.0-6.5 aralığında bulunmuştur. Erkek kuzuların ortalama rumen pH değeri 6.23 iken, besi sığırlarının pH değeri 6.37 olarak belirlenmiş ve rumen pH'sı açısından gözlenen farklılıklar istatistiksel olarak önemli bulunmamıştır ($P>0.05$).

Rumen NH_3-N konsantrasyonları erkek kuzularda belirgin şekilde daha yüksek bulunmuştur ($P\leq0.001$). Besi sığırlarının rumenindeki asetat konsantrasyonu (67.72 mmol/L), erkek kuzuların rumenindeki asetat konsantrasyonuna (61.12 mmol/L) kıyasla anlamlı derecede daha yüksek bulunmuştur. Bu fark istatistiksel olarak oldukça anlamlıdır ($P \leq 0.001$) ve besi sığırlarının rumeninde

daha fazla asetat üretildiğini göstermektedir. Propiyonat seviyeleri her iki türde de benzerdir ve aralarındaki fark istatistiksel olarak anlamlı değildir. Erkek kuzuların rumen bütirat düzeyi 12.83 mmol/L, besi sığırlarında ise bu değer 10.95 mmol/L olarak belirlenmiş olup bu fark istatistiksel olarak anlamlı bulunmuştur (P=0.004).

Çizelge 1. Kesimhaneye gelen Karakaş ırkı erkek kuzuların ve Simental ırkı sığırların rumen fermentasyon özellikleri

Tür	n	pH	NH_3-N, mg/L	Asetik Asit mmol/L	Propiyonik Asit, mmol/L	Bütirik Asit mmol/L
Koyun	10	6.23±0.09	11.13±0.15a	61.28±0.50b	18.80±0.49	12.83±0.18a
Sığır	10	6.37±0.13	9.02±0.12b	67.72±1.40a	18.36±0.82	10.95±0.55b
P değeri		0.376	≤0.001	≤0.001	0.645	0.004

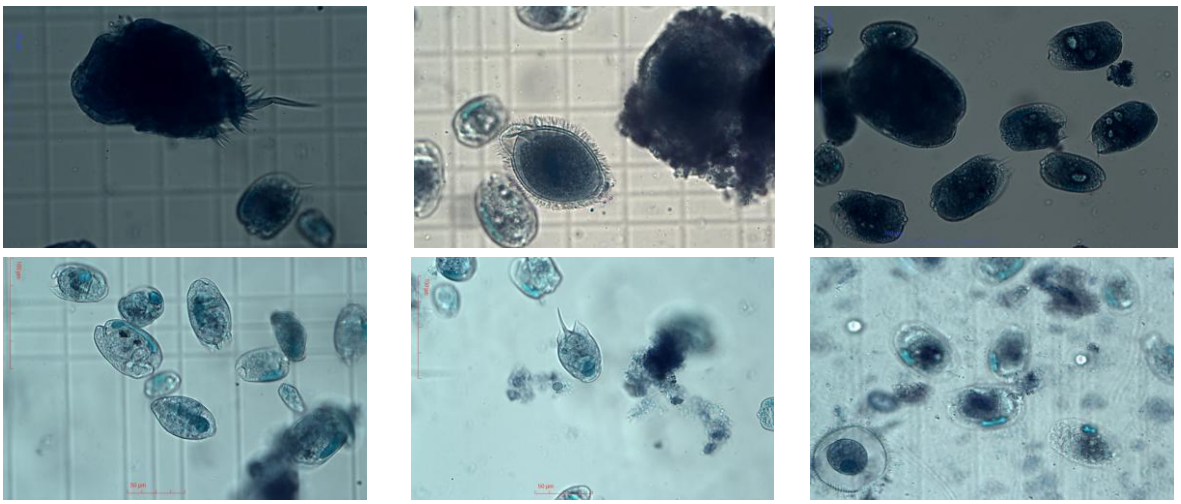
3.2. Koyunlarda ve besi sığırlarında rumen siliyatları

Çizelge 2'de besiye alınan erkek kuzular ile besi sığırlarının rumeninde bulunan siliyatların sayısal olarak yoğunluğunu (x 10^4 mL^{-1}) ve Mann-Whitney U testi ile elde edilen istatistiksel sonuçları sunulmuştur. Çizelge incelendiğinde kuzular daha düşük siliyat yoğunluğuna sahipken, sığırlar bu konuda belirgin bir üstünlük göstermiştir (P<0.005).

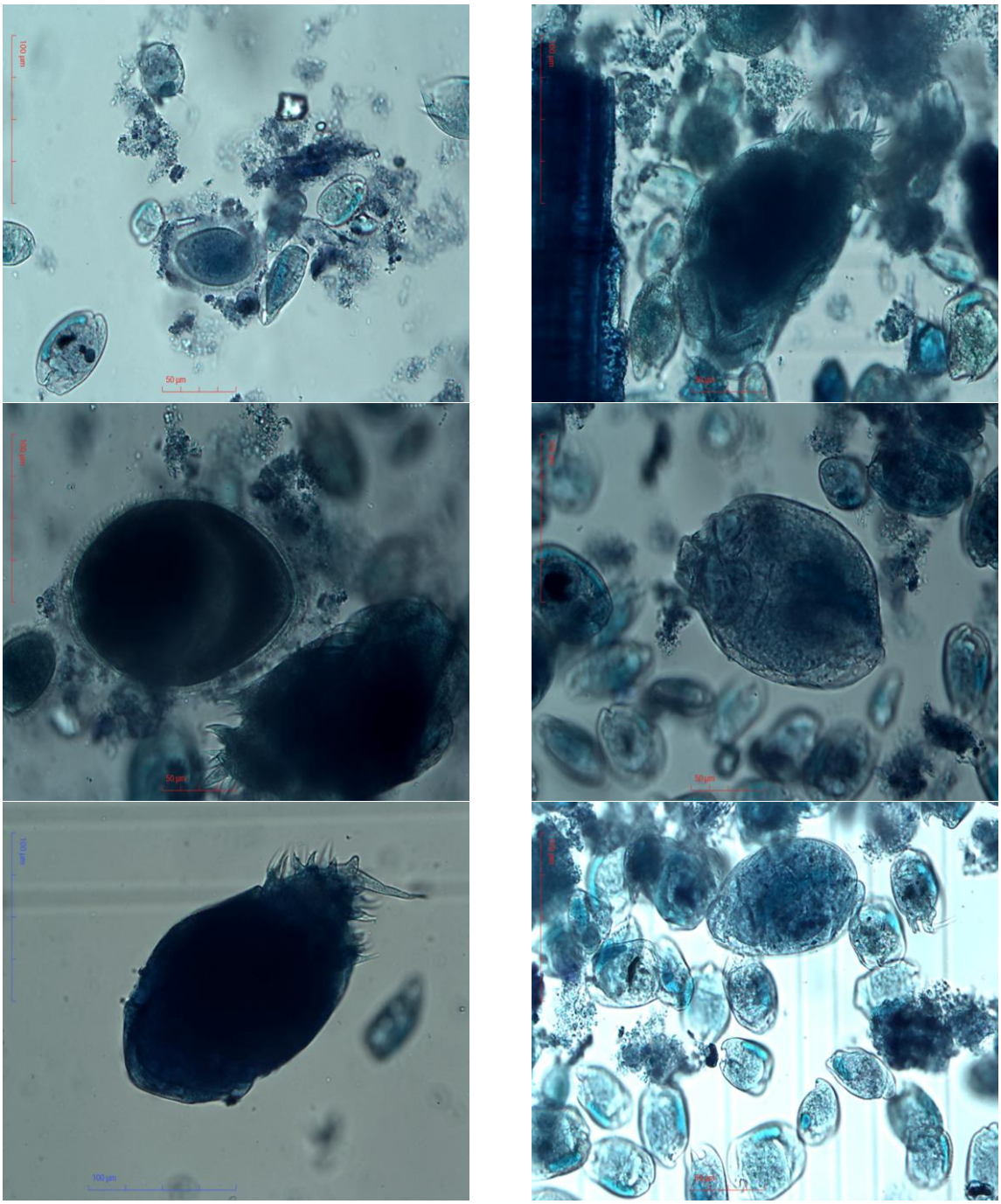
Çizelge 2. Besiye alınmış Karakaş ırkı erkek kuzuların ve Simental ırkı sığırların rumen içeriklerindeki toplam siliyat yoğunluğu

Tür	n	Rumen siliyatları, x10^4 mL^{-1}
Koyun	10	32.9
Sığır	10	69.1
Mann-Whitney U istatistiği ve P değeri		12.000-0.005

Şekil 1 ve 2'de görüldüğü üzere besi yapılan kuzu ve sığırlarda dane yem oranı yüksek olması nedeniyle en yüksek oranda Entodiniomorphida familyasından Entodinium sp daha yoğun olduğu görülmektedir.



Şekil 1. Karakaş erkek kuzularının rumen sıvısındaki bazı siliyatlar (Epidinium sp, Entodinium sp, Diplodinium sp, Isotricha sp, Dasytricha sp, Metadinium sp).



Şekil 2. Besi sığırlarının rumen sıvısındaki bazı siliyatlar (Epidinium sp, Entodinium sp, Diplodinium sp, Isotricha sp, Dasytricha sp, Metadinium sp).

4. Tartışma ve Sonuç

Yapılan çalışmada sığır ve koyun türleri karşılaştırıldığında rumen fermentasyon özellikleri bakımından rumen NH_3-N konsantrasyonu, rumen asetat ve bütirat konsantrasyonu açısından farklılıklar bulunmuştur. Rumendeki amonyak seviyeleri, diyet protein içeriği, protein yıkım hızı, rumen pH'sı, diyet bileşimi ve mikrobiyal aktivite ilişkili çeşitli faktörlerden etkilenmektedir. Amonyak azotu (NH_3-N), mikrobiyal protein sentezi için kritik bir azot kaynağıdır ve konsantrasyonu, rumendeki yem fermentasyonunun durumunu gösteren önemli bir göstergedir (Cao ve ark., 2024). Rumendeki amonyak seviyelerini etkileyen birincil faktörlerden biri, diyetin protein içeriğidir. Yüksek düzeyde rumende parçalanabilir protein (RDP), protein yıkımının artması nedeniyle amonyak konsantrasyonlarını artırır (Holder ve ark., 2013). Örneğin, daha yüksek ham protein (CP) konsantrasyonuna sahip diyetlerin,

rumen amonyak ve plazma üre seviyelerini artırdığı gösterilmiştir; çünkü artan RDP miktarı, doğrudan amonyak üretimiyle ilişkilidir (Gabler & Heinrichs, 2003; Holder ve ark., 2013). Buna karşılık, düşük protein içeren diyetler yetersiz amonyak seviyelerine yol açabilir ve bu durum, mikrobiyal aktiviteyi ve rumen sağlığı ile işlevi için gerekli olan UYA'nin üretimini sınırlayabilir (Ismartoyo ve ark., 2024). Çizelge 1 incelendiğinde besi sığırlarına göre erkek kuzularda daha yüksek rumen NH_3-N seviyeleri ve bütirat konsantrasyonları belirlenmiştir. Hayvan sahipleri ile görüşüldüğünde besi kuzularının karma yeminin ham protein içeriği 165 g/kg kuru madde olduğu ve karma yem içerisinde protein ek yemi olarak kenevir tohumu küspesi ve kaba yemin ise %15 ham protein içerikli yonca kuru otu olduğu bildirilmiştir. Sığırların ise köylü koşullarında arpa (ezme), buğday samanı, çayır kuru otu ve şeker pancarı posası ile oluşturulan rasyonla besiye alındıkları ifade edilmiştir. Dolayısıyla erkek kuzularda rumen NH_3-N seviyeleri ile bütirat konsantrasyonun yüksek olması rasyonlarında daha yüksek oranda protein olduğunu ve daha fazla protein tükettiğini göstermektedir. Rumen asetat konsantrasyonu ise kuzularla karşılaştırıldığında besi sığırlarında anlamlı derecede daha yüksek asetat üretimi belirlenmiştir. Asetat, rumen fermentasyonunda özellikle selülozun sindirimi sonucu üretilen ana uçucu yağ asididir. Sonuçlar değerlendirildiğinde sığırlardaki daha yüksek asetat üretimi, onların genellikle daha fazla lifli yemlerle beslendiğinin bir göstergesidir. Köylü koşullarında besiye alınan Simental ırkı sığırların rasyonları kaba yem ağırlıklı olup (çayır kuru otu, saman ve şeker pancarı posası) dane yem olarak yalnızca arpa ezmesi kullanılmıştır. Bu noktadan hareketle erkek kuzuların rumen NH_3-N konsantrasyonunun daha yüksek, rumen asetik asit konsantrasyonunun ise daha düşük olması rasyonun bileşimden kaynaklanabileceğini düşündürmektedir.

Farklı seviyelerde ham protein içeren yemlerin, Morkaraman kuzu besisinde rumen pH'sı ve amonyak azotu (NH_3-N) konsantrasyonu üzerine etkilerini inceleyen Kaya ve ark. (2009) rumen sıvısında pH değerinin rasyondaki ham protein oranının artmasıyla değişmediğini ancak NH_3-N seviyesinin arttığını bildirmişlerdir. Aynı şekilde Xia ve ark. (2018) ve Xu ve ark. (2019) yapmış oldukları çalışmalarda HP alımı ile hem ruminal pH hem de amonyak konsantrasyonu arasında pozitif bir korelasyon olduğunu bildirmişlerdir.

Rumen fermentasyon parametreleri genellikle beslenme koşullarına göre değişir. Rumen uçucu yağ asitleri konsantrasyonu, enerji seviyesinin artması veya yüksek konsantre yemle birlikte artar. Rasyonun metabolik enerji düzeyinin yüksek olması aynı zamanda rumen bütirat konsantrasyonunu da önemli ölçüde artırır (Wang ve ark., 2020). Ayrıca, yüksek asetik asit ve bütirat konsantrasyonları, yüksek tahıl yemi alımıyla ilişkilidir (Xie ve ark., 2021). Bu çalışmada, bütirik asit seviyelerinin, diyet enerji konsantrasyonu ile arttığı gözlemlenmiştir.

Diyet enerjisi, genel olarak rumen ortamındaki mikrobiyotayı etkiler (Park ve ark., 2020). Genellikle, rumen mikrobiyota çeşitliliği, diyet enerjisi arttıkça azalır (Wang ve ark., 2020). Bu çalışmada besiye alınan erkek kuzuların rumeninde bulunan siliyatların sayısal olarak yoğunluğu besi sığırlarınkinden daha düşük bulunmuş olup sığırlar bu konuda belirgin bir üstünlük göstermiştir. Ayrıca her iki türde de protozoonlardan Entodiniamorphida familyasına ait Entodinidim sp. Yaygın olarak belirlenmiştir. Koyunların sığırlara göre siliyat yoğunluğunun düşük olması muhtemelen, her iki türün beslenme stratejileri, rumen hacmi ve fermentasyon süreçleriyle bağlantılıdır.

Rumen ekosisteminin karmaşıklığına rağmen, rumen mikrobiyotasının kompozisyonu ve bolluğu, filum seviyesinde nispeten istikrarlı olup en yaygın olarak Ciliophora (Siliyat) iken Sarcomastigophora (Kamçılılar) daha düşük yoğunluğa sahiptir. Epidinium, Entodinium, Diplodinium, Isotricha, Dasytricha ve Metadinium sp koyun ve sığır rumeninde en yaygın olarak bulunan protozoon türleridir (Williams ve ark., 1992). Çalışmamızda Entodinium sp daha yoğun oranda görülmektedir. Ruminantların rumeninde bulunan ve tüm siliyat cinsleri içinde en zengini olan Entodinium, nişasta sindiren bir protozoon olup, düşük pH derecelerine karşı dayanıklıdır (Fluharty ve Dehority, 1996). Rumendeki silli protozoonlardan Entodinium toplam protozoal populasyonun yaklaşık %80'ini, Epidinium, Dasytricha, Isotricha ve Ophryoscolex türler %19'unu ve Polyplastron, Metadinium ve Diplodinium türleri ise %1.2'sini oluşturmaktadır (Kreikemeier ve ark., 1990).

Sonuç olarak, koyunlar ve sığırlar rumen fermentasyonu açısından bazı benzerlikler paylaşsa da özellikle NH_3-N ve uçucu yağ asitleri dağılımı açısından önemli farklılıklar mevcuttur. Bu farklılıklar, iki türün beslenme stratejilerinin rumendeki metabolik süreçleri nasıl etkilediğini göstermektedir.

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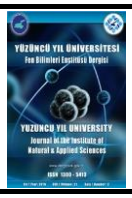
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Derleme Makale

Glisemik İndeksin Azaltılmasında Geleneksel ve Teknolojik Yöntemler

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Öz: Diyabet ve diğer kronik hastalıkların yaygınlaşması, bu hastalıkların önlenmesi ve yönetimi için çeşitli yöntemlerin araştırılmasını teşvik etmiştir. Bu yöntemler arasında karbonhidrat alımını azaltarak düşük karbonhidratlı diyet uygulamak bulunmaktadır. Diyet müdahaleleri, diyabetin önlenmesi ve yönetiminde önemli bir rol oynayarak yemek sonrası kan şekeri seviyelerini düşük ve stabil tutmayı hedeflemektedir. Glisemik indeks (GI), besinlerin kan şekeri seviyeleri üzerindeki etkilerini değerlendiren ve kan şekeri düzenlenmesine katkıda bulunan önemli bir ölçüttür. Düşük GI değerine sahip olan gıdalar (55 ve altı), kan şekerini yavaşça yükseltirken, yüksek GI değerine sahip olan gıdalar (70 ve üzeri) hızla yükseltmektedir. GI değerinin düşük olması, diyabet, obezite ve kardiyovasküler hastalıklar gibi kronik rahatsızlıkların önlenmesinde kritik bir rol oynamaktadır. GI değerini azaltmak için haşlama, pişirme ve kurutma gibi geleneksel yöntemlerin yanı sıra kızılötesi enerji, mikrodalga teknolojisi ve ultrasonikasyon gibi modern teknolojiler de kullanılmaktadır. Bu yöntemler, yiyeceklerin yapısını değiştirerek ve sindirim sürelerini uzatarak GI değerini düşürmeye yardımcı olmaktadır. Derlemenin amacı, GI değerinin sağlıklı beslenme ve hastalık yönetimindeki rolünü açıklamak ve düşük GI değerine sahip gıdaların üretiminde kullanılan geleneksel ve teknolojik yöntemleri incelemektir. Ayrıca, bu alandaki bilimsel çalışmalardan örnekler sunularak sağlıklı gıda tercihlerine yönelik bilinçlendirmeye katkı sağlanması hedeflenmektedir.

Anahtar Kelimeler: Diyabet, Düşük glisemik indeks, Düşük karbonhidratlı diyet, Nişasta sindirilebilirliği

Traditional and Technological Methods for Reducing the Glycemic Index

Abstract: The prevalence of diabetes and other chronic diseases has encouraged the research of various methods for the prevention and management of these diseases. These methods include implementing a low-carbohydrate diet by reducing carbohydrate intake. Dietary interventions play an important role in the prevention and management of diabetes and aim to keep post-meal blood sugar levels low and stable. The glycemic index (GI) is an important measure that evaluates the effects of foods on blood sugar levels and contributes to blood sugar regulation. Foods with a low GI value (55 and below) raise blood sugar slowly, while foods with a high GI value (70 and above) raise it rapidly. A low GI value plays a critical role in the prevention of chronic diseases such as diabetes, obesity and cardiovascular diseases. In addition to traditional methods such as boiling, cooking and drying, modern technologies such as infrared energy, microwave technology and ultrasonication are also used to reduce the GI value. These methods help lower the GI value by changing the structure of foods and extending their digestion time. The aim of this review is to explain the role of GI value in healthy nutrition and disease management and to examine the traditional and technological methods used in the production of foods with low GI value. In addition, it is aimed to contribute to the awareness of healthy food preferences by presenting examples from scientific studies in this field.

Keywords: Diabetes, Low carbohydrate diet, Low glycemic index, Starch digestibility

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1. Giriş

Günümüzde insan sağlığı üzerinde çeşitli olumsuz etkileri bulunan gıda ürünlerinin tüketimi oldukça fazladır (Shridhar ve ark., 2015). Gıda ve Tarım Örgütü (FAO) ve Dünya Sağlık Örgütü'ne (WHO) göre sağlıksız beslenme kronik hastalık risklerinin oluşmasına neden olan en önemli faktörlerden biridir (Galanakis, 2021). Bu durum, tüketicilerin yaşam tarzı ve gıda tercihlerini etkileyerek sağlıklı beslenme konusunda daha fazla bilinçlenmelerine neden olmuştur.

Son zamanlarda diyabet ve bazı kronik hastalıkların yaygınlaşması, bu durumun önüne geçmek için yöntemler üzerine daha çok araştırma yapılmasını teşvik etmiştir. Yaygın olarak önerilen yaklaşımlar arasında karbonhidrat alımını azaltmak ve düşük karbonhidratlı bir diyete uymak yer almaktadır (Jeevarathinam ve ark., 2024). Diyet müdahale yöntemleri, diyabetin önlenmesi ve yönetiminde kritik öneme sahip olup, yemek sonrası kan şekeri seviyelerini düşük ve stabil tutmayı hedeflemektedir (Jenkins ve ark., 1984). Kan şekeri düzenlenmesi, çeşitli sağlık sorunlarının önlenmesi için kritik bir fizyolojik süreçtir. GI, besinlerin kan şekeri seviyeleri üzerindeki etkilerini değerlendirmede ve karbonhidratlı bir gıdanın kan şekerini yükseltme potansiyelini belirlemede önemli bir göstergedir (Kaur ve ark., 2016). Kan şekerinin düzenlenmesi vücutta enerji dengesinin sağlanması ve metabolizmanın düzenlenmesi, beyin fonksiyonu ve bilişsel sağlığın iyileştirilmesi, kronik hastalıkların önlenmesi, sindirim sağlığının sürdürülebilirliğinin sağlanması, bağışıklığın iyileştirilmesi ve hormonal dengenin sağlanması bakımından önemlidir (Jeevarathinam ve ark., 2024). Araştırmalar, yüksek GI değerine sahip diyetlerin düzenli tüketiminin tip II diyabet riskini artırdığını göstermektedir (Salmerón ve ark., 1997).

Sanayileşmiş ülkelerde tüketilen karbonhidrat içeren gıdaların çoğunun düşük kaliteye sahip olması, sağlıklı diyetlerde önerilen karbonhidrat miktarı ve türü hakkında soruların ortaya çıkmasına neden olmuştur. Son on yılda, yüksek proteinli diyetlerin kilo kaybı için popülerlik kazanması ve karbonhidratların kardiyovasküler hastalık riski açısından doymuş yağlardan daha kötü olabileceğine dair yeni bulguların elde edilmesi, diyette karbonhidratların olumsuz bir imaj kazanmasına neden olmuştur (Jakobsen ve ark., 2009; Jakobsen ve ark., 2010).

Bir gıdanın GI değeri, kan şekeri seviyesini kontrol etmeye ve genel sağlığı iyileştirmeye yönelik yiyecek seçimlerinde rehberlik eden bir sağlık göstergesidir (Zafar ve ark., 2019). GI değeri, gıdalardaki karbonhidratların ne kadar hızlı glikoza dönüştüğünü ve kan dolaşımına salındığını ölçmektedir (Priyadarshini ve ark., 2021). Glisemik yanıt (GY) ise glikozun yemek sonrası kan dolaşımına girmesiyle ortaya çıkan, glikozun dolaşıma giriş hızı, emilen glikoz miktarı, dokular tarafından alınma hızı ve karaciğerin glikoz salınımını düzenlemesine bağlı olarak gerçekleşen fizyolojik bir olaydır (Triplitt, 2012). Düşük GI diyeti, genellikle diyabet hastaları veya kan şekeri seviyelerini kontrol etmeye çalışan bireyler için tavsiye edilmektedir. GI değerini azaltmaya yönelik ilerlemeler, diyetle kan şekeri seviyelerini yönetmede daha kişiselleştirilmiş ve hassas bir yaklaşım sunmaktadır (Jukanti ve ark., 2020).

Bir gıdanın GI değeri, içerdiği karbonhidrat türüne ve gıdanın sindirilebilirliği, gastrointestinal motilite veya insülin salgısını etkileyen diğer beslenme faktörlerine bağlıdır (Wolever ve ark., 1991). Karbonhidratların GI değerlerine ve lif içeriklerine bağlı olarak bazı kaynaklarının sağlık üzerine olumlu, bazılarının ise olumsuz etkileri bulunmaktadır (Mirrahimi ve ark., 2012). Bağırsakta polisakkaritlerin hidroliz hızını sınırlayıcı bir faktör olmadığından, rafine nişastalı yiyeceklerin GI değeri glikozunkine yakındır. Buna karşılık, fruktoz ve galaktoz karaciğerde metabolik dönüşümden geçmektedir. Bu yavaş süreç, fruktoz ve galaktozun nispeten düşük bir GI değerine sahip olmasına yol açmaktadır (Ludwig, 2003).

Derlemenin amacı, GI değerinin sağlıklı beslenme ve hastalık yönetimi açısından önemini açıklamak ve düşük GI değerine sahip gıdaların üretimi için kullanılan çeşitli teknolojileri incelemektir. GI değerinin kan şekeri düzenlenmesi ve kronik hastalıkların önlenmesi üzerindeki etkilerine vurgu yapılarak, düşük GI diyetlerin özellikle diyabet hastaları ve kan şekeri yönetimi ihtiyacı olan bireyler için faydaları incelenmiştir. Ayrıca GI değerini azaltmak için kullanılan geleneksel ve teknolojik yöntemler detaylandırılarak düşük GI'li gıdaların üretimine yönelik mevcut teknolojiler açıklanmaktadır. Son olarak, GI üzerine yapılan araştırmalardan örnekler verilerek bu alandaki bilimsel birikim ortaya konulmaktadır. Çalışma sağlıklı gıda seçeneklerine yönelik bilinçli tercihler yapılmasına katkı sağlamayı hedeflemektedir.

2. GI Değerinin Azaltılmasının Önemi

Araştırmalar, GI değeri ile obezite ve bir dizi kronik hastalık arasındaki ilişkiyi doğrulamaktadır (Brand-Miller, 2003). Bir gıda ürününün GI değerini azaltmak için özellikle tam tahıllı besinleri içeren bir beslenmenin benimsenmesi gerekmektedir. Düşük GI değeri içeren karbonhidratlı gıdaların tüketimiyle pankreastan salgılanan insülin seviyesi azaltılabilmektedir. İnsülin seviyesinin azalmasıyla obezite ve diyabet dahil olmak üzere pek çok kronik hastalığın önlenmesi ya da geciktirilmesi sağlanabilmektedir. Ayrıca düşük GI değerine sahip gıdalar, yavaş sindirim ve emilim hızıyla tokluk hissini arttırarak kilo yönetimini kolaylaştırmaktadır (Brand-Miller ve ark., 2002). Öte yandan yüksek GI değerine sahip gıdaların, iştahı artırıcı etkisiyle enerji alımını artırdığı gözlemlenmiştir (Ludwig, 2003). Kan şekerinin dengeli bir şekilde kontrol edilmesini sağlayan bazı alternatifler Çizelge 1'de sunulmaktadır.

Çizelge 1. GI değerinin azaltılması için bazı alternatifler (Foster-Powell ve ark., 2002; Panlasigui & Thompson, 2006; Atkinson ve ark., 2008; Sagili ve ark., 2022)

Yüksek GI değerine sahip gıdalar	GI değerleri	Düşük GI alternatifleri
Beyaz ekmek	75	Tam tahıllı ekmek, kepekli ekmek veya çavdar ekmeği
Tam buğday ekmeği	77	
Mısır gevreği	81	Yulaf ezmesi, kepekli / doğal müsli gibi rafine edilmemiş tahıllar
Buğday gevreği	59	
Beyaz pirinç	78	Kahverengi pirinç, arpa, erişte veya bulgur
Beyaz makarna	38	Tam buğday makarna, mercimek eriştesi veya karabuğday eriştesi
Patates	82	Tatlı patates veya kabak
Kola	63	Taze sıkılmış meyve suları
Meyveli gazlı içecek	68	
Beyaz unlu ürünler	68	Badem unu, hindistancevizi unu, yulaf unu ve tam buğday unu kullanılan ürünler
Sade bisküvi veya kraker	78	Kurutulmuş meyve, yulaf ve tam tahıllarla yapılan bisküviler

GI değeri 55'in altında olan gıdalar düşük; 59 ile 69 arasında olanlar orta ve 70'in üzerinde olanlar ise yüksek GI değerli olarak tanımlanmaktadır (Zhang ve ark., 2021). Patates cipsi (GI=75), patates püresi (GI=87), beyaz baget ekmek (GI=95), balkabağı (GI=75), karpuz (GI=76) ve kavun (GI=72) gibi gıdalar GI değeri yüksek olan gıdalar arasında yer almaktadır (Foster-Powell ve ark., 2002; Atkinson ve ark., 2008). GI değeri düşük gıdalar ise mercimek (GI=32), elma (GI=36), bulgur (GI=48) ve kinoa (GI=53) olarak sayılabilmektedir (Jenkins ve ark., 2002; Foster-Powell ve ark., 2002; Atkinson ve ark., 2008). Baklagiller, yavaş sindirilen karbonhidratlar ve lif açısından zengin olduğundan, diyetin GI değerini düşürmede önemli bir rol oynamaktadır (Jenkins ve ark., 2012). Zengin tekli ve çoklu doymamış yağ asitleri, bitkisel protein ve lif içeriğiyle dikkat çeken fındık, diyetin glisemik yükünü azaltmak için faydalı bir seçenek sunmaktadır.

Asya ülkelerinde yaygın olarak tüketilen beyaz pirinç, yüksek GI değerine sahip olan tahıl çeşididir. Beyaz pirince alternatif olarak daha düşük GI değerine sahip olan kahverengi pirinç (GI=65) tercih edilebilmektedir (Panlasigui & Thompson, 2006). Pirinç çeşitlerinin amiloz içeriği, bu ürünlerin GI değerlerinin farklı olmasına neden olabilmektedir. Daha yüksek amiloz içeriğine sahip olan pirinç çeşitleri genellikle daha düşük GI değerine sahiptir. Bunun nedeni, amilozun kompakt yapılar oluşturarak enzimatik sindirime dirençli olmasıdır (Hu ve ark., 2004; Lu ve ark., 2013). Ancak, bazı çalışmalar farklı amiloz içeriklerine rağmen GI değerlerinde fark olmadığını göstermiştir. Bu nedenle, pirincin sindirilebilirliğinde amiloz içeriği tek belirleyici faktör değildir (Frei ve ark., 2003).

Sindirilemeyen bir nişasta türü olan dirençli nişasta, bağırsakta fermente edilerek kısa zincirli yağ asitlerine dönüşmektedir. Gıdalardaki dirençli nişasta oluşumu, sindirim ve emilimin daha yavaş gerçekleşmesine yol açmaktadır. Bu durum, gıdaların GI değerini düşürerek kan şekeri seviyelerinin daha yavaş yükselmesini sağlamaktadır (Jenkins ve ark., 1981). Dirençli nişasta, nişasta türlerinin doğal yapılarından kaynaklandığı gibi nişastanın pişirilip soğutulmasıyla da (retrogradasyon) oluşabilmektedir. Retrogradasyon süreci, nişasta moleküllerinin yeniden düzenlenerek daha

sindirilemez bir formda olmasını sağlamaktadır. Pişirilip soğutulmuş patates, makarna ve baklagiller, daha fazla dirençli nişasta içerdiği için düşük GI değerine sahip olup salata şeklinde tüketilmeleri daha sağlıklı bir seçenek sunabilmektedir (Behall ve ark., 1988; Leszczyński, 2004).

Meyvelerde ise GI değeri üzerinde lif içeriği oldukça önemli bir etkidir. Meyve suları, lif içeriğinin az olması ve içeriğinde yer alan şekerlerin hızla emilmesi nedeniyle yüksek GI değerine sahiptir (portakal suyu GI=50-60) (Foster-Powell ve ark., 2002). Meyvelerin ise lif bakımından zengin olmaları onların sindirimini yavaşlatarak GI değerinin düşük olmasını sağlamakta (elma GI = 36) ve diyabet yönetimi ile genel sağlık açısından önemli faydalar sunmaktadır (Jenkins ve ark., 2002).

Yüksek GI değerine sahip gıdalar doygunluk hissini azaltarak yağ yakımını azaltmaktadır. Bu gıdaların kilo kontrolü üzerindeki olası ters etkileri nedeniyle son yıllarda obezite toplumsal düzeyde artış göstermektedir (Brand-Miller, 2003). Düşük kalorili düşük GI değerli diyetler, aynı enerji düzeyindeki yüksek GI değerli diyetlere göre daha yüksek bazal metabolik hız sağlamaktadır (Slabber ve ark., 1994). Yapılan bir çalışmada, fazla kilolu 129 genç yetişkinde, 12 hafta boyunca kilo kaybı sırasında diyetlerindeki değişen GI değerlerine bakılmıştır (Brand-Miller ve ark., 2009). Bu amaçla yüksek karbonhidrat, düşük GI diyet ve düşük karbonhidrat, yüksek GI diyet yöntemleri karşılaştırılarak, kilo verme bakımından düşük GI içeren yöntemin çok daha etkili olduğu bulunmuştur.

Klinik araştırmalar, düşük GI diyetlerin diyabet hastalarında glikoz kontrolünü arttırdığını, serum lipidlerini ve diğer kardiyovasküler risk faktörlerini azalttığını göstermektedir (Jenkins ve ark., 2008). Yapılan bir çalışmada, tip II diyabet hastalığına sahip kişilerin farklı GI değerlerinde diyet ile beslenmeleri ve kan şekeri seviyelerinin tespit edilmesi amaçlanmıştır (Rizkalla ve ark., 2004). Hastalar iki gruba ayrılarak 4 hafta boyunca bir gruba düşük GI değerinde diyet uygulanırken, diğer gruba ise yüksek GI değerinde diyet uygulanmıştır. Elde edilen sonuçlara göre, düşük GI değeri içeren diyetlerin tüketimiyle daha düşük insülin salınımı ve daha düşük tokluk kan glikozu seviyelerinin elde edildiği belirlenmiştir. Buna bağlı olarak, düşük GI değerli besinlerin tüketilmesinin diyabetin hastalığının kontrolünde etkili olduğu söylenebilmektedir. Ayrıca birçok çalışma, düşük GI değerli diyetleri, koroner kalp hastalığı ve belirli kanser risklerinin azalması ile ilişkilendirmektedir (Barclay ve ark., 2008). Düşük GI değerine sahip gıdalarla beslenmek, vücutta insülin dalgalanmasını minimuma düşürmektedir. Bu durum, yüksek GI değerli gıdalarla beslenen kişilere kıyasla düşük GI değerli gıdalarla beslenen kişilerin insülinin fazla salgılanmasıyla bağlantılı karşılaşabilecekleri kanser riskini azaltmaktadır. Yapılan çalışmalar, beslenmede GI değerinin kolorektal ve meme kanseri ile doğrudan ilişkili olduğunu göstermektedir (Gnagnarella ve ark., 2008). Ayrıca yapılan birçok araştırma, işlenmiş karbonhidratların, özellikle de şeker içeren yiyeceklerin, depresyon riski ile de bağlantılı olduğunu ortaya koymuştur (Nabb & Benton, 2006).

3. GI Değerini Azaltmak İçin Kullanılan Bazı Teknolojiler

Gıdalardaki GI değerini azaltmada kullanılan yöntemler, karbonhidratların fiziksel ve kimyasal özelliklerinde değişikliklere yol açarak vücutta karbonhidratların sindirilme ve emilme hızlarını etkilemektedir (Jeevarathinam ve ark., 2024). GI değerini azaltmak için kullanılan teknolojiler arasında yüksek basınçlı işleme ve düşük sıcaklıkta pişirme gibi yöntemler bulunmaktadır (Çizelge 2). Bu yöntemler, yiyeceklerin yapılarını değiştirerek ve sindirilme sürelerini uzatarak GI değerini düşürmeye yardımcı olmaktadır.

Çizelge 2. Termal ve termal olmayan işleme yaklaşımları (Singh ve ark., 2003; Kaur ve ark., 2016; Zeng ve ark., 2016; Akyereko ve ark., 2020; Lal ve ark., 2021; Hall & Moraru, 2022; Jeevarathinam ve ark., 2024; Subaitha ve ark., 2024)

Geleneksel yöntemler	Teknolojik yöntemler
Haşlama	Kızılötesi enerji
Pişirme	Yüksek basınç işleme
Kurutma	Darbeli elektrik alan
Fermantasyon	Ultrasonikasyon
Ekstrüzyon	Soğuk plazma
	Mikrodalga teknolojisi
	Radyasyon uygulamaları

3.1. Geleneksel yöntemler

Haşlama: Pirinç gibi nişastalı ürünler, haşlama işlemi sırasında yüksek sıcaklığa maruz kalmaktadır. Haşlama işlemi sırasında nişasta granülleri jelatinleşerek retrogradasyon meydana gelmektedir. Bu durum, pirinç tanesinde besinsel ve kalite parametreleri açısından birçok değişikliğe neden olmaktadır (Sivakamasundari ve ark., 2020). Haşlama işlemi, dirençli nişasta miktarını arttırmak için kullanılan bir yöntemdir ve nişastanın parçalanmasını sınırlayarak pirinç gibi nişastalı ürünlerin GI değerini %30 oranında azaltmaktadır (Kumar ve ark., 2022; Jeevarathinam ve ark., 2024).

Pişirme: Pirinç, patates ve mısır gibi nişastalı gıdalar genellikle pişirilerek tüketilmektedir. Pişirme işlemi, nişasta granüllerinin hidroliz hızını yavaşlattığından nişasta granüllerinin jelatinleşme derecesi artmaktadır. Yüksek sıcaklıkta pişirme, lipitler ile amiloz arasında sindirilmesi zor etkileşimlerin gelişmesini teşvik etmektedir. Bu durum, kaynatma işleminde de olduğu gibi nişastanın parçalanmasını engelleyerek nişastalı ürünlerin GI değerini azaltmaktadır (Jeevarathinam ve ark., 2024). Pişirme süresi nişasta hidroliz hızını ve gıdanın glisemik etkisini belirlemektedir. Nişastalı gıdanın fazla pişirilmesi, nişastanın daha fazla parçalanmasına ve gıdanın glisemik etkisinin artmasına neden olmaktadır (Lal ve ark., 2021). Yapılan bir çalışmada, 5-10 dakika arasında pişirilen makarnanın daha uzun süre pişirilen makarnaya göre biraz daha düşük GI değerine sahip olduğu bildirilmiştir (Kirpitch & Maryniuk, 2011).

Kurutma: Kurutma yöntemiyle gıdalardaki nem içeriğindeki azalmaya bağlı olarak, kısmi nişasta jelatinizasyonu, nişasta kaybı ve düşük sindirilebilirlik nedeniyle düşük GI değerleri elde edilebilmektedir (Akyereko ve ark., 2020).

Fermentasyon: Fermantasyon, gıdaların glisemik etkisini azaltmak için kullanılan bir işleme yöntemidir. Fermente un hamurunda, amilozun daha yüksek oksidatif depolimerizasyonu nedeniyle amiloz içeriğinin arttığı bildirilmiştir (Singh ve ark., 2003). Yapılan bir çalışmada haşlama, pişirme ve kurutma işlemlerinin cassava unu üzerindeki etkileri Çizelge 3'te sunulmaktadır.

Çizelge 3. Farklı işleme yöntemlerine tabi tutulan cassava ununun amiloz, amilopektin, diyet lifi ve GI değerleri (Akyereko ve ark., 2020)

Ürün	Amiloz	Amilopektin	Diyet lifi	GI değeri
Taze un	4.23±0.09	38.18±0.52	1.23±0.02	47.75
Fermente işlemi	3.49±0.16	36.32±0.39	2.761±0.06	46.47
Güneşte kurutma	14.74±0.33	23.49±1.07	1.63±0.04	47.49
Güneş enerjisiyle kurutma	8.28±0.31	25.04±0.23	1.21±0.01	48.50
Güneşte kurutma + pişirme	2.38±0.07	34.81±0.21	2.84±0.10	40.20
Güneş enerjisiyle kurutma + pişirme	4.53±0.03	42.54±0.79	1.53±0.02	61.11
Haşlama	6.91±0.33	38.47±0.42	1.80±0.03	77.30

Ekstrüzyon: Ekstrüzyon, hammaddelerin ısı ve basınç uygulanarak bir makineden geçirilmesiyle karışmalarını, doku ve yapılarının değişmesini sağlayan işlemdir (Subaitha ve ark., 2024). Ekstrüzyon sırasında, nişastanın jelatinizasyonu, amiloz ve lipitler arasında bağ oluşumu gibi çeşitli moleküler ve yapısal değişiklikler meydana gelmektedir (Ren ve ark., 2016). Ekstrüzyon işlemi, dirençli nişasta oluşumunu sağlayarak GI değerini düşürebilmektedir. Pirinçlere uygulanan ekstrüzyon işlemi, amiloz ve amilopektinin moleküler ağırlığını azaltarak sindirilemeyen, kırılması zor bağlar oluşturmaktadır. Bu durum, pirinçlerdeki GI değerinin azalmasını sağlamaktadır (Kaur ve ark., 2016).

3.2. Teknolojik yöntemler

Kızılötesi enerji: Hem ışıma hem de iletken ısı transferi mekanizmaları kullanıldığından geleneksel termal işleme göre önemli avantajlar sunmaktadır. Tahıl taneleri kızılötesi işlemine tabi tutulduğunda, nişasta molekülleri arasında oluşan hidrojen bağları ile düzenli bir yapı oluşumu meydana gelmektedir. Bunun sonucunda, dirençli nişasta artarak düşük GI değerine sahip gıdaların üretilmesini sağlamaktadır (Kaur ve ark., 2016).

Yüksek basınçlı işleme: Gıda endüstrisinde yaygın olarak kullanılan, termal olmayan bir işlemdir. Soğuk pastörizasyon olarak da adlandırılan yüksek basınçlı işleme, gıdaların korunması ve ürünlerin raf ömrünün uzatılması amacıyla uygulanmaktadır. Nişasta ürünleri, yüksek basınç karşısında

jelatinleşerek sindirilebilirliği azalmaktadır. Nişasta granülleri yüksek basınç işlemiyle, ısıl işlem görmüş nişastaya kıyasla, daha düşük GI değerine sahiptir (Hall & Moraru, 2022).

Darbeli elektrik alan: Darbeli elektrik alan işleminin GI değerine etkisi gıdanın türüne ve işleme koşullarına bağlı olarak değişmektedir. Örneğin bu işlem, nişasta asetat nano yapılarındaki yavaş sindirilebilir nişasta miktarını arttırarak GI değerinin düşmesini sağlamaktadır (Wang ve ark., 2018). Ancak bu işlem, pirinç dokularının parçalanmasını kolaylaştırarak daha fazla nişasta granülünün enzimatik parçalanmaya maruz kalmasına da neden olabilmektedir. Sonuçta, pişirilmiş pirinçlerin GI değerlerinde artış gözlenebilmektedir (Zeng ve ark., 2016).

Ultrasonikasyon: Ultrasonikasyon işlemi, nişastanın fizikokimyasal özelliklerini ve amiloz-amilopektin zincir etkileşimini değiştirdiğinden nişastanın hidroliz hızını belirlemektedir. Nişasta hidroliz hızının azalması durumunda, nişasta granülleri güçlü moleküler etkileşimleriyle düşük GI değerine sahip olmaktadır (Jeevarathinam ve ark., 2024).

Soğuk plazma: Soğuk plazma, istenmeyen yan ürünler oluşturmadan nişastanın granüler ve kristal yapısını değiştiren ısıl olmayan bir işlemdir. İşlem sırasında, gaz iyonizasyonu çeşitli serbest radikaller oluşturarak radikallerin nişasta ile etkileşime girmesine neden olmaktadır. Soğuk plazma işlemiyle GI değerlerinde görülen farklılıklar, işleme koşullarına ve nişasta kaynaklarına bağlı olarak değişmektedir (Babu ve ark., 2019). Proso darısı üzerinde yapılan soğuk plazma çalışmasında, kısa süreli (1 dakika) soğuk plazma uygulamasının nişasta granülleri ve kristallik üzerinde hiçbir etkisi olmadığı gözlemlenmiş ve bu nedenle dirençli nişasta oluşumunun arttığı tespit edilmiştir. Ancak bu işlemin 3-5 dakika arasında uygulanması, kristalliğin azalmasına ve sağlam nişasta granüllerinin zarar görmesine neden olmuştur. Bu durum nişasta sindirimini arttırarak yüksek GI değerlerinin elde edilmesi ile sonuçlanmıştır (Sun ve ark., 2022).

Mikrodalga teknolojisi: Mikrodalga teknolojisi, toplam dirençli nişasta içeriğini arttırdığından GI değerini azaltmaktadır. Nişasta granülleri mikrodalga ile ısıtıldığında jelleşmektedir (Wang ve ark., 2023). Mikrodalga işlemi, nişasta moleküllerini parçalayarak bu molekülleri sindirim enzimlerine uygun hale getirmektedir. Ayrıca nişasta moleküllerinin vücut tarafından emilme yeteneğini de arttırmaktadır. Ancak mikrodalga teknolojisinin nişasta üzerindeki etkileri, nişasta türüne ve mikrodalga parametrelerine bağlı olarak değişebilmektedir (Jeevarathinam ve ark., 2024). Yapılan bir çalışmada, yulaf kepeği ile yulaf ezmesi, 5 dakika boyunca 2000 MHz mikrodalga uygulamasına tabi tutularak GI değerleri incelenmiştir. Yulaf kepeği, sindirim enzimlerinin nişastayı parçalanmasını engellerken, yulaf ezmesi, nişastanın sürekli sindirilmesini destekleyen bir yapıya sahiptir. Bu nedenle yulaf kepeğinin GI değeri daha düşük elde edilmiştir (Harasym & Olędzki, 2018).

Radyasyon uygulamaları: Gama radyasyonunun GI değerine olan etkisi, nişasta türüne, uygulanan radyasyon dozuna ve işleme koşullarına bağlı olarak değişmektedir. Genel olarak gama radyasyonu nişasta granüllerinde yapısal dönüşümlere ve moleküler parçalanmalara yol açarak, dirençli nişasta oluşumuna neden olduğu gözlemlenmiştir. Bu durum, nişastanın sindirilebilirliğini azaltarak GI değerinin düşmesine katkıda bulunmaktadır (Shanmugam ve ark., 2022).

4. Glisemik İndeks Hakkında Yapılan Bazı Çalışmalar

Yapılan bir çalışmada, düşük GI değerli kestane unlarının hazırlanması için enzimatik dallandırma (debranching) ve ısı-nem uygulaması olmak üzere iki işlem uygulanmıştır (Huang ve ark., 2024). Enzimatik dallandırma işlemiyle kestane unlarındaki nişasta moleküllerinin dallanmalarının azaltılması amaçlanmıştır. Uygulama, nişasta moleküllerinin daha düzgün ve düzenli bir yapıya sahip olmasını sağlayarak GI değerinin azaltılmasına katkıda bulunmaktadır. Bu amaçla kestane unu, pH 4.4'te bir sodyum asetat tamponu ile karıştırılarak jelatinizasyon sağlamak için kaynar su banyosunda 20 dakika ısıtılmıştır. Her 1 gram kestane unu için 40 U/mg pullulanaz eklenerek ve dallandırma işlemi gerçekleştirmek için 55◦C'de su banyosunda 7 saat boyunca karıştırılmıştır. Dallandırma işleminden sonra, pullulanaz, 30 dakika boyunca kaynar su banyosuna yerleştirilerek inaktive edilmiştir. Son olarak, örnek 50◦C'de 24 saat kurutulmuştur. Isı-nem işlemi ise nişastanın jelatinizasyonunu arttırarak nişasta moleküllerinin daha dirençli hale gelmesi amacıyla uygulanmıştır. Bu amaçla nem içeriği %28'e ayarlanmak istenen kestane unları, destile suda 24 saat boyunca bekletilmiştir. Ardından sıcak hava kurutma yöntemiyle 92◦C'de 90 dakika boyunca kurutulduktan sonra 24 saat oda sıcaklığında bekletilmiş ve tekrardan 50◦C'de 24 saat kurutulmuştur. Çalışmanın sonucunda, enzimatik dallandırma ve ısı-nem uygulaması gibi işlemlerin, kestane unlarının GI değerini düşürmede etkili olduğu

görülmüştür. Başlangıçta 67.3 GI değere sahip olan kestane unları, işlem sonunda 49.1-53 aralığında GI değerlerini göstermiştir.

Bir başka çalışmada ise, pişirme, kaynatma ve fermantasyon işlemlerinin pirincin GI değeri üzerindeki etkisi incelenmiştir (Bagchi ve ark., 2023). Bir gece boyunca 4◦C'de suda bekletilen pirinçler buharda pişirilmiştir. 1 saat dinlendirilen pirinçler, %13-14 neme ulaşması amacıyla 2-4 saat güneşte kurutulmuştur. Kaynatma işlemi, basitçe suda kaynatılarak uygulanmıştır. Fermente işleminde ise pirinçler musluk suyu kullanılarak oda sıcaklığında bir gece boyunca anaerobik fermantasyona tabi tutulmuştur. Sonuçlar, her üç işlemin pirincin besin değerlerinde ve GI değerinde önemli değişikliklere neden olduğunu göstermiştir. Kaynatma işlemiyle en düşük GI değeri (60-65) elde edilirken, fermentasyon işlemiyle en yüksek GI değeri (69-73) elde edilmiştir.

Pirinç kullanılarak yapılan bir başka çalışmada ise, beyaz pirinç tanelerinin farklı amiloz içeriği ile daha düşük GI içeriği elde etmek amacıyla ultrason-soğutma destekli ısıl işlemin etkisi araştırılmıştır (Kunyanee ve ark., 2022). Bu amaçla %16.9 amiloz içeriğine sahip Jasmin pirinci (KDML105) ve %29.35 amiloz içeriğine sahip Chai-Nat1 (CN1) pirinci kullanılmıştır. Pirinç örnekleri, 15 dakika boyunca 60 kHz frekansta, 665 W güce sahip, 30-35◦C'deki bir ultrasonik banyoya yerleştirilmiştir. Ultrasonik işlem görmüş pirinç tanesi örnekleri çıkarıldıktan sonra 1 dakika boyunca süzülmüştür. Süzülmüş pirinç taneleri 4 ◦C'de 24 saat boyunca bekletilerek 40 ± 5◦C'de 5 saat kurutulmuştur. Nem içeriği %11'e ayarlanan pirinç örnekleri toz haline getirilmiştir. Öğütülmüş pirinç örnekleri (100 ± 5 mg), 0.1 M sodyum maleat tamponu (pH 6) içeren ve 10 mg/ml pankreatik α-amilaz ile 3.3 U/mL amiloglukozidaz içeren 4 mL'lik bir çözeltide 37 °C'de 0, 30, 60, 120, 150 ve 180 dakika boyunca çalkalamalı bir su banyosunda inkübe edilmiştir. Hidrolize edilmiş pirinç örneklerine etanol eklenerek oda sıcaklığında 10 dakika boyunca 1500 g'de santrifüj işlemi uygulanmıştır. Sonuçlar, ultrasonik soğutma destekli ısıl işlemin, farklı amiloz içeriğine sahip beyaz pirinç tanelerinde önemli ölçüde daha düşük bir GI elde etmede etkili olduğunu göstermiştir. Pirinç tanesi örneklerinin GI değerleri Çizelge 4'te belirtilmektedir.

Çizelge 4. Pirinç tanesi örneklerinin GI değerleri

Pirinç çeşitleri	Yerli pirinç	UC[1]	UC + ANN[2]
KDML105	74.09	72.02	45°C'de 70.98- 50°C'de 69.50- 55°C'de 67.94
CN1	64.19	62.05	45°C'de 60.09- 50°C'de 59.89- 55°C'de 57.75

[1]UC= Ultrason-soğutma işlemi
[2]UC+ANN= Ultrason-soğutma + tavlama işlemi

Fernandes ve ark., (2005) tarafından yapılan bir çalışmada, Kuzey Amerika'da yaygın olarak tüketilen patateslerin GI değerlerinin belirlenmesi amaçlanmıştır. Çalışmanın hedefi, farklı pişirme yöntemlerinin patateslerin GI değerini nasıl etkilediğini incelemektir. Çalışma, sağlıklı yetişkin katılımcılar üzerinde gerçekleştirilerek üç farklı yöntemle (haşlama, kızartma, mikrodalga) pişirilen patates örnekleri kullanılmıştır. Katılımcılara, farklı pişirme yöntemleriyle hazırlanmış patatesler verilerek kan şekeri seviyeleri belirli aralıklarla ölçülmüştür. Haşlanmış patateslerin GI değeri (56-60), diğer pişirme yöntemlerine göre daha düşük bulunmuştur. Elde edilen sonuçlar, nişasta granüllerinin daha az parçalanması ve daha yavaş sindirilmesi ile açıklanmıştır. Kızartılmış patateslerin GI değeri (75-80), haşlanmış patateslere kıyasla daha yüksek bulunmuştur. Yağ varlığının, nişastanın jelatinleşmesini arttırarak daha hızlı sindirilmesine neden olduğu düşünülmektedir. Mikrodalgada pişirilmiş patateslerin GI değeri de (65-70), haşlanmış patateslere göre daha yüksek bulunmuştur. Mikrodalga işlemi, nişasta granüllerinin yapısını değiştirerek sindirimi hızlandırmıştır. Çalışma, farklı pişirme yöntemlerinin patateslerin GI değerini önemli ölçüde etkilediğini göstermektedir.

Yapılan bir başka çalışmada ise, gama radyasyonunun nişastanın yapısal ve fonksiyonel özellikleri üzerindeki etkileri araştırılmıştır. Çalışma, gama radyasyonunun nişasta moleküllerinin yapısını nasıl değiştirdiğini ve bu değişikliklerin nişastanın fizikokimyasal özelliklerine nasıl yansıdığını incelemektedir. Çalışmada, farklı bitkilerden elde edilen nişasta örnekleri kullanılarak bu örneklere 5 ve 10 kGy dozlarında gama radyasyonu uygulanmıştır. Işınlama öncesi ve sonrası nişasta örneklerinin amiloz içeriği, amiloz/amilopektin oranı, şişme gücü; çözünürlük indeksi ve FTIR spektroskopisi ile moleküler yapıları analiz edilmiştir. Elde edilen sonuçlara göre, gama radyasyonu

uygulamasının, amiloz içeriğini ve amiloz/amilopektin oranını arttırdığı görülmüştür. 10 kGy dozunda ışınlanmış nişastada amiloz içeriği %30.2 olarak bulunurken, ışınlanmamış nişastada bu değer %17.27 olarak elde edilmiştir. Gama radyasyonu, nişastanın şişme gücünü azaltarak su çözünürlüğünü arttırmıştır. FTIR analizi, gama radyasyonunun nişastanın moleküler yapısını değiştirdiğini doğrulamıştır. Bu değişiklikler, nişasta moleküllerinin yeniden düzenlenmesi ve parçalanması ile ilişkilidir. Nişastanın yapısındaki değişiklikler, GI değerinin düşmesine neden olmuştur. Işınlama işlemi, dirençli nişasta oluşumunu arttırarak, nişastanın sindirilebilirliğini azaltmış ve GI değerinin düşmesine katkıda bulunmuştur. Bu çalışma, gama radyasyonunun nişastanın yapısal ve fonksiyonel özelliklerini önemli ölçüde değiştirdiğini ve bu değişikliklerin nişastanın sindirilebilirliğini ve GI değerini etkilediğini göstermektedir. Gama radyasyonu, amiloz içeriğini arttırarak ve nişasta granüllerinin yapısını değiştirerek, nişastanın daha yavaş sindirilmesini sağlamış ve sonuçta daha düşük GI değeri elde edilmiştir (Razzak ve ark., 2021). GI hakkında yapılan diğer çalışmalar Çizelge 5'te özetlenmektedir.

Çizelge 5. GI hakkında yapılan diğer çalışmalar

Amaç	Sonuç	Referans
Farklı iki pirinç çeşidinde pişirme yöntemlerinin GI, fizikokimyasal özellikler ve sindirim özellikleri üzerindeki etkilerinin incelenmesi amaçlanmıştır.	Elde edilen sonuçlara göre, başlangıçtaki GI değeri 78.1 olan pirinç örnekleri, yüksek sıcaklık ve düşük basınç plazma işlemi ile 56-69 aralığındaki GI değerlerine düşmüştür. Yüksek basınç ve yüksek sıcaklıkta pişirme yönteminde ise pirinç örneklerinin GI değeri 60-65 aralığında bulunarak orta GI kategorisinde yer almıştır.	Yao ve ark., 2023
Raf ömrü uzun, düşük GI değerine sahip esmer pirinç ve bakliyat içeren (nohut (A), mercimek ve fasulye (B)) risotto ürünü geliştirilmesi amaçlanmıştır. Bu amaçla mikrodalga teknolojisi kullanılarak iki formülasyon için de (A, B) GI değerlerine bakılmıştır.	Her iki formülasyon için de düşük GI değerleri (A=43.5 ± 6.8; B= 31.8 ± 6.5) elde edilmiştir. Çalışma, baklagillerle birlikte esmer pirincin kullanılarak, düşük GI değerine sahip, raf ömrü uzun ve tüketici tarafından kabul gören hazır yemeklerin geliştirilmesinin mümkün olduğunu göstermektedir.	Baggio ve ark., 2023
Çalışmanın amacı, glütensiz düşük GI ve glisemik yük (GL) değerlerine sahip kurabiyeler geliştirmektir. Bu amaçla pişirme sıcaklığı ve pişirme sürecinin GI ve GL üzerindeki etkileri incelenmiştir.	Elde edilen sonuçlara göre düşük pişirme sıcaklığının ve uzun pişirme süresinin GI değerini düşürdüğü görülmektedir. Optimum koşullar, 158°C pişirme sıcaklığı ve 20 dakika pişirme süresi olarak belirlenerek; bu koşullar altında glutensiz kurabiyelerin GI değerinin 78.1'den 56.98 değerine düştüğü görülmüştür.	Olawoye ve ark., 2020
Çalışmanın amacı, yüksek β-glukan içeriğine sahip arpa kullanılarak düşük GI değerine sahip fonksiyonel bulgur üretmektir.	Chifaa arpasından üretilen bulgurun GI değeri 56.25 olarak bulunarak bu bulgurun sağlık açısından faydalı olduğu kabul edilmiştir. Bulgular, yüksek β-glukan içeriğine sahip arpanın, düşük GI değerine sahip, sağlık açısından faydalı fonksiyonel bulgur üretiminde kullanılabileceğini göstermektedir.	Tekin-Cakmak ark., 2024
Amaç yüksek hidrostatik basınç işleminin sağlıklı bireylerde taze mango püresinin GI değerini azaltma potansiyelini değerlendirmektir.	Sonuç olarak yüksek hidrostatik basınç işleminin taze mango püresinin GI değerini azaltabileceği gösterilmektedir. İşlem görmemiş mango püresinin GI değeri 42.7 ± 19.5 iken yüksek hidrostatik basınç işlemi sonucunda bu değer 32.7 ± 13.4 olarak belirlenmiştir.	Elizondo-Montemayor ve ark., 2015
Bu çalışmada taftan adı verilen bir ekmek çeşidine arpa unu ilavesinin hamur reolojisi, GI değeri, dokusal ve duyusal özellikleri üzerindeki etkilerinin araştırılması amaçlanmıştır.	Sonuçta 83.14 GI değerine sahip olan kontrol örneği, arpa unu ilavesiyle 70.10 GI değerine düşmüştür. Sonuçlar, arpa unu ilavesinin taftan ekmeğinin GI değerini düşürmekte etkili olduğunu ve bu ekmeğin lif içeriğini arttırarak sağlık açısından fayda sağlayabileceğini göstermektedir.	Mansoor ve ark., 2022

Çizelge 5. GI hakkında yapılan diğer çalışmalar (devam)

Amaç	Sonuç	Referans
Çalışmada kimyasal olarak modifiye edilmiş nişastanın (RS4) *in vitro* sindirilebilirliği, termal olmayan bir işleme teknolojisi olan ultrasonik işlem ile modüle edilmesi amaçlanmıştır.	Sonuçta 78.5 GI değerine sahip olan kontrol örneklerinin, ultrasonik işlem uygulandığında 57.6 GI değerine düştüğü görülmektedir. Ultrasonik işlem, nişasta moleküllerinin fizikokimyasal özelliklerini değiştirerek, daha yavaş sindirilmelerine ve böylece GI değerinin düşmesine neden olmuştur.	Ding ve ark., 2021
Çalışma, yüksek basınç işleminin (HPP) farklı basınç seviyelerinde uygulanmasının nişasta yapısında neden olduğu değişimleri ve bu değişimlerin GI üzerindeki etkilerini değerlendirmeyi hedeflemiştir.	HPP ile işlenen güvercin bezelye sütündeki nişastanın GI değeri önemli ölçüde düşmüştür. 400 MPa'da işlenen nişasta, en yüksek dirençli nişasta içeriği ve en düşük GI değeri (52.4) ile sonuçlanmıştır. Bulgular, yüksek basınç işleminin güvercin bezelye sütündeki nişasta yapısını değiştirerek sindirilebilirliği azaltmada ve GI değerini düşürmede etkili olduğunu göstermektedir.	Hsiao & Wang, 2020
Çalışmanın amacı, ısı-nem işleminin (HMT) karabuğday nişastasında GI değeri ve nişasta fraksiyonları üzerindeki etkileri incelemektir.	HMT uygulanan karabuğday nişastasının GI değeri belirgin şekilde düşmüştür. Kontrol grubunun GI değeri 85.67 iken, 45 dakika süreyle HMT uygulanan nişastanın GI değeri 61.23'e düşmüştür.	Goel ve ark., 2020
İnci darı üzerinde kuru ısı ve ultrasonikasyon işlemlerinin etkilerinin araştırılması amaçlanmıştır. Çalışma, bu işlemlerin nişasta sindirilebilirliğini ve GI değerini nasıl etkilediğini belirlemeyi hedeflemiştir.	Kontrol örneğinde 58.35 GI değeri, 70◦C'de uygulanan kuru ısıl işlem sonrasında 48.49 olarak elde edilmiştir. 20 dakika boyunca 44 Hz frekanslı ultrasonikasyon işlemi uygulanan nişasta örneklerinin GI değerinde de azalma gözlemlenerek bu değer, 48.2 olarak bulunmuştur. Bulgular, kuru ısı ve ultrasonikasyon işlemlerinin inci darı unu nişastasının sindirilebilirliğini azaltmada ve GI değerini düşürmede etkili yöntemler olduğunu göstermektedir.	Vidhyalakshmi & Meera, 2023

5. Sonuç

GI, gıdaların içerdiği karbonhidratların, tüketildikten sonra kan şekerini ne kadar hızlı ve ne kadar yüksek seviyelere çıkarabileceğini gösteren bir ölçüttür. Gıdaların GI değerinin yüksek olması, kan şekerinde ani değişimlere neden olmaktadır. Bu durum, insülin seviyelerinde dalgalanmalara, açlık hissinde artışa ve uzun vadede diyabet gibi metabolik hastalıkların riskinin artmasına neden olmaktadır. Dolayısıyla, düşük GI değerli bir diyete geçiş, özellikle diyabet veya obezite gibi metabolik sorunlarla mücadele edenler için oldukça önemlidir. Araştırmalar, düşük GI değerli diyetlerin diyabet hastalarında glikoz kontrolünü arttırdığını, serum lipidlerini ve diğer kardiyovasküler risk faktörlerini de azalttığını göstermektedir. Ayrıca birçok çalışma, düşük GI değerli diyetleri, koroner kalp hastalığı ve belirli kanser risklerinin azalması ile ilişkilendirmektedir. Yüksek lifli yiyecekler tüketmek, sindirimi yavaşlatarak GI değerinin düşmesini sağlamaktadır. Lifli yiyecekler, karbonhidratların emilimini geciktirdiği gibi, kompleks karbonhidrat tercihleri GI değerinin düşmesine yardımcı olmaktadır. Diyette rafine edilmiş karbonhidratlar yerine, kepekli tahıllar, yulaf ezmesi ve bulgur gibi kompleks karbonhidratlar tüketmek daha sağlıklı bir seçenektir. Günümüzde sürekli ilerleyen teknolojik gelişmeler, GI değeri düşürme konusunda oldukça önemli bir rol oynamaktadır. Özellikle, bazı işleme teknikleri, karbonhidratların sindirimini yavaşlatarak GI değerinin düşmesini sağlamaktadır. Bu teknolojiler arasında ısıl işlemler, ultrasonik işlem ve fermantasyon gibi yöntemler bulunmaktadır. Gıdalara uygulanan bu işlemler ile nişastalar daha dirençli hale getirilebilmektedir. Dirençli nişasta, sindirimi ve emilimi zor olan bir nişasta türüdür. Bu nedenle, dirençli nişasta içeren gıdalar daha yavaş sindirilmekte, kan şekeri seviyelerinde daha yavaş ve daha az ani artışlar görülmektedir. Bu durum, gıdaların GI değerini düşürerek, kan şekeri seviyelerinin daha stabil kalmasına ve uzun süreli tokluk hissine katkıda bulunmaktadır. Sonuç olarak, GI değerini düşürmek, sağlıklı bir yaşam tarzını desteklemeye katkı sağlayarak metabolik sağlığın korunmasında önemli bir rol oynayabilmektedir. Bu

hedefe ulaşmak için GI değeri düşük gıdaların üretilmesi ve bireylerin bu gıdaları günlük diyetlerine eklemeleri önerilmektedir.

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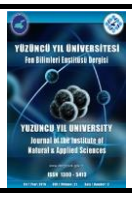
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Öz: Yüzyıldan kısa bir süreçte yenilenebilen, çeşitli atıkları ve bitkileri içeren biyokütle, çevresel sorunları ve enerji ihtiyacını karşılayabilen bir enerji kaynağıdır. Ancak biyokütlenin düşük enerji yoğunluğu ve güçlü hidrofibik yapı gibi dezavantajları vardır, bu da yüksek biyokütle dönüşümü ve nakliye maliyetlerine neden olur. Bu nedenle torrefaksiyon ön işlemi, biyokütlenin kalitesini ve yakıt olarak kullanılabilirliğini artırmak için gerekir. Torrefaksiyon, genellikle fosil yakıtların yakılmasıyla sağlanan enerji kaynağına ihtiyaç duyar. Enerjinin yenilenemez enerji kaynakları tarafından sağlanması, torrefaksiyon işleminin enerji verimliliğini etkiler. Bu sorun güneş enerjisinin kullanılmasıyla çözülebilmektedir. Solar torrefaksiyon olarak adlandırılan bu ön işlem, herhangi bir karbonlu ham maddenin güneş enerjisi kullanılarak katı, sıvı ve gaz halindeki ürünlere dönüşmesini sağlar. Solar ve elektrikli torrefaksiyonda katı ve enerji verimi yüzdeleri birbirine yakındır. Bir literatür örneğine bakıldığında ortalama katı veriminin elektrik ısıtmalı torrefaksiyonda %43.2, solar torrefaksiyonda %42.9 ve enerji veriminin elektrikli torrefaksiyonda %50.8, solar torrefaksiyonda %51.3 olduğu görülmüştür. Her iki sistemde verimler birbirine yakın iken solar torrefaksiyonun öne çıkan avantajı enerji tasarrufudur. Kaynak olarak güneş enerjisinin kullanıldığı solar torrefaksiyon enerji ve yakıt üretmek için karbon açısından zengin atıkları kullandığından son zamanlarda oldukça dikkat çekmektedir.

Anahtar Kelimeler: Biyokömür üretimi, Solar torrefaksiyon, Yenilenebilir enerji

Use of Solar Energy in Torrefaction Biomass

Abstract: Biomass, which can be renewed in less than a century and includes various wastes and plants, is an energy source that can meet environmental problems and energy needs. However, biomass has disadvantages such as low energy density and strong hydrophilic structure, which causes high biomass conversion and transportation costs. Therefore, torrefaction pretreatment is required to increase the quality of biomass and its usability as fuel. Torrefaction generally requires an energy source provided by burning fossil fuels. The provision of energy by non-renewable energy sources affects the energy efficiency of the torrefaction process. This problem can be solved by using solar energy. This pretreatment, called solar torrefaction, allows any carbonaceous raw material to be converted into solid, liquid and gaseous products using solar energy. In solar and electric torrefaction, solid and energy efficiency percentages are close to each other. When a literature example is examined, it is seen that the average solid efficiency is %43.2 in electrically heated torrefaction, %42.9 in solar torrefaction and the energy efficiency is %50.8 in electrical torrefaction and %51.3 in solar torrefaction. While the efficiencies in both systems are close to each other, the prominent advantage of solar torrefaction is energy saving. Solar torrefaction, which uses solar energy as a source, has recently attracted considerable attention because it uses carbon-rich waste to produce energy and fuel.

Keywords: Biochar production, Renewable energy, Solar torrefaction

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1. Giriş

Dünyanın enerji talebi son yıllarda istikrarlı bir şekilde artmaktadır. Bunun nedeni sanayileşmenin ve nüfusun hızla artması ve sonuç olarak toplumların yaşam standartlarını yükseltme arayışlarıdır. Enerji talebindeki artış, küresel ısınmaya ve iklim değişikliğine sebep olarak, çevre üzerinde geri dönüşü olmayan bir tahribata neden olmuştur. Modern toplumlar, temiz enerji kaynağı arayışlarında fosil kaynaklardan yenilenebilir enerjiye (rüzgâr, güneş, gelgit, jeotermal ve biyokütle gibi) geçişin gerekli olduğunu vurgulamaktadırlar. Bu yenilenebilir enerji kaynakları, fosil enerji kaynaklarının tersine zamanla tükenmez ve kömür, petrol, doğalgaz gibi yenilenemeyen enerjilere alternatiftirler.

Biyokütle, organik formda karbon içeren tüm malzemeleri tanımlamak için kullanılan terimdir. Bu organik karbon formu, güneş enerjisi kullanılarak hidrojen ve oksijen gibi diğer elementlerle bağlar oluşturarak fotosentez yoluyla inorganik hale dönüştürülür. Bu bağların (moleküllerin) fiziksel veya biyolojik yollarla yıkılması, döngünün kapanmasına ve CO_2'nin yeniden oluşmasına neden olur. Bu oluşum esnasında diğer enerji biçimlerine dönüştürülebilen enerji açığa çıkar. Bu nedenle, üretim ve kullanım arasında bu denge korunduğu sürece, biyokütle yenilenebilir veya tükenmez bir enerji kaynağıdır (Garba, 2020).

Biyokütlenin, küresel enerji ihtiyacının yaklaşık %10-15'lik bölümünü karşılayacak potansiyele sahip enerji türü olması beklenmektedir. Bununla birlikte biyokütle, gelişmekte olan ülkelerin uzak ve kırsal bölgeleri için toplam enerji ihtiyacının yaklaşık %90'lık bölümünü karşılamaktadır. Bu nedenle, dünya nüfusunun yaklaşık %90'ının 2050 yılına kadar gelişmekte olan ülkelerde yaşaması beklendiğinden, biyokütlenin bu ülkeler için gelecekteki lider enerji kaynağı olmaya devam etmesi muhtemeldir (Bhavanam & Sastry, 2011).

Biyokütleye gazlaştırma, piroliz, anaerobik bozundurma, fermantasyon ve transesterifikasyon gibi işlemler uygulanarak sıvı ve gaz yakıtlara dönüştürülür. Ayrıca biyokütle hiçbir ön işlem uygulanmadan katı yakıt olarak ısı ve güç üretiminde kullanılabilir. Bununla birlikte, biyokütlenin doğal dezavantajları, kapsamlı kullanımını engeller. Düşük enerji ve kütle yoğunlukları ile büyük hacimli olması uzun mesafe taşımacılığını olumsuz etkiler (Rousset ve ark., 2011); yüksek nem içeriği, buharlaşma nedeniyle termokimyasal dönüşüm maliyetlerini artırır (Haykiri Acma ve ark., 2016); hidrofilik yapısı uzun süreli depolamaya engel olur; lifli yapı, öğütme için enerji tüketimini artırır; zayıf küresel şekil, düşük akışkanlığa ve zayıf akışkanlaştırma davranışına yol açar (Yanging ve ark., 2019). Belirtilen dezavantajlardan dolayı biyokütlenin, herhangi bir işlem uygulanmadan yakıt olarak kullanılması zordur. Bu dezavantajları azaltmak için bazı biyokütle iyileştirme (dönüşüm) metotları geliştirilmiştir. Katı yakıt üretimi için uygulanan piroliz ve torrefaksiyon işlemi de bu metotlardan biridir. Piroliz, torrefaksiyon işlemine göre daha yaygın ancak bunun yanında torrefaksiyon çalışmaları da gün geçtikçe artmaktadır.

Piroliz, oksijensiz ortamda biyokütleden karbon bazlı materyaller üretmek için yapılan termal bozunma işlemidir. Piroliz işlemi, kömürden sıvı yakıt üretiminde kullanılan klasik bir yöntemdir. Halen, atık plastik ve lignoselülozik atıkları değerli ürünlere dönüştürmek için kullanılmaktadır. Torrefaksiyon ise bir düşük sıcaklık pirolizidir. Pirolizin aksine asıl amaç katı madde üretimini en üst düzeye çıkartmaktır. Bu işlem ile biyokütlenin neminin uzaklaştırılması ve ısıl değerinin artırılması amaçlanmaktadır. Torrefaksiyon işlemi sonucunda biyokütlenin enerji yoğunluğunun ve suya karşı direncinin arttığı, O/C ve H/C oranlarının azaldığı, öğütülebilirliğinin arttığı ve biyokütleye daha üniform özellikler kazandırdığı belirtilmiştir. Ayrıca torrefaksiyon işlemi uygulanan biyokütlenin nem oranı azaldığı için kısa sürede tutuştuğu, uçucu bileşikler ayrıldığı için yanma esnasında daha az duman oluştuğu ve sabit karbon oranı arttığı için daha uzun sürede yandığı tespit edilmiştir (Chen ve ark., 2021).

Biyokütleye uygulanan termokimyasal dönüşüm proseslerinden olan torrefaksiyonda harici ısı kaynakları gerekir. Bu harici enerji girdisi genellikle çevre üzerinde olumsuz etkisi olan yenilenemeyen bir kaynaktan elde edilir. Torrefaksiyon işlemi için kullanılan bu harici ısı kaynağı aynı zamanda maliyetin artmasına da neden olur (Chen ve ark., 2022). Bu nedenden dolayı yapılacak çalışmalarda alternatif bir enerji kaynağı olan güneş enerjisinin kullanılmasının ekonomik olarak faydalı olacağı düşünülür. Açıkça, en bol bulunan iki enerji kaynağı olan güneş ve biyokütleyi birleştiren bir solar torrefaksiyon teknolojisi oldukça cazip olacaktır.

Solar biyokütle torrefaksiyonu, gerekli ısının konsantre güneş enerjisi ile sağlandığı atmosferde biyokütlenin dönüştürülmesinin endotermik bir işlemidir. Doğrudan güneş ışığı, konsantre edilir ve bir optik sistem tarafından pirolitik reaktöre yönlendirilir. Bu konsantre enerji, reaktörün ve biyokütlenin pirolitik sıcaklıklara ulaşmasını sağlar.

Sunulan çalışmada tükenme sınırına gelen ve sera gazı etkisiyle çevre kirliliğine sebep olan fosil kaynaklara alternatif olarak temiz yenilenebilir enerji kaynaklarının kullanılabileceğinden bahsedilmiştir. Bunun yanında yenilenebilir enerji kaynaklarını verimli kullanılabilmek için biyokütleye uygulanabilecek dönüşüm prosesleri incelenmiştir. Özellikle, önümüzdeki dönemlerde kullanımı artacak olan güneş enerjisinin, torrefaksiyon üzerindeki etkisi ve kaliteli katı yakıt üretimi üzerinde uygulanabilirliği sunulmuştur.

2. Biyokütle

Biyokütle, enerji kaynağı olarak kullanılabilecek malzeme ve bitki atıklarını tanımlamak için kullanılan bir terimdir. Selüloz, hemiselüloz, lignin, nişasta, proteinler, lipitler ve karbonhidratlardan oluşur. Coğrafi konuma ve kaynağa bağlı olarak bu bileşenler ve oranları değişebilir. Şekil 1'de gösterildiği gibi tarım ürünleri ve atıkları, enerji bitkileri ve bunların yan ürünleri, odun atıkları, belediye atıkları, su bitkileri ve algler dahil olmak üzere çok sayıda biyokütle kaynağı mevcuttur (Deora ve ark., 2022).

Farklı biyokütle formlarının kimyasal ve elementel bileşimlerinin belirlenmesiyle, biyokütleden oluşan hidrokarbonların yapısı ve içeriği kesin olarak tahmin edilebilir. Bitkiler, fotosentez süreci yoluyla güneş enerjisinden dönüştürülen kimyasal enerjiyi biriktirirler. Sonuç olarak biyokütle enerjisi güneş, rüzgâr, hidroelektrik ve jeotermal enerjinin yanı sıra yenilenebilir bir enerji kaynağı olarak kabul edilmektedir. Günümüzde biyokütleden elde edilen enerji, ısıtma ve pişirme, elektrik üretimi ve ulaşım yakıtı da dahil olmak üzere dünyanın artan enerji gereksinimlerini karşılamak için yaygın olarak kullanılır. Proximate (kısa) ve elementel analiz verilerine göre biyokütle, az miktarda klor ve kükürt içeren değerli bir karbon, hidrojen, oksijen ve azot kaynağıdır (Mishra ve ark., 2019).



Şekil 1. Başlıca biyokütle kaynaklarının şematik sunumu (Deora ve ark., 2022).

Biyokütleye uygulanan gazlaştırma, piroliz vs gibi termokimyasal süreçler biyokütleyi biyoenerjiye dönüştürmenin yanı sıra, birçok petrokimya endüstrisi ürünlerini üretmek amacıyla da kullanılabilir. Elde edilebilecek ürünlerin verimi ve bileşimi açısından en yüksek esnekliğe sahip termokimyasal işlemlerden biri torrefaksiyondur.

2.1. Biyokütlenin yapısı

Biyokütle esas olarak selüloz, hemiselüloz ve ligninden oluşur. Uygulanan termokimyasal işlem sonucu oluşan ürünlerinde, her bir bileşenin varlığı ve içeriği önemli bir rol oynar. Selüloz içeriği ne kadar yüksek olursa o kadar fazla sıvı ürün elde edilir; hemiselüloz içeriği ne kadar yüksek olursa, o kadar fazla gaz ürünü üretilir; lignin içeriği ne kadar yüksek olursa, o kadar fazla katı ürün üretilir (Kumar ve ark., 2020).

Selüloz, D-glikoz içeren en bol doğal doğrusal karbonhidrat polimeridir ve bitkinin hücre duvarıdır. Selüloz içindeki hemiselüloz ve ligninin kovalent çapraz bağlanma etkileşimi, lignoselüloz biyokütlesinin herhangi bir dış biyolojik ve kimyasal saldırıya karşı direnmesine yardımcı olur (Zheng ve ark., 2014). Selüloz aynı zamanda kendine özgü mekanik güce ve kimyasal kararlılığa sahip susuz glikopiranozun bir polisakkariti olarak da tanımlanır (Dhyani & Bhaskar, 2018). Selülozun kimyasal formülü $(C_6H_{10}O_5)_n$'dir (Bandgar ve ark., 2022).

Çeşitli dallanmış polisakkaritlerin birleşiminden oluşan hemiselüloz, selüloz liflerini çevreler ve selüloz ile lignini birbirine bağlar. Hemiselüloz amorftur, zayıf asitler, bazlar ve enzimler tarafından kolayca hidrolize edilir ve kimyasallara daha az dayanıklıdır. Glikoz, galaktoz, mannoz, ksiloz, arabinoz ve glukuronik asit içeren monomerlerden oluşur. Kovalent etkileşimlerinin ve birbirleriyle hidrojen bağlarının bir sonucu olarak hemiselülozlar, termokimyasal ön işleme tabi tutulduğunda monosakkaritlere daha kolay parçalanır. Hücre duvarının sertliği ve esnekliği, hemiselüloz ve selüloz arasındaki hidrojen bağlantısından etkilenirken selüloz, lignine kovalent olarak bağlanır (Chen ve ark., 2023). Hemiselüloz, selüloza kıyasla seyreltilmiş asitler, bazlar veya enzimler tarafından kolayca çözülür ve selüloza göre daha az fiziksel güce sahiptir (Kumari & Singh, 2018).

Lignin, karmaşık yapıya sahip çapraz bağlı polimerler ve fenolik monomerlerin bileşimini içeren karmaşık bir makromoleküler yapıdır. Lignoselülozik biyokütlede lignin daha yüksek bir enerji yoğunluğuna sahiptir (Yu ve ark., 2016). Lignin, yapısal sertlik için eşit olmayan şekilde konumlandırılmış fenilpropan birimleri tarafından bir araya getirilmiş, karbonhidrat olmayan kompleks aromatik bir polimerdir (Dhyani & Bhaskar, 2018). Selüloz ve hemiselüloza bağlanır ve hücre duvarına güç ve sağlamlık kazandırır. Aynı zamanda suya dayanıklı, mikrobiyal saldırılara karşı fiziksel ve kimyasal dirence sahip, aşılmaz bir duvar oluşturur. Lignin hidrofobiktir ve suda çözünemez (Zhang ve ark., 2021).

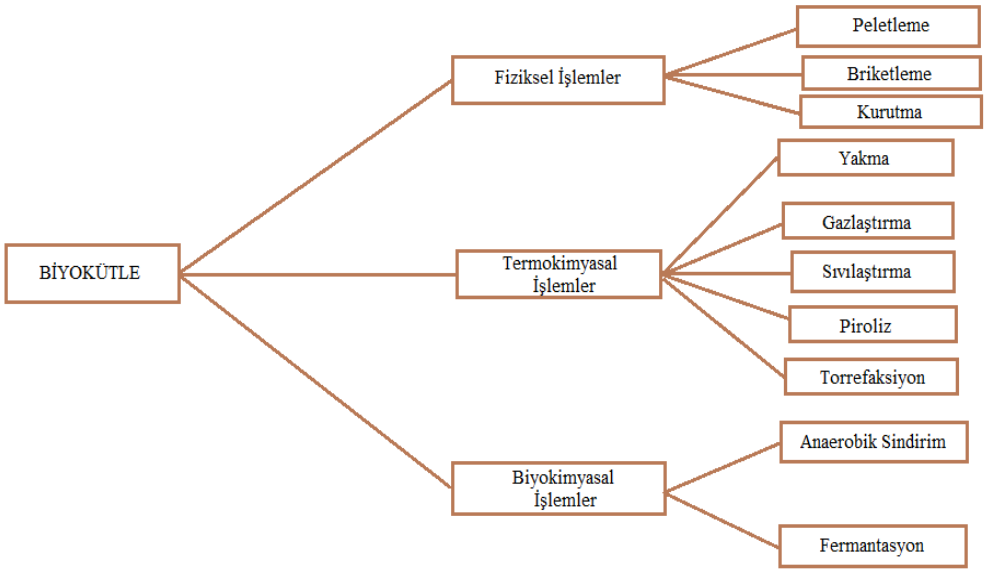
Biyokütledeki selüloz, hemiselüloz ve ligninin ayrıntılı içeriği ve termal bozunma sıcaklıkları Şekil 2'de gösterilmektedir (Bui ve ark., 2015).



Şekil 2. Lignoselülozik biyokütlede genel selüloz, hemiselüloz ve ligninin içerikleri (Bui ve ark., 2015).

3. Biyokütleye Uygulanan Dönüşüm Prosesleri

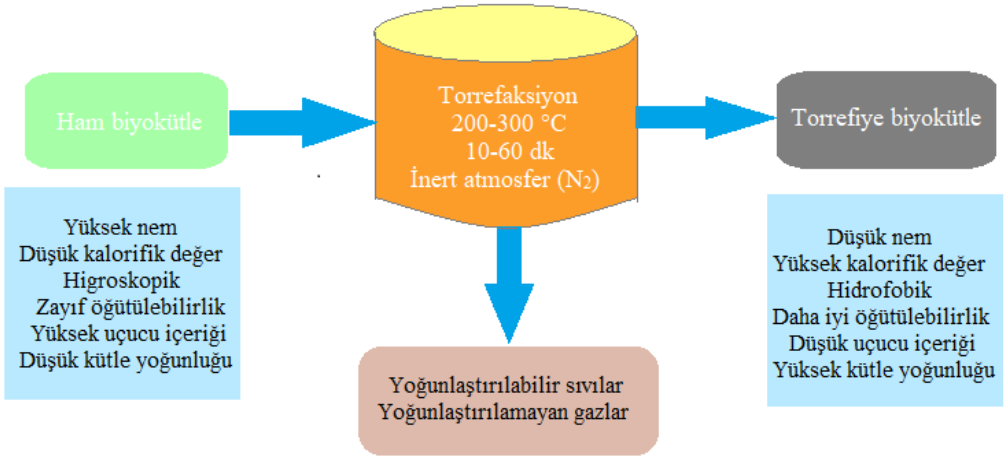
Biyokütle, enerji üretimi ve kimyasallar için çeşitli yararlı ürünlere dönüştürülür. Bu dönüşüm süreçlerinde birçok proses kullanılır. Kullanılan prosesler fiziksel, biyokimyasal ve termokimyasal olmak üzere üç ana başlıkta toplanmaktadır. Ancak biyokütleye uygulanacak bu dönüştürme teknolojilerinin seçimini etkileyen bazı faktörler vardır. Bu faktörler, biyokütle kalitesi ve miktarını, mevcudiyetini, nihai ürünlerin seçimini, proses ekonomisini ve çevresel sorunları içerir. Biyokütlenin dönüşüm prosesleri Şekil 3'de gösterilmiştir.



Şekil 3. Biyokütle dönüşüm prosesleri (Ong ve ark., 2019).

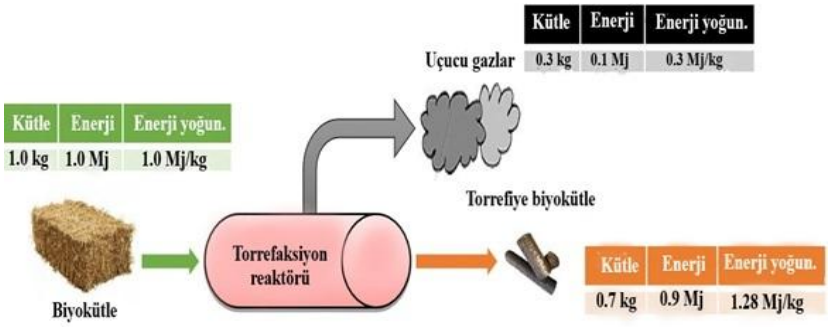
4. Torrefaksiyon

Torrefaksiyon, biyokütleyi orijinal enerjisinin %90'ına kadar muhafaza eden bir katı ürüne yükseltmek için kullanılan termokimyasal bir dönüşüm prosesidir (Thengane ve ark., 2022). İşlem, düşük ısıtma hızlarında ve 350°C'nin altındaki sıcaklıklarda gerçekleştirilen piroliz işlemidir. Proses ürünleri orijinal biyokütlenin yanı sıra reaksiyon sıcaklığı, ısıtma hızı, kalış süresi ve reaksiyon ortamı gibi farklı parametrelere de bağlıdır. Torrefiye biyokütle, ham biyokütle ile karşılaştırıldığında çeşitli avantajlara sahip mükemmel bir katı enerji taşıyıcısıdır. Torrefaksiyon sonucu biyokütle özelliklerinin değişimi Şekil 4'te gösterilmiştir (Sarker ve ark., 2021).



Şekil 4. Ham biyokütle ve torrefiye biyokütle arasındaki ayrımlar (Sarker ve ark., 2021).

Torrefaksiyon, biyokütledeki hidrojen ve oksijen içeriğini azaltırken karbon içeriğini arttırır, bu da uçucu maddenin kısmen ortadan kaldırılmasıyla sonuçlanır ve böylece enerji yoğunluğunu artırır (Acharya & Dutta, 2016). Torrefaksiyon, yavaş pirolize göre daha düşük sıcaklıklarda ve daha kısa kalma süresinde çalıştığı için de daha az işletme maliyeti gerektirdiğinden, katı ürünün kalitesini artırmak için daha uygundur. Torrefaksiyona maruz kalan biyokütlenin kütle ve enerji değişimleri Şekil 5'te verilmiştir (Negi ve ark., 2020).



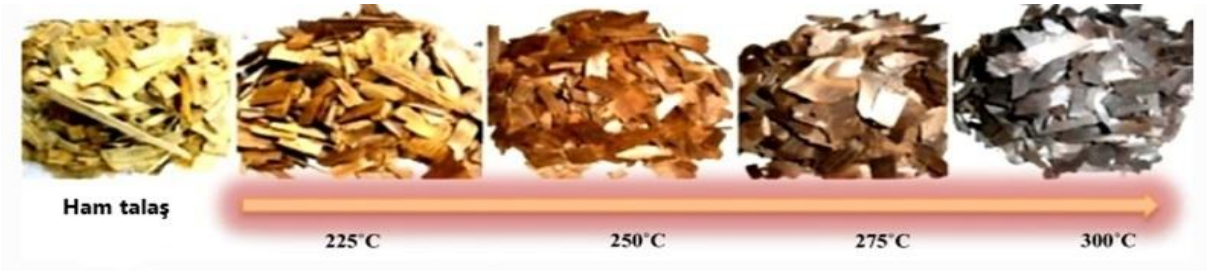
Şekil 5. Torrefiye biyokütlenin kütle ve enerji değişimi (Negi ve ark., 2020).

Torrefiye biyokütlenin genellikle enerji ve hacim olarak daha yoğun, daha kırılgan, hidrofobik ve mikrobiyal ayrışmaya dirençli olduğu tespit edilmiştir (Zhang ve ark., 2020). Bu faktörler, torrefiye biyokütlenin depolanması ve uzun mesafeli nakliyesi veya katı yakıt peletlerinin üretimi için oldukça fayda sağlar (Zhang ve ark., 2019). Ayrıca piroliz, gazlaştırma ve yakma gibi diğer termokimyasal dönüşüm teknolojileri için torrefaksiyon bir ön işlem olarak kullanılabilir. Torrefaksiyon, biyokütlenin doğal yapısal kimyasını zayıflatır, böylece diğer termokimyasal dönüştürme teknolojilerinde termal olarak bozunmasını kolaylaştırır.

Torrefaksiyon prosesinin performansı sıcaklık, süre, taşıyıcı gaz akış hızı ve bileşimi, parçacık boyutu, katalizör türü vb. gibi bazı faktörlerden etkilenir. Bu parametrelerin torrefaksiyon prosesi üzerindeki etkileri aşağıda açıklandığı şekildedir.

Torrefaksiyon sıcaklığı, çalışma parametreleri arasında en önemli parametredir. Hemiselüloz ve selülozun termal ayrışma sıcaklıkları sırasıyla 220-315°C ve 315-400°C aralığındadır ve torrefaksiyon 200-300°C sıcaklıklarda çalıştırılırken, çalışma sıcaklığının torrefaksiyon sonuçları üzerinde önemli bir etkiye sahip olduğu bilinmektedir. Torrefaksiyon, çalışılan sıcaklığa göre hafif torrefaksiyon (200°C ile 235°C), orta torrefaksiyon (235°C ile 275°C) ve şiddetli torrefaksiyon (275°C ile 300°C) olarak kategorize edilir. Hafif torrefaksiyon sırasında, biyokütledeki nem ve uçucu maddeler serbest bırakılır. Biyokütledeki hemiselüloz, selüloz ve lignin arasında en aktif bileşenlerdir. Hemiselüloz, hafif torrefaksiyon sırasında termal olarak belirli bir ölçüde parçalanırken, selüloz ve lignin yalnızca hafif etkilenir veya neredeyse hiç etkilenmez. Bu nedenle, hafif torrefaksiyondan sonra biyokütlenin ağırlık kaybı belirgin değildir ve enerji yoğunluğu veya kalorifik değeri yalnızca biraz artar. Biyokütle hafif torrefaksiyona uğradığında, hemiselülozların ayrışması ve uçucu maddelerin serbest bırakılması kolaylaşır. Hemiselüloz önemli ölçüde, selüloz ise belirli bir ölçüde parçalanır. Şiddetli torrefaksiyon durumunda, hemiselüloz neredeyse tamamen tükenir ve selüloz büyük ölçüde termal olarak parçalanır. Bileşenler arasında, lignin termal olarak parçalanması en zor olanıdır ve torrefaksiyon sıcaklık aralığındaki ağırlık kaybı düşüktür. Hemiselüloz ve selüloz, biyokütlenin ana bileşenleridir. Şiddetli torrefaksiyonla biyokütleden hemiselüloz ve selülozun önemli ölçüde uzaklaştırılması nedeniyle, yakıtın enerji yoğunluğu büyük ölçüde artırılmış olmasına rağmen, biyokütlenin ağırlığı ve enerji verimi genellikle şiddetli bir şekilde azalır (Chen & Kuo, 2011).

Torrefaksiyon sıcaklığının ham biyokütle malzemesinin görsel görünümleri üzerindeki etkisi Şekil 6'da gösterilmektedir (Phanphanich & Mani, 2011).



Şekil 6. Torrefaksiyon sıcaklığının çam talaşlarının fiziksel özellikleri üzerindeki etkisi (Phanphanich & Mani, 2011).

Şekil 7, ısıl işlem sırasında lignoselülozik malzemenin ayrışması üzerinde sıcaklığın etkisini göstermektedir (Christoforou & Fokaides, 2016).



Şekil 7. Torrefaksiyon mekaniği (Christoforou & Fokaides, 2016).

Sıcaklığın yanı sıra, torrefaksiyon süresi, torrefaksiyon performansını değerlendirmede bir diğer önemli faktördür. Torrefaksiyon düşük ısıtma hızları (<50°C/dk) kullanılarak ve hammaddenin türüne bağlı olarak birkaç dakikadan birkaç saate kadar değişebilir (Christoforou & Fokaides, 2018; Ho ve ark., 2018). Torrefaksiyon süresinin artmasıyla, elde edilen katı yakıt veya biyokömürün kalorifik değeri ve karbon içeri artar. Örneğin, 250°C'de 0.5, 1 ve 1.5 saat gerçekleştirilen odun briketlerinin torrefaksiyonu sonucunda biyokütlenin kalorifik değerlerinin 20.0 kj/kg 'dan 22.7 kJ/kg'a çıktığı tespit edilmiştir (Chen ve ark., 2021).

Isıtma hızının lignoselülozik polimerlerin parçalanması üzerinde önemli bir etkisi vardır. Daha yüksek ısıtma hızı, biyokütlenin daha fazla depolimerizasyonuna neden olur ve kütle verimini önemli ölçüde azaltır. Isıtma hızı yavaş olduğunda, yoğunlaşabilir uçucu maddeler reaktörde son torrefaksiyon sıcaklığına ulaşana kadar yani süre olarak daha fazla kalır. Uçucu maddelerin reaktörden kademeli olarak uzaklaştırılması, ikincil bozunma reaksiyonlarını kolaylaştırır ve böylece son katı, sıvı ve gaz ürün dağılımlarını etkiler (Mundike ve ark., 2016; Persson & Yang, 2019).

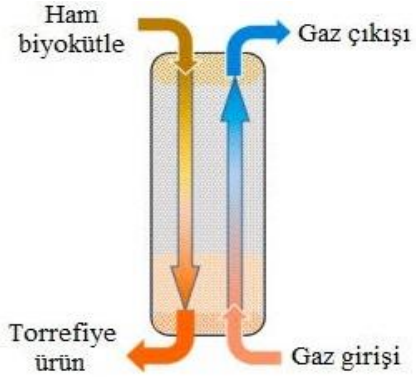
Bir diğer parametre olan parçacık boyutu, torrefaksiyon işlemi sırasında reaktördeki ve biyokütle içindeki iletken ısı transferini etkiler (Medic ve ark., 2012; Nhuchhen ve ark., 2014; Wang ve ark., 2017). Bu nedenle, parçacık boyutu azaldıkça biyokütle, birim kütle başına daha fazla yüzey alanına sahip olur. Bunun sonucunda parçacık boyutu ne kadar küçükse, ısı transfer hızı o kadar iyi olacak ve bu da nemin ve bazı uçucu maddelerin daha iyi uzaklaştırılmasıyla sonuçlanacaktır. Böylece son torrefiye üründe O/C ve H/C atom oranları minimum olacak, aynı zamanda ürün daha yüksek kalorifik değere sahip olacaktır (Rudolfsson ve ark., 2015).

Ayrıca çalışmalarda kullanılan reaktör tipi ve taşıyıcı gazda önemlidir. Genel olarak torrefaksiyon, N_2 atmosferinde gerçekleştirilir. Ancak inert ortam torrefaksiyonun ekonomikliğini olumsuz yönde etkilediğinden bununla ilgili araştırılmalar yapılmaktadır. Ayrıca ortamın içerdiği O_2'den dolayı yanma ve tutuşma gibi bazı durumlar da söz konusudur. Son zamanlarda bazı çalışmalarda hava, baca gazı, CO_2 vb. gibi farklı taşıyıcı gazların torrefaksiyon performansı üzerindeki etkileri değerlendirilmiştir (Thanapal ve ark., 2014). CO_2 ile muamele edilmiş biyokütle, N_2 ile muamele edilmiş biyokütle ile karşılaştırıldığında numunelerdeki gözenek yüzey alanında daha fazla artış olduğu görülmüştür.

Torrefaksiyonda kullanılan O_2 miktarı çoğunlukla %15'ten azdır (Chen ve ark., 2014; Uemura ve ark., 2015; Chen ve ark., 2016). Genel olarak atmosferdeki havanın %21'i O_2'den oluşur. Yüksek O_2 yüzdesi, torrefaksiyon işleminden ziyade yanmaya yol açar. O_2 eklemenin asıl amacı, torrefaksiyon reaksiyonunu hızlandırmaktır. Biyokütlenin oksidatif torrefaksiyonu, yalnızca biyokütlenin termal ayrışmasını ve buharlaşmasını değil aynı zamanda ekzotermik oksidasyon reaksiyonlarını da içerir (Chen ve ark., 2014; Chen ve ark., 2016; Wang ve ark., 2018). Oksidasyon reaksiyonlarının reaksiyon hızları normalde ayrışma reaksiyonları ve buharlaşma reaksiyonlarından daha hızlı olduğu için bu da torrefaksiyon süresinin azalmasına yol açar (Wang ve ark., 2018). Oksijen konsantrasyonlarının (%2, %6, %10, %21) 240 ve 280°C'de torrefaksiyon üzerindeki etkileri Rousset ve ark. (2012) tarafından değerlendirilmiştir. Sonuçlar, oksijen miktarının katı verimi ve torrefiye ürün özellikleri üzerindeki etkilerinin, 280°C'lik bir torrefaksiyon sıcaklığı altında daha belirgin olduğunu göstermiştir.

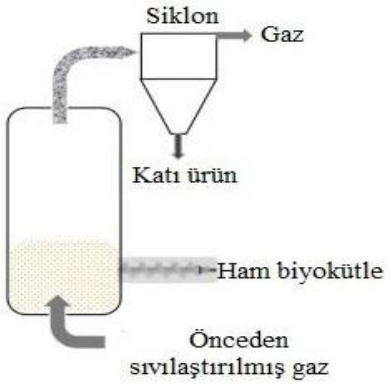
Torrefaksiyona etki eden parametreler arasında sayılan reaktör tipleri ise; hareketli yataklı, akışkan yataklı, döner tambur, çok ocaklı fırın, mikrodalga, vidalı konveyör, auger ve sabit yataklı reaktördür.

Hareketli yataklı bir reaktördeki temel özellik, kimyasal reaksiyon boyunca hem sıvı hem de katı fazların hareketleridir. Torrefaksiyon, sıcak gazlar reaktöre alttan girdikten sonra yukarı doğru hareket ettiğinde gerçekleşir. Gaz halindeki yan ürünler reaktörün üst kısmında geri kazanılırken, torrefiye biyokütle altta toplanır ve soğutulur. Katı ve sıvının yönlerine bağlı olarak bu teknik, çapraz akış, eş zamanlı veya karşı akımlıdır. İşlem sıcaklığı yaklaşık 250–300°C ve kalma süresi 30–60 dakikadır. Ancak, bu parametreler gereksinimlere göre ayarlanır (Negi ve ark., 2020; Thengane ve ark., 2020). Bu reaktör, biyokütlenin tüm reaktör haznesinde tutulması nedeniyle diğerlerine göre daha fazla dolar. Hareketli yataklı reaktördeki başlıca sınırlama, biyokütlenin düzgün bir şekilde karıştırılamamasından dolayı, ısı transfer işleminde genellikle homojen olmamaya eğilimli olmasıdır. Bu homojen olmama durumu özellikle dolaylı bir ısıtma yönteminde (örn: yan veya alt duvarlardan) söz konusu olur (Şekil 8).



Şekil 8. Hareketli yatak reaktörü (Thengane ve ark., 2022).

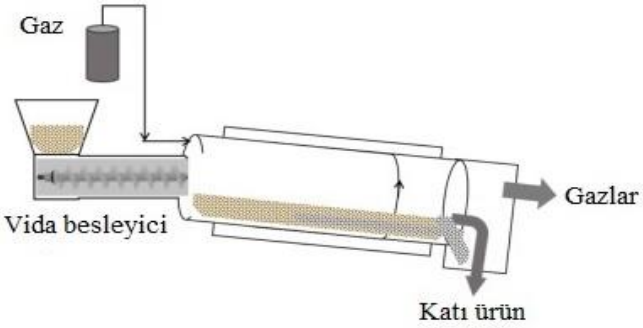
Akışkan yataklı reaktörlerde, biyokütleyi akışkanlaştırmak için reaktörün tabanından sıcak inert gazlar beslenir. Ham biyokütle boyutu, reaktörün yatak içinde sabit sıcaklık dağılımını korumasına izin vermek için akışkanlaştırılmadan önce daha küçük parçacıklara küçültülür. Biyokütlenin küçültülmesi amacıyla gerçekleştirilen öğütme işlemi sırasında kullanılan enerji miktarı, öğütme boyutu ve nem içeriğiyle dolaylı olarak bağlantılıdır. Genellikle minimum akışkanlaştırma hızından daha büyük olan yeterli bir inert gaz hızı, akışkanlaştırma kriterlerini karşılamak için kullanılır. Laboratuvar ölçekli deneyler, bu tür reaktörler için torrefiye biyokütle ince tanelerde önemli kayıpların olduğunu göstermiştir (Li ve ark., 2012). Sonuç olarak, ısı ve kütle transfer oranları, daha hızlı ve daha etkili işlem sağlayan diğer reaktör türlerinden daha yüksektir (Şekil 9).



Şekil 9. Akışkan yatak sistemi (Thengane ve ark., 2022).

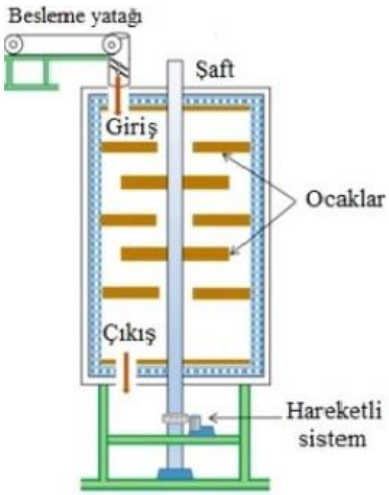
Döner tambur reaktörü biyokütleye uygulanan termal süreçlerin gerçekleştiği, dolaylı veya doğrudan aşırı ısıtılmış buhar veya uçucu kimyasalların salınımının kullanıldığı sürekli bir reaktördür

(Piersa ve ark., 2022). Bu reaktörler bir tamburun sabit bir nokta etrafında dönmesine yardımcı olmak için dönen bir şaft kullanır. Tambur dikey veya eğimli olarak yönlendirilir. Biyokütle parçacıkları, parçacıklar arasında kütle ve ısı transferi sağlayan tamburun dönüşü sonucunda sıcak gaz akımları altında yuvarlanır. Reaktörün uzunluğu, sıcaklık, dönüş hızı ve eğim gibi işlem faktörlerini doğru bir şekilde değiştirerek torrefaksiyon işleminin etkinliğini artırmak mümkündür. Ham biyokütle, inert gaz yüksek hızda kullanıldığında sıvıya benzer şekilde davranır. Yüksek termal verimlilik ve kontrollü bir şekilde yönetilen sistem sıcaklığı bu tür reaktörlerin sadece birkaç avantajıdır. Öte yandan, döner tambur tasarımının bir yararı, biyokütle kurutma ve piroliz gibi diğer uygulamalarla nispeten kanıtlanmış bir teknoloji olmasıdır. Bu nedenle, Avrupa'daki şirketlerin çoğu, ya mevcut döner tambur tedarikçilerini kullanarak ya da özel olarak tasarlanmış parçalar geliştirerek, döner tambur tasarımına dayalı torrefaksiyon teknolojileri geliştirmeyi tercih etmiştir (Şekil 10) (Benanti ve ark., 2011).



Şekil 10. Döner tambur sistemi (Thengane ve ark., 2022).

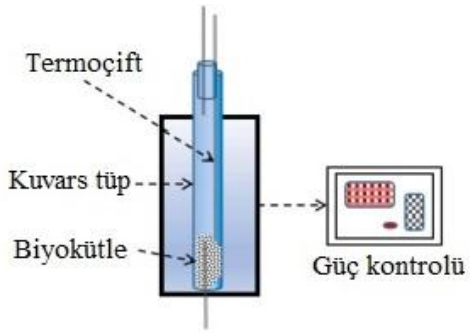
Herreshoff fırını adının yanı sıra çoklu ocak fırını olarak da bilinen bu reaktör, bir merkez şaft etrafında yatay bir düzlemde dönen dairesel ocaklar içeren refrakterle kaplı dikey bir silindirdir. Biyokütle, çok küçük bir alandan geçer ve üst taraftan altta bulunan ocaklara beslenir ve ocak sayısına bağlı olarak reaktör içinde 0.5 ile 3 saat tutulur. Reaktörün çoklu katmanları, düzgün karıştırma ve kademeli ısıtmaya yardımcı olur. Birinci katmandan sonra, sonraki katmanlarda biyokütlenin sıcaklığı kademeli olarak artar, örneğin 200°C'den 300°C'ye. Çoklu ocak reaktörlerinin çapı 8 m'ye kadar çıkar. Çoklu ocak teknolojisi, talaş tozundan daha büyük talaşlara ve hatta torrefaksiyon uygulaması için çok küçük parçalara kadar çeşitli hammadde parçacık boyutlarını işler (Şekil 11) (Acharya ve ark., 2012).



Şekil 11. Çoklu ocak fırını (Thengane ve ark., 2022).

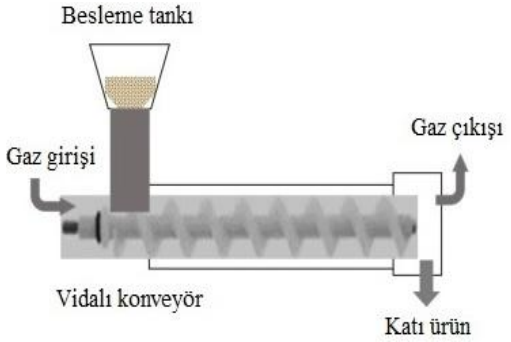
Kullanılan bir başka reaktör olan mikrodalga reaktörlerinde kullanılan ısı kaynağı, biyokütlenin biyoyakıtlara dönüşümünü gerçekleştiren mikrodalga radyasyonudur (Aziz ve ark., 2024). Biyokütle, dış ısı kaynaklarından gelen ısı iletimine dayanan tasarımlara kıyasla daha hızlı ve

genel olarak daha eşit şekilde ısıtılır. Elektromanyetik radyasyon, su moleküllerinin titreşmesine neden olarak, kavurmayı destekleyen biyokütlenin iç enerjisini artırır. Mikrodalga reaktörü tipik olarak 300 MHz ile 300 GHz arasındaki frekanslarda çalışır (Satpathy ve ark., 2014). Mikrodalgadan hızlı ve üniform ısıtma nedeniyle (Ren ve ark., 2012), katı kalma süresi ve belirli bir katı verimi için reaktör boyutu azaltılabilir (Huang ve ark., 2012). Bununla birlikte bu reaktörlerin kalın biyokütle parçacıklarında şiddetli parçacık içi sıcaklığa ve torrefaksiyon homojensizliğine neden olduğu belirtilmiştir. Mikrodalga reaktör kullanmanın bir diğer önemli dezavantajı, gereken radyasyon enerjisinin en kolay şekilde elektrik enerjisinden sağlanmasıdır. Isıdan veya torrefaksiyon işleminden salınan uçucu gazların içerdiği kimyasal enerjiden elektrik üretmek çok zordur. Mikrodalga radyasyonu ile gerçekleştirilecek büyük ölçekli tasarımlarda genellikle en önemli problem yüksek sermaye maliyeti ve işletme giderleridir (Şekil 12).



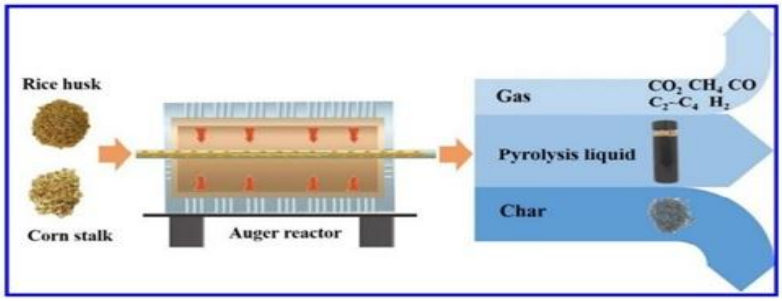
Şekil 12. Mikrodalga reaktörü (Thengane ve ark., 2022).

Bir vidalı konveyörde bir veya daha fazla spiral kullanılır ve bunlar bir tüp veya U şeklinde oluğun içine yerleştirilir. Sonuç olarak, biyokütle hareket eden spiral önünde birikip ve vida döndükçe kanaldan itilir. Bazı çalışmalarda yatay veya dikey olarak yerleştirilebilen ve çeşitli malzeme ve akış hızı gereksinimlerine uyum sağlayabilen çeşitli vida tasarımları bulunur. Reaktörde kalma süresini hesaplamak için dönme hızları ve vida uzunluğu kullanılır. Biyokütle, eritilmiş tuz, sıcak yağ ve sıcak buhar gibi daha büyük sıcaklık ısı transfer ajanları kullanılarak vidalı konveyör kurutucusunun ceketli konveyöründe aynı anda kurutulur ve ısıtılır. Vidalı konveyörlerde genellikle minimum alan gereksinimiyle daha iyi bir ısı iletim alanı sağlayan dolaylı bir ısıtma yöntemi kullanılır (Piersa ve ark., 2022). Ancak, çift vidalı bir konveyör sistemi kullanılarak reaktör doğrudan ısıtılabilir. Dolaylı ısıtma için bu reaktörün dezavantajı, çoğu durumda, yetersiz ısı değişimi, yüksek bakım maliyetleri ve ısıtma alanı için karbonize malzeme geliştirilmesini içerir. Bazı avantajlar, iyileştirilmiş biyokütle akışı, makul derecede uygun fiyatlı bir reaktör ve çeşitli biyokütle parçacıklarının kurutulmasıdır (Şekil 13) (Acharya ve ark., 2012).



Şekil 13. Vidalı konveyör (Thengane ve ark., 2022).

Auger reaktör hem biyokömürün hem de biyo-yağın büyük miktarlarda üretimi için kullanılan bir piroliz teknolojisidir (Şekil 14). Farklı ürün verimleri ve özellikleri için çalışma koşulları değiştirilebilmektedir.



Şekil 14. Auger piroliz reaktörü (iç cap 26 mm, uzunluk 50 cm, inert gaz N_2 ve katının geçiş hızı 0.35 kg/h) (Yu ve ark., 2016).

Auger piroliz reaktörleri, birçok küçük ve orta ölçekli endüstrilerde artan bir ilgi görmektedir. Bu teknoloji, yapım ve çalıştırma kolaylığı nedeniyle son zamanlarda pek çok alanda ilgi çekmektedir. Bir Auger reaktöründe, biyokütle sürekli olarak tek veya çift vidaya beslenir ve ardından burgu dönüşü, ürünü ısıtma bölgesinin sonuna kadar eksen boyunca hareket ettirir. Biyokütle ayrıştıkça, gazlar ve organik uçucu maddeler reaktörü terk eder ve biyokömür altta toplanır. Auger piroliz reaktörlerinin çalıştırılması basit, çok az taşıyıcı gaz gerektiren veya hiç gerektirmeyen ve az enerji tüketen bir reaktördür. Ayrıca, bu reaktörlerin önemli bir avantajı da, ısıtılmış bölgede biyokütlenin kalma süresinin ve vidanın dönüş hızının değiştirilmesiyle kolaylıkla kontrol edilebilmesidir (Brassard ve ark., 2017).

Sabit yataklı reaktör, en yaygın kullanılan torrefaksiyon reaktörlerinden biridir (Yang ve ark., 2018; Szufa ve ark., 2021; Han ve ark., 2021). Basit kurulumu ve düşük fiyatı endüstrilerde çokça kullanılmasını sağlamaktadır. Sabit yataklı reaktörlerde esas olarak ham biyokütleyi yerleştirmek için cam veya paslanmaz çelik silindirik bir tüp, ısıyı sağlamak için bir fırın, biyokütle ve reaktör sıcaklık rejimlerini bulmak için termoçift gibi ekipmanlar kullanılmaktadır. N_2 tipik olarak sürekli torrefaksiyon bağlamında oksidatif olmayan bir atmosfer hazırlamak için taşıyıcı gaz olarak uygulanır. Sabit yataklı reaktörün çeşitli endüstriyel uygulamaları vardır; örneğin Cheng ve ark. (2022), sabit yataklı bir reaktörde, 250-350°C sıcaklık değişiminde, inert bir ortam altında, günde 150 ıslak ton kapasiteli, tam ölçekli bir arıtma çamuru torrefaksiyon tesisinde cıva (Hg) aktivitelerini değerlendirmiştir. Sukiran ve ark. (2020) tarafından yapılan daha ileri bir çalışma, sabit yataklı bir reaktörde torrefaksiyona tabi tutulmuş boş meyve salkımlarının kullanılmasıyla, yaklaşık 25.73 kj/kg'lık önemli bir üst ısı değerine sahip yüksek kaliteli kömür üretilebildiğini kanıtlamıştır.

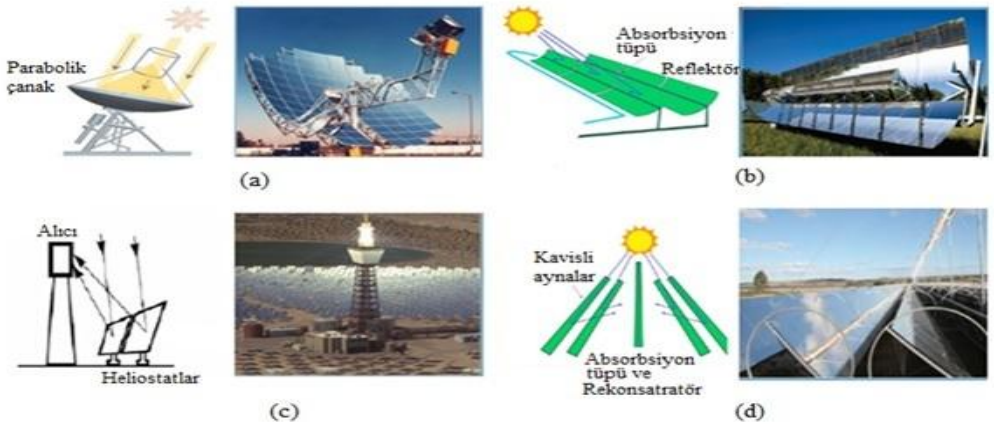
5. Solar Torrefaksiyon

Güneş enerjisi, potansiyel olarak net sıfır karbon ayak izine sahip, çekici ve sınırsız bir yenilenebilir enerji kaynağıdır. Biyokütle ile birlikte değerlendirildiğinde, her iki kaynağın da gelecekteki enerji arzını güvence altına almada önemli bir rol oynayacağı tahmin edilmektedir. Biyokütlenin güneş enerjisi ile termokimyasal dönüşümü, biyokütleyi yüksek yoğunluklu yakıtlara dönüştürürken uzun süreli güneş depolaması sağlar. Bu yüzden endotermik biyokütle termokimyasal reaksiyonunu yürütmek için konsantre bir güneş ısısının kullanılması ve bu enerjinin gaz ve biyokömüre ek olarak biyo-yağ şeklinde yüksek yoğunluklu bir enerji üretebileceği önerilmektedir (Bashir ve ark., 2017).

Solar torrefaksiyon, bir termo-solar sistemi kullanılarak gerçekleştirilebilir. Bir termo-solar sistemi, bu enerjiyi bir ısıtma kaynağı olarak kullanmak için güneş radyasyonunu geniş bir alandan daha küçük bir alana yoğunlaştırıp, yönlendirir. Termo-solar sistemleri, güneş yoğunlaştırıcı, güneş kollektörü ve destekleyici yapı olmak üzere üç ana parçadan oluşur.

Çalışma sıcaklığına ulaşmak için güneşten gelen seyreltik güneş radyasyonunu yoğunlaştırmak gereklidir ve bunun için çeşitli yoğunlaştırıcı sistemler geliştirilmiştir. Yoğunlaştırıcının performansı, güneş radyasyon açısına, güneş yoğunluğuna ve güneşin ve reaktörün göreceli konumuna bağlıdır. Karbonlu malzemelerin termokimyasal bozunması için kullanılan yoğunlaştırıcı, optik özelliklerine göre genel olarak dört ana kategoride

sınıflandırılır. Bunlar Şekil 15'de gösterilen parabolik çanak, parabolik oluk, heliostat alan ve doğrusal Fresnel yoğunlaştırıcılarıdır.

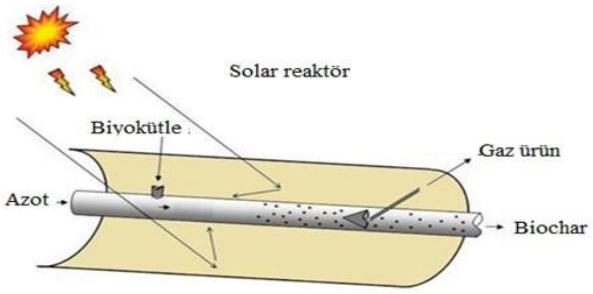


Şekil 15. Çeşitli güneş yoğunlaştırıcı türlerinin şematik ve resimli gösterimi (a) parabolik çanak, (b) parabolik oluk, (c) heliostat alanı, (d) doğrusal Fresnel (Rahman ve ark., 2021).

En yaygın olarak kullanılan güneş enerjisi yoğunlaştırma teknolojilerinden biri parabolik oluk sistemidir. Bu sistem, güneş ışınımının bir dizi kavisli ayna (parabol) tarafından odak hattı boyunca yer alan küçük bir boru şekilli alıcı/toplayıcıya yönlendirilmesine dayanır. Parabolik kanallı bir yoğunlaştırıcı odaksal bir radyasyon hattı ürettiğinden, bu cihaz boru şeklindeki reaktörleri biyokütle pirolizi için gereken sıcaklıklara ısıtmak için ideal bir seçenektir (Rahman ve ark., 2021).

Bu tip yoğunlaştırıcı hem düşük sıcaklık hem de yüksek sıcaklık uygulamaları için kullanılır. Elde ettiği maksimum sıcaklık, önemli ısı kayıpları olmaksızın çoğunlukla 400-550^{o}C arasındadır. Bu tip kollektör, Şekil 15 (b) ve Şekil 16'da gösterildiği gibi kollektörün odak hattı boyunca yerleştirilen silindirik bir reaktör üzerine ışığı konsantre eden bir dizi paralel kavisli (parabolik) ayna ile yapılır.

Kolektörler genellikle kuzey-güney veya doğu-batı yönünde monte edilir. Güneşin doğuşundan batışına kadar düzenli güneş ışınımını yakalamak için kollektör kuzey-güney yönünde, mevsimsel radyasyonu yakalamak için kolektör doğu-batı yönünde yerleştirilir. Bu nedenle, reaktör entalpisini yükseltmek ve güneş ışınının eksenine paralel düşmesini sağlamak için tek eksenli bir izleme sistemi yeterlidir. Bu teknoloji son zamanlarda artan bir ilgi görmüştür ancak bir piroliz sistemine entegrasyon şimdiye kadar araştırmacılar için kritik bir işlemdir.



Şekil 16. Solar piroliz reaktörünün ve gaz-katı ayırma mekanizmasının detayları (Bashir ve ark., 2017).

Son zamanlarda biyokütlenin termokimyasal dönüştürülmesi proseslerinde güneş enerjisi toplama sistemlerinden elde edilen enerjinin kullanılması ilgi çekmektedir. Örneğin Chen ve ark. (2022), üç biyokütle malzemesinin torrefaksiyonunu (yer fıstığı kabuğu, soya fasulyesi samanı ve çam ağacı), 200–300°C sıcaklık aralığında, 15-45 dakika süreyle yeni bir güneş enerjisiyle çalışan torrefaksiyon (Solar-T) kullanarak gerçekleştirmiştir. Biyokütlenin elektrikli ısıtmalı torrefaksiyon işlemi (Elektrik-T) için gereken özellik değişimi ve enerji kullanımı karşılaştırma için analiz edilmiş, sonuçlar torrefiye biyokütlenin özelliklerinin hem biyokütle türlerinden hem de torrefaksiyon

yöntemlerinden büyük ölçüde etkilendiğini göstermiştir. Üç biyokütle malzemesi arasında soya fasulyesi samanının, en şiddetli koşullarda (300°C, 45 dk) en düşük katı verime (Elektrik-T'de %43.2, Solar-T'de %42.9) ve enerji verimine (Elektrik-T'de %50.8, Solar-T'de %51.3) sahip olduğu görülmüştür. Enerji kullanım sonuçları, Elektrik-T sırasında tüketilen elektrik enerjisinin artan torrefaksiyon şiddeti ile arttığını ancak enerji verimliliğinin düştüğünü göstermiştir. Solar-T'nin dikkate değer avantajı enerji tasarrufudur, çünkü Solar-T için elektrik enerjisi gerekmemektedir. Enerji-kütle eş-fayda indeksi göz önüne alındığında, güneş enerjisi ile torrefiye biyokütle numunelerinin, Elektrik-T kullanılarak elde edilen torrefiye ürünlere göre daha fazla taşınabilir olduğu görülmüştür. Ülkemizde yapılan önemli çalışmalardan biri Cellatoğlu & İlkan (2016) tarafından gerçekleştirilen, bir parabolik çanak yoğunlaştırıcıdan konsantre güneş enerjisi kullanarak 250°C'de 10 dakika boyunca katı zeytin değirmeni kalıntısının torrefaksiyonudur. Güneş enerjisini yoğunlaştırmak için parabolik çanak anten kullanılmıştır. Deney sonunda artan karbon içeriğine ve daha yüksek üst ısı değerine sahip, oksijeni giderilmiş bir katı yakıt elde edilmiş, güneşle torrefaksiyon ürünlerinin geleneksel torrefaksiyon kullanılarak elde edilenlere benzer özelliklerde olduğu bulunmuştur. Sonuçlar, torrefaksiyon işleminin güneş termal enerjisi ile yapılabileceğini ve güneş enerjisi kullanımının ham biyokütleye kıyasla kaliteli katı yakıt üretimi için umut verici olduğunu göstermiştir. Bir başka çalışmada Tregambi ve ark. (2019) tarafından, lignin açısından zengin bir tortunun güneş enerjisiyle çalışan sistemde torrefaksiyonu gerçekleştirilmiştir. Çalışmalar 250, 275, 300°C sıcaklık ve 30 dk da yapılıp, ticari olarak kullanılan odun peletleri büyüklüğündeki silindirik peletlerle deneysel sonuçlar elde edilmiştir. H/C ve O/C atomik oranlarının artan torrefaksiyon sıcaklığı ile düştüğü gözlemlenmiş, bu da beklendiği gibi, malzeme özelliklerinin daha karbonize malzemelere doğru kaydığını göstermiştir. Sonuç olarak, torrefaksiyon şiddetinin ürün özelliklerine etkisinin doğrudan güneş ışınımı kullanılan sistemde daha belirgin olduğu tespit edilmiştir. Biyokütle atığı olarak Ashe Juniper tercih eden Rodriguez-Alejandro ve ark. (2023), yeni bir güneş enerjisiyle çalışan termokimyasal dönüşüm reaktörü tasarlamıştır. Torrefaksiyon sıcaklığının ve kalma süresinin biyokütle atığının özellikleri üzerindeki etkisi araştırılmış ve sonuçlar, torrefaksiyon sıcaklığının, kalma süresinin etkisine kıyasla ürün özelliklerinde daha etkili olduğunu göstermiştir. En yüksek enerji verimi (%90'ın üzerinde) 210°C'de elde edilirken, en yüksek enerji yoğunluğu (∼1.51) 360°C'de elde edilmiştir. Ayrıca güneş enerjisiyle çalışan termokimyasal dönüşüm reaktörlerinin, ekonomik (enerji tasarrufu) ve çevresel (CO_2 azaltma etkisi) faydalar açısından endüstriyel uygulamalarda biyokütle atığının torrefaksiyonu için aday olma potansiyeline sahip olduğu görülmüştür. Parvej ve ark. (2022), güneş enerjisini su sümbül biyokütlesini değerli kimyasallara dönüştürmek için hem torrefaksiyonda hem de pirolizde kullanmışlardır. Bu amaçla, maksimum 450°C'lik bir reaksiyon sıcaklığı üretebilen parabolik çanak tipi bir güneş reaktörü kullanılmıştır. TG analizi, bu sıcaklığın hammaddeleri işlemek için yeterli olduğunu doğrulamaktadır. Parçalama sıcaklığındaki bir artış, kömür içeriğini (ağırlıkça %27.4'ten ağırlıkça %59.4'e) büyük ölçüde iyileştirirken, biyo-yağları (ağırlıkça %40.2'den ağırlıkça %15.3'e) ve sentez gazı verimlerini (ağırlıkça %32.4'ten %15.3'e) azaltmıştır. Bu nedenle, torrefaksiyonun su sümbül biyokütlesinden kömür üretimi için ideal olduğu tespit edilmiştir. Solar piroliz gerçekleştiren bir diğer araştırmacı olan Rahman (2020), numune olarak algleri kullanmış, Bengal Körfezinden topladığı algleri önce yıkayıp daha sonra kurutmuştur. Kurutulmuş alg biyokütlesi 0.5 mm, 0.5-1 mm, 1-1.5 mm, 1.5-2 ve 2-2.5 mm olmak üzere beş farklı boyut aralığında sınıflandırmıştır. Deneyde dikey bir güneş fırını kullanılmış ve odak noktasına sabit yataklı silindirik bir reaktör yerleştirilip, sistemde parabolik yoğunlaştırıcı kullanılmıştır. Biyokütle numunesi (50 g) reaktöre beslenmiş ve ardından reaktör içindeki sıcaklık 50°C'lik artışlarla 250 ile 600°C arasında değiştirilmiştir. Isıtma hızı ve azot gazı akış hızı sırasıyla 50°C/dk ve dakikada 100 mL'de sabit tutulmuştur. Biyoyağ verimleri kademeli olarak 400°C'ye kadar artmış, ancak bu sıcaklığın ötesinde biyoyağ verimleri tekrar düşmüştür. Öte yandan, biyokömür verimlerinin daha düşük bir sıcaklıkta daha yüksek olduğu ve artan sıcaklıkla birlikte kademeli olarak azaldığı tespit edilirken, gaz halindeki ürün (yoğuşmayan gaz) verimlerinde zıt eğilimler gözlenmiştir. Chintala ve ark., (2017), Jatropha tohumlarının sıvı, katı ve gaz halindeki yakıtlara solar termokimyasal piroliz işlemi ile dönüştürülmesi üzerinde çalışmışlardır. Jatropha tohumları biyokütlesinin solar termo-kimyasal pirolizi, paslanmaz çelik bir piroliz reaktöründe gerçekleştirilmiş ve biyoyağ, biyokömür ve pirolitik gaz olmak üzere üç piroliz ürünü elde edilmiştir. Maksimum biyoyağ verimi %20, biyokömür %51 ve pirolitik gaz %29 olarak tespit edilip, Jatropha tohumları biyokütlesi için pirolitik sıcaklık bölgesi, TGA ve DTG sonuçlarına göre 203°C ile 508°C olarak belirlenmiştir. Genel olarak, bu

çalışma biyokütleden katı, sıvı ve gaz yakıtların üretimi için solar termal işleminin uygun olduğunu göstermiştir. Başka bir çalışma örneğinde ise Chen ve ark., (2020), çalışmada deney materyali olarak sırasıyla yer fıstığı kabuğu, soya samanı ve çam ağacı biyokütlelerini kullanmıştır. Bu üç tip biyokütle ilk önce geleneksel asit yıkama yerine sulu faz biyo-yağı ile ön işlemden geçirilmiş, daha sonra yıkanan numuneler parabolik oluklu bir güneş alıcı sistemi kullanılarak kurutma (100°C, 30 dakika) ve torrefaksiyon (250°C, 30 dakika) ile ön işlemden geçirilmiştir. Sonraki piroliz, parabolik çanak güneş alıcı sistemi kullanılarak 10 dakika boyunca 550°C'de gerçekleştirilmiştir. Sonuçlar, güneş enerjisinin biyokütle kurutma, torrefaksiyon ve piroliz için gerekli sıcaklığı etkili bir şekilde sağlayabileceğini ve böylece geleneksel elektrikli ısıtma veya fosil yakıtlı ısıtmanın yerini alma potansiyeline sahip olduğunu göstermiştir.

5.1. Solar torrefaksiyonun geleneksel torrefaksiyon sistemine göre avantajları

Geleneksel ototermal reaktörde, ürünleri üretmek için yüksek sıcaklık gereklidir. Bu ısı, fosil yakıtın yanmasından veya tedarik edilen hammaddenin proses verimliliğini azaltan, ürünleri ve çevreyi kirleten bir kısmının yakılmasından gelir. Bununla birlikte, solar torrefaksiyon durumunda, zararlı gazların üretilmesine ilişkin bu tür tehlikeler veya proses verimliliğini düşürme olasılıkları yoktur. Ayrıca, geleneksel ototermal reaktöre kıyasla önemli miktarda CO_2 emisyonunu (~%32.4) azaltır.

Reaksiyon entalpisinin ürünlere aktarılması nedeniyle hammaddelerin enerji içeriği yükseltilir. Genel olarak, solar torrefaksiyon ürünleri güneş enerjisini kimyasal enerji şeklinde depoladıkları için daha yüksek kalorifik değerler içerir.

Reaktörün yüksek optik absorpsiyon kapasitesi ve pencere camının yüksek geçirgenliği, reaktörün yüksek bir sıcaklığına ulaşılmasına yardımcı olur. Bu nedenle, reaksiyonlar için mevcut olan daha fazla yüzey nedeniyle torrefaksiyonun işlem verimliliği artar. Reaktörün yoğunlaştırıcı ile uygun şekilde entegrasyonu sonucu, maksimum güneşten yakıta dönüşüm veriminin %50'den fazla olduğu bulunmuştur. Bu, güneş torrefaksiyon sisteminin üretim maliyetini üçte bir oranında düşürür ve güneş enerjisi yakıtlarını geleneksel yakıtla karşılaştırıldığında rekabetçi bir maliyetle sunar.

Güneş enerjisinin kesintili doğası, depolanabilir ve taşınabilir yakıt üretilerek kısmen ortadan kaldırılabilir.

Saf oksijenin enerji yoğun işlenmesi ihtiyacı ortadan kalkar.

Solar piroliz sisteminin işletme maliyeti çok düşüktür. Güneş reaktörü ücretsiz olan radyasyon kullanır. Ayrıca, ototermal reaktöre ısı sağlamak için kullanılan belirli bir miktarda enerji/yakıt tasarrufu sağlar.

Geleneksel ısıtma sistemleriyle karşılaştırıldığında, güneş enerjisiyle torrefaksiyon tesislerinin tasarımı ve deneysel kurulumu nispeten daha az karmaşıktır.

Güneş enerjisi reaktörünü yüksek konsantre ısı akışı ile hızlı bir şekilde ısıtmak mümkündür ve ayrıca geleneksel reaktörlere kıyasla hızlı kapatma mümkündür.

6. Sonuç

Nüfusun hızlı bir şekilde artması ile birlikte fosil yakıtların, tükenme riskiyle karşı karşıya kalması bilim insanlarını yenilenebilir enerji kaynağı arayışına yönlendirmiştir. Yenilenebilir enerji kaynaklarına geçiş, iklim değişikliğine bağlı çevre sorunlarıyla mücadele etmede etkili bir stratejidir. Bu stratejinin sürdürülebilir bir şekilde devam edebilmesi için biyokütle enerjisinin kullanımı oldukça uygundur. Biyokütle atıklarından enerji kullanımının amacı çevre kirliliğini en aza indirmek, sera gazlarına neden olan atıkları yönetmek ve bir yenilenebilir enerji türü olan biyoatıklardan enerji üretmektir. Biyokütlenin işlenmesiyle elde edilebilen biyoyakıtlar sürdürülebilir, çevre dostu ve fosil yakıtlara alternatif kaynaktırlar.

Biyokütlenin torrefaksiyon işlemiyle enerji yoğunluğunun artırılması, yüksek kaliteli yakıtların elde edilmesi açısından büyük önem taşımaktadır. Ancak bu işlem, enerji gereksinimi bakımından dikkatli bir şekilde değerlendirilmelidir. Geleneksel torrefaksiyon yöntemlerinde enerji genellikle fosil yakıtların kullanımıyla sağlanır ve bu durum karbon emisyonlarını artırarak çevresel sürdürülebilirliği olumsuz etkileyebilir. Ortalama olarak, geleneksel torrefaksiyon süreçlerinde enerji

verimliliği %70 ile %90 arasında değişmektedir, ancak sistemdeki enerji kayıpları bu verimliliği düşürmektedir.

Solar torrefaksiyon, enerji ihtiyacını yenilenebilir güneş enerjisiyle karşılamayı hedefleyen çevre dostu bir alternatif olarak öne çıkmaktadır. Yapılan araştırmalar, solar torrefaksiyonun enerji tasarrufu ve çevresel etkiler açısından önemli avantajlar sunduğunu ortaya koymaktadır. Örneğin, elektrikle ısıtılan torrefaksiyon süreçlerinde enerji verimliliği %50.8 düzeyinde iken, solar torrefaksiyonda bu oran %51.3'e kadar çıkmaktadır. Güneş enerjisinin yenilenebilir, ücretsiz ve karbon nötr bir kaynak olması, bu yöntemi hem ekonomik hem de çevresel sürdürülebilirlik açısından daha avantajlı kılmaktadır.

Güneş enerjisi ile çalışan torrefaksiyon sistemleri ile diğer enerji girdileri kullanan sistemlerin performans karşılaştırmasını sunmak için oluşturulan Tablo 1'de, bu sistemlerin enerji verimliliği, karbon emisyonları ve maliyet gibi temel performans parametreleri detaylandırılmıştır.

Tablo 1. Güneş enerjisi ve diğer enerji girdileriyle çalışan torrefaksiyon sistemlerinin karşılaştırılması

Kriter	**Güneş Enerjisi ile Çalışan Torrefaksiyon**	**Diğer Enerji Girdileri ile Çalışan Torrefaksiyon**
Enerji Verimliliği (%)	50.0 - 51.3 (Solar sistemlere bağlı)	50.0 - 50.8 (Elektrikli veya fosil yakıtlı sistemler)
Karbon Emisyonu	Çok düşük (Neredeyse sıfır karbon salımı)	Yüksek (Fosil yakıt kullanımı kaynaklı karbon salımı)
Maliyet	Düşük işletme maliyeti, ancak başlangıçta yüksek kurulum maliyeti	Düşük kurulum maliyeti, ancak yüksek işletme maliyeti
Enerji Kaynağının Sürdürülebilirliği	Yenilenebilir ve sınırsız	Sınırlı ve yenilenemez
Çevresel Etki	Pozitif (karbon ayak izi azaltımı)	Negatif (karbon ayak izi artışı)
Sistem Verimliliği	Güneş ışınımına bağlı değişkenlik gösterebilir	Sabit enerji sağlayabilir, ancak fosil yakıtların etkisiyle olumsuz çevre etkisi yaratır
Teknolojik Uygulanabilirlik	İleri teknoloji gerektirir	Mevcut altyapılarla kolayca uygulanabilir

Güneş enerjisi ile gerçekleştirilen torrefaksiyon işlemleri, enerji verimliliği açısından elektrikle çalışan sistemlere benzer sonuçlar elde etmektedir. Bununla birlikte, güneş enerjisinin yenilenebilir ve ücretsiz bir kaynak olması, çevre dostu bir seçenek olarak bu yöntemin öne çıkmasını sağlamaktadır.

Güneş enerjisi kullanan sistemler, sıfır karbon emisyonu hedefiyle çevresel sürdürülebilirliğe katkıda bulunurken, fosil yakıt kullanan sistemler enerji üretimi sırasında yüksek karbon emisyonlarına yol açmaktadır. Bunun yanı sıra, güneş enerjisi ile çalışan sistemlerin ilk kurulum maliyetleri, gerekli ekipmanların teknolojik altyapısı ve sistem entegrasyonu nedeniyle yüksek olabilir. Ancak uzun vadede işletme maliyetlerinin düşük olması, bu yöntemi ekonomik açıdan da sürdürülebilir hale getirmektedir. Buna karşılık, fosil yakıt tabanlı sistemlerin kurulum maliyetleri daha düşük olmasına rağmen, işletme sürecinde enerji kaynağı için sürekli maliyet gereksinimi ve çevresel etkiler, bu sistemlerin dezavantajları arasında yer almaktadır.

Sonuç olarak, güneş enerjisi tabanlı torrefaksiyon sistemleri, yenilenebilir enerji kaynaklarının kullanımıyla çevresel zararları en aza indirirken karbon emisyonlarını azaltma ve enerji maliyetlerini düşürme potansiyeline sahiptir. Bu bulgular, güneş enerjisi kullanımının fosil yakıtlara kıyasla hem çevresel hem de ekonomik açıdan daha etkili bir çözüm sunduğunu göstermektedir.

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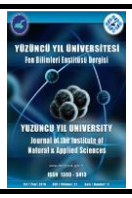
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Derleme Makale

Ekstrüde Ambalajlar ve Aktif Ambalaj Teknolojileri: Gıda Endüstrisindeki Kullanım Potansiyeli ve Yenilikçi Yaklaşımlar

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Öz: Gıda ambalajları, ürünlerin korunması, taşınması ve tüketiciye sunulmasında kritik bir rol oynamaktadır. Ancak, mikrobiyal bozulma gibi sorunlar endüstri için ciddi bir sorun olmaya devam etmektedir. Bu problem doğrultusunda, modifiye atmosferde ambalajlama teknolojisi, akıllı ambalajlama teknolojisi ve aktif ambalajlama teknolojisi gibi çeşitli gıda ambalajlama uygulamaları geliştirilmiştir. Bu teknolojilerden biri olan aktif ambalajlama, ambalajın içine veya yüzeyine aktif bileşenlerin eklenmesiyle gıdaların raf ömrünü uzatmayı ve kalitesini artırmayı hedefleyen bir sistem olup özellikle mikrobiyal bozulma gibi sorunlara karşı etkili bir çözüm sunmaktadır. Bu amaçla, gıda ambalaj endüstrisinde genellikle düşük maliyetli ve iyi mekanik performansa sahip doğal, sentetik ve yarı sentetik polimerler kullanılmaktadır. Bu polimerler, ekstrüzyon kalıplama gibi teknolojilerle işlenerek çeşitli ambalaj filmleri elde edilmektedir. Gıda ambalajlama endüstrisindeki ambalaj filmlerinin aktif ambalaj olarak kullanım potansiyellerinin incelenmesinin hedeflendiği bu çalışmada çeşitli gıdalardaki uygulama örnekleri incelendiğinde, endüstride kullanılan aktif ambalajlama sistemlerinin başarılı sonuçlar verdiği, uygulanan ürünlerin raf ömrüne ve kalitesine katkıda bulunduğu görülmüştür.

Anahtar Kelimeler: Aktif ambalajlama teknolojisi, Ekstrüzyon kalıplama, Film, Kalite, Polimer, Raf ömrü

Extruded Packages and Active Packaging Technologies: Potential Usage and Innovative Approaches in the Food Industry

Abstract: Food packaging plays a critical role in product protection, transportation, and presentation to consumers. However, issues such as microbial spoilage continue to pose serious challenges for the industry. In response, various food packaging technologies have been developed, including modified atmosphere packaging, smart packaging technology, and active packaging technology. One of these technologies, active packaging, is a system aimed at extending the shelf life and enhancing the quality of food by incorporating active components into or onto the packaging. This technology offers an effective solution, particularly against problems like microbial spoilage. For this purpose, the food packaging industry typically employs low-cost natural, synthetic, and semi-synthetic polymers with good mechanical performance. These polymers are processed using technologies such as extrusion moulding to produce various packaging films. This study aims to examine the potential of packaging films in the food packaging industry as active packaging. By reviewing application examples in various foods, it was found that active packaging systems used in the industry have yielded successful results, contributing to the shelf life and quality of the products.

Keywords: Active packaging technology, Extrusion molding, Film, Polymer, Quality, Shelf life

1. Giriş

Gıda ambalajları, gıda ürünlerini çevresel faktörlere karşı koruyarak, ürünlerin güvenli koşullarda taşınması ve dağıtılmasını sağlayan gıda işleme endüstrisinin temel unsurlarından biridir. Ürünlerin işlenmesinden nihai tüketimine kadar her aşamada kritik bir rol oynamaktadır. Ambalaj, sadece ürünün korunmasını sağlamakla kalmaz, aynı zamanda ürün ile tüketici arasında bilgi aktarımını

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kolaylaştıran bir iletişim aracı işlevi görür (Pascall ve ark., 2022; Abbas ve ark., 2023). Bununla birlikte, gıdanın hazırlanmasını hızlandırması, kullanım kolaylığı, ergonomik tasarımı gibi özellikler, tüketici deneyimini optimize etmektedir. Tüketicilerin uzun raf ömrüne sahip, daha kaliteli, taze ve güvenli gıda ürünlerine olan artan talebi, ambalaj bilimi ve teknolojisinin sürekli yenilik ve gelişim göstermesini teşvik etmektedir (Yan ve ark., 2022; Stanley ve ark., 2023; Deshmukh ve ark., 2023).

Polimer bazlı malzemeler, esneklik, mekanik dayanıklılık ve üretim kolaylığı gibi avantajlı özellikleri nedeniyle günümüzde ambalaj malzemelerinin üretiminde önemli bir yer tutmaktadır (Zhang ve ark., 2022; Perera ve ark., 2023). Ancak gıda ambalajlama sektöründe, mikrobiyal bozulma hâlâ et, peynir, unlu mamuller, meyve ve sebze gibi birçok gıda ürününü tehdit eden kritik bir sorun olmaya devam etmektedir. Bu bağlamda, gıdaların raf ömrünü uzatmak ve tüketicilerin daha güvenilir ve yüksek kaliteli gıda taleplerini karşılamak amacıyla çeşitli teknikler geliştirilmiştir. Bu yaklaşımlardan biri olan aktif ambalajlama, yirminci yüzyılın başlarında literatüre girmiş olup, geleneksel ambalajlama yöntemlerine kıyasla daha gelişmiş bir koruma mekanizması sunmaktadır (Yuvaraj ve ark., 2021; Stanley ve ark., 2023; Deshmukh ve ark., 2023).

Geleneksel ambalajlama yöntemlerinden farklı olarak aktif ambalajlama, gıdanın raf ömrünü uzatmak, gıda güvenliğini sağlamak ve duyusal kaliteyi artırmak amacıyla geliştirilmiş bir yaklaşımdır (Ahmed ve ark., 2022). Bu sistem, etilen tutucu, nem düzenleyici, oksijen tutucu ve antimikrobiyal maddeler gibi aktif bileşenlerin çeşitli yöntemlerle ambalaj materyalinin yapısına veya yüzeyine entegre edilmesi ve polimerlerle kombinasyonu yoluyla ambalajlama koşullarının optimize edilmesine dayanır (Fadiji ve ark., 2023). Aktif ambalajlama, ambalajın gıdayı koruma kapasitesini artırarak, ambalaj içerisindeki ürünlerin yüksek kalitede muhafazasını mümkün kılmaktadır (Çelebi Sezer & Bozkurt, 2021; Bakırcı & Terzioğlu, 2022; Tan ve ark., 2024).

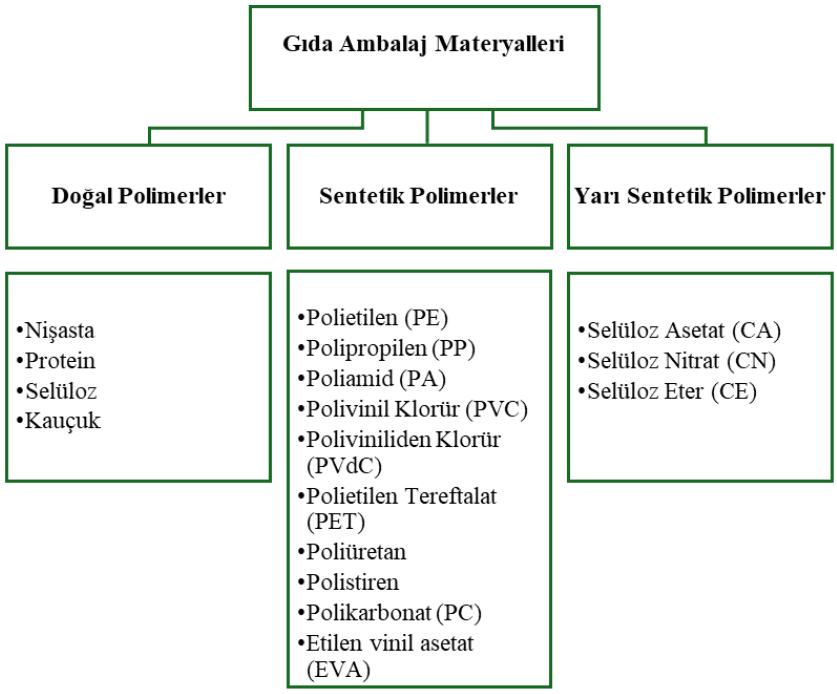
Gıda ambalaj endüstrisinde genellikle polietilen tereftalat (PET), polipropilen (PP), polivinil klorür (PVC), polietilen (PE), poliamid (PA) ve polistiren (PS) gibi düşük maliyetli ve iyi mekanik performansa sahip polimerler kullanılmaktadır (Shaikh ve ark., 2021). Bununla birlikte, biyobozunur ve doğal kaynaklı malzemelere olan ilginin artmasıyla birlikte nişasta bazlı polimerler, polilaktik asit (PLA) ve selüloz türevleri gibi çevre dostu alternatifler de ambalaj üretiminde giderek daha fazla tercih edilmektedir (Ghasemlou ve ark., 2024). Streç film, lamine poşet, plastik ambalaj, plastik kap gibi çeşitli renk, tasarım ve şekillere sahip ambalajların seri üretiminde polimer işleme teknolojileri kullanılmaktadır. Bu teknolojilerden biri olan ekstrüzyon, büyük tasarım esnekliğine, düşük üretim maliyetine ve üretim sonrası işlemlere sahip olması nedeniyle gıda ambalaj endüstrisinde en yaygın kullanılan yöntemlerden biri olarak kabul edilmektedir (Nilsen-Nygaard ve ark., 2021; Stanley ve ark., 2023; Deshmukh ve ark., 2023).

Ekstrüzyonun endüstrideki yaygın kullanımı ve aktif ambalajlama teknolojisinin geleneksel yöntemlerin ötesinde sunduğu fonksiyonel avantajlar göz önüne alındığında gıda ambalajlama uygulamalarına yönelik bu çalışmada ekstrüde ambalajların aktif ambalaj olarak gıda endüstrisinde kullanım potansiyelleri konusundaki bilgilerin derlenmesi amaçlanmıştır.

2. Gıdalarda Ambalaj Materyali Olarak Kullanılan Materyallerin Sınıflandırılması

Gıda endüstrisinde ambalaj malzemelerinin çeşitliliği ve özellikleri, ürünlerin türüne ve ambalajlama gereksinimlerine göre değişiklik göstermektedir. Bu nedenle, ambalaj malzemelerinin doğal, sentetik ve yarı sentetik polimerler gibi farklı kategorilere ayrılması önem arz etmektedir. Yapılan sınıflandırma ve önemli örnekleri Şekil 1'de görülmektedir.

Doğal polimerler, doğal kaynaklardan elde edilen organik bileşiklerdir ve moleküler düzeyde tekrarlanan yapı birimlerinden oluşurlar. Sentetik polimerler, laboratuvar ortamında sentezlenen organik bileşiklerdir ve moleküler düzeyde yapı birimlerinden oluşurlar. Yarı sentetik polimerler ise doğal ve sentetik bileşenlerin bir karışımıdır (Kılınç & Toplan, 2023).



Şekil 1. Gıda ambalaj materyallerinin sınıflandırılması (Yoruç & Uğraşkan, 2017; Rahardiyan ve ark., 2023).

2.1. Doğal polimerler

Geleneksel plastiklere çevre dostu alternatifler geliştirme çabaları, biyolojik olarak parçalanabilen ambalaj malzemelerine yönelik araştırmaları teşvik etmiştir. Bu bağlamda, doğal polimerler biyobozunur ambalaj malzemeleri için önemli bir araştırma alanı haline gelmiştir (Dhumal & Sarkar, 2018). Doğal polimerler; nişasta, protein, selüloz ve kauçuk gibi biyolojik kökenli makromoleküllerden oluşmaktadır (Tüylek, 2017).

Nişasta, hidroksil gruplarının oluşturduğu hidrojen bağları nedeniyle hidrofilik özellik gösteren doğal bir polimerdir. Ancak, nemin varlığında mekanik dayanıklılığının zayıflaması ve aşınmaya eğilimli olması nedeniyle doğrudan plastik malzeme olarak kullanımı sınırlıdır. Bununla birlikte, gliserol, sorbitol ve ksilitol gibi plastikleştiricilerle işlenerek termoplastik özellik kazanabilmektedir. Plastikleştiriciler, polimer zincirleri arasındaki moleküler etkileşimleri azaltarak polimerin hareketliliğini artırır, camsı geçiş sıcaklığını düşürür ve geçirgenlik özelliklerini iyileştirir. Nişasta bazlı termoplastik malzemeler, yüksek oksijen bariyeri özellikleri, biyobozunurluk ve yenilenebilirlik gibi avantajları sayesinde özellikle kısa ömürlü plastik uygulamalarında, gıda ambalajı sektöründe önemli bir potansiyele sahiptir (Tekin & Ersus, 2024).

Proteinler, amino asit bileşimlerine bağlı olarak üç boyutlu doğrusal yapıya sahip hetero-biyopolimerlerdir (Zubair & Ullah, 2020). Doğal polisakkaritlerden daha güçlü mekanik özelliklere sahip olmaları, düşük maliyetleri ve biyokütle atıklarından elde edilebilmeleri nedeniyle biyobozunur film üretiminde yaygın olarak kullanılmaktadırlar. Ayrıca, protein bazlı filmler, düşük yoğunluklu polietilene kıyasla daha iyi oksijen (O_2) ve karbon dioksit (CO_2) bariyer özellikleri sunmaktadır (Chen ve ark., 2019). Sistin açısından zengin olan keratin, soya proteini ve buğday glüteni gibi proteinler, içerdikleri disülfit bağları sayesinde yüksek su stabilitesi sergileyerek ambalaj malzemesi olarak kullanım açısından avantaj sağlamaktadır (Hassan ve ark., 2024).

Bitki hücre duvarlarının temel bileşeni olan selüloz, günümüzde en yaygın kullanılan yenilenebilir polimer kaynaklarından bir diğeridir. Bitki liflerinden elde edilen selüloz, sürdürülebilir ve biyouyumlu malzemelere olan talebi karşılamak açısından büyük bir potansiyel sunmaktadır. Yüksek kristalli yapısı nedeniyle suda ve birçok organik çözücüde çözünmemesi, selülozun doğal stabilitesini artırmaktadır. Bununla birlikte, üstün mekanik dayanıklılığı ve suya karşı yüksek direnci sayesinde biyobozunur ambalaj uygulamalarında önemli bir bileşen olarak değerlendirilmektedir (Khalil ve ark., 2017; Abolore ve ark., 2024).

Kauçuk, bazı bitkilerin sütümsü öz suyundan doğal olarak veya petrol ve alkol bazlı sentetik süreçlerle elde edilen elastomerik bir polimerdir (Elfaleh ve ark., 2023). Günlük yaşamda geniş bir kullanım alanına sahip olan kauçuk ürünleri, özellikle gıda ve içme suyu ile temas eden uygulamalarda, sağlık endüstrisinde (şırınga, eldiven, tıbbi hortum ve tıpalar gibi) önemli bir yer tutmaktadır. Kauçuğun yaygın olarak tercih edilmesinin başlıca nedenleri arasında çapraz bağlanma derecesinin yüksekliği, düşük sıvı geçirgenliği, iyi fiziksel ve kimyasal dayanıklılığı yer almaktadır. Ayrıca, farmasötik, gıda ve kozmetik ürünlerle uyumluluğu ve sıkı düzenleyici gereklilikleri karşılaması, kauçuk bazlı malzemelerin tercih edilme sebeplerini güçlendirmektedir (Vahapoğlu, 2013).

2.2. Sentetik polimerler

Sentetik polimerler, polietilen (PE), polipropilen (PP), poliamid (PA), polivinilklorür (PVC), poliviniliden klorür (PVdC), polietilen tereftalat (PET), poliüretan (PU), polistiren (PS), polikarbonat (PC) ve etilenvinilasetat (EVA) olarak on kategoriye ayrılmıştır.

Polietilen (PE), etilen molekülünün yüksek basınç altında veya düşük basınç ile katalizörler eşliğinde katılma polimerizasyonu ile üretilir (İbiş, 2013). Ucuz, hafif, esnek, birçok çözücüye dayanıklı ve çok yönlü olmasıyla birlikte tüm ticari plastikler arasında en basit yapıya sahip olan dünyanın en popüler plastiğidir. Su buharına karşı düşük geçirgenliği nedeniyle polietilen, birçok malzemenin kaplanmasında yaygın olarak kullanılmaktadır (Melikoğlu ve ark., 2023).

Polipropilen (PP), propilenin polimerizasyonu ile elde edilen yarı kristal bir polimerdir. Sıkı, sert, dayanıklı ve kimyasal maddelere karşı dirençlidir (Torun, 2024). Yaygın olarak kullanılan plastikler arasında en hafif plastiktir. Erime noktası 165-170 °C olup yumuşamadan 120 °C'ye kadar kullanılabilmektedir. Polipropilenin özellikleri molekül ağırlığına göre değişmekte olup, molekül ağırlığı yüksek olan yumuşak, düşük olan ise sert ve kırılgan yapıdadır. Kimyasal davranış bakımından yüksek yoğunluklu polietilene (HDPE) benzer ancak, HDPE'den daha sert ve şeffaf, su buharı ve gaz geçirmezlik değerleri bakımından ise HDPE'ye yakındır. Yağ geçirmezlik özelliği ve yırtılmalara karşı direnci iyi olup soğuğa dayanımı azdır (Aydemir, 2017).

Poliamid (PA), kaplama, kalıplama, lif gibi uygulanabilirliği yüksek, polimer zincirinin tekrarlanan bölümü olarak amid grubu içeren doğrusal, termoplastik bir polimerdir (Yurtbaşı, 2019). Yüksek mukavemet, yüksek elastikiyet, yüksek sıcaklık dayanımı ve yüksek aşınma direnci gerektiğinde poliamid (PA) polimerleri sıklıkla tercih edilmektedir (Nguyen ve ark., 2023). Organik buharlara karşı düşük geçirgenlik göstermesi sayesinde gıdalarda lezzet kaybı veya tat karışması gibi problemlerin önlenmesinde rol almaktadır (Aydemir, 2017).

Polivinilklorür (PVC), polietilen ve polipropilenden sonra dünya çapında en çok kullanılan termoplastik malzemelerden biridir. Yüksek ısıya karşı direnç göstermesi, yağlara, asitlere, hidrokarbonlara karşı dayanıklı olması ve düşük molekül ağırlığına sahip olmasıyla gıda ambalajlamada, temizlik ürünlerinde, tekstilde, tıbbi cihazlarda kullanılabilmektedir (Boztepe, 2021).

Poliviniliden klorür (PVdC), doğrudan etilenden veya klordan elde edilebilen, ticari ismi 'Saran' olan şeffaf bir polimerdir. Su buharı, oksijen ve karbondioksit geçirimi diğer plastiklere göre daha azdır. Isı yalıtımı yüksektir. Su buharı, gazlar, kimyasal maddeler, yağ ve yağlı ürünlere karşı dayanıklı olması ve yüksek bariyer yeteneği bu maddenin gıda, ilaç, kozmetik, yağ vb. ürünlerin ambalaj uygulamalarında tercih edilmesini sağlamaktadır (Bozkurt, 2020).

Polietilen Tereftalat (PET), tereftalik asit (TPA) veya dimetil tereftalat (DMT) ile etilen glikolün (EG) adım polimerizasyonu ile üretilmektedir. Gaz ve su buharı geçirgenlik oranları düşük, kimyasallara karşı dirençli, yüksek transparanlığa sahip bir malzemedir. Polietilen Tereftalat kahve (koku geçirgenliğinin düşük olması sebebiyle), çay, dondurulmuş gıda, kuruyemiş, baharat gibi gıdaların ambalajlarında kullanılmakta ve yaklaşık olarak 300 °C'ye kadar ısıya dayanıklı bir yapısı bulunmaktadır (Aydemir, 2017; İşçi, 2023).

Poliüretanlar (PU), termoplastik elastomer ailesinde önemli bir yere sahiptir. Poliüretan elastomerlerin avantajları arasında istenilen modülde yüksek sağlamlık, aşınma ve kimyasallara karşı direnç, mükemmel mekanik ve elastik özellikler bulunmaktadır (Akdoğan ve ark., 2015).

Polistiren (PS), renksiz, şeffaf ve suya dayanıklı olan inert, lineer bir polimerdir. Asitlere ve bazlara karşı dayanıklı olan polistiren, yüksek dielektrik özelliği nedeniyle optik camlar ve optik cihazlar yapımında kullanılır. Elektrik yalıtım özelliğinin güçlü olması, üretim maliyetinin düşük olması, nem tutmaması, rutubetli ortamlarda elektrik özelliğini kaybetmemesi, şeffaflığı ve

kalıplanabilirliği gibi avantajlarından dolayı polistiren, geniş bir kullanım alanına sahip olan bir plastik malzemedir (Koçyiğit & Yalçın, 2019).

Polikarbonatlar (PC), çeşitli çekici mekanik özelliklere sahiptirler; bunlar arasında yüksek tokluk, şeffaflık, yüksek darbe direnci, yüksek sıcaklık direnci, iyi elektrik yalıtımı, UV direnci, sürünme direnci ve hafiflik bulunmaktadır (Kausar, 2018). Polikarbonlar, enjeksiyon kalıplama, ekstrüzyon, şişirme, termoform gibi seri üretim yöntemleriyle kolayca işlenebilmektedir. Özellikle gıda ile temas eden malzemelerde su damacanaları ve sofra malzemeleri üretiminde yaygın olarak kullanılan Polikarbon, karbonik asidin bisfenol esterinden ve bisfenol A [2, 2-bis (4-hidroksifenil) propan] (BPA) 'nın karbonil klorür veya difenil karbonat ile kondensasyon polimerizasyonu yoluyla elde edilmektedir (Wnuczek ve ark., 2021).

Etilen-vinil asetat (EVA) kopolimeri düşük sıcaklıklarda yüksek mekanik özelliklere ve dayanıma sahip olmakla birlikte polivinil klorürün bazı özelliklerini sergilemekte ancak vulkanize olmamaktadır. Etilen-vinil asetat kauçuğu ise parlak, net, yumuşak olup, düşük sıcaklıklarda yüksek tokluk, stres çatlaklarına karşı yüksek direnç ve UV ışınlarına karşı direnç gibi özelliklere sahiptir. EVA kopolimeri berrak, esnek ve yumuşak bir termoplastiktir. Düşük sıcaklıklarda bile esnektir, yüksek sürtünme katsayısına ve kimyasallara karşı dirence sahiptir. Uygulama alanları arasında ambalaj, yapıştırıcılar, streç filmler, ayakkabı tabanları, tek kullanımlık tıbbi ekipman, esnek oyuncaklar ve tel yalıtımı bulunur (Öksüz, 2019).

2.3. Yarı sentetik polimerler

Yarı sentetik polimerler; selüloz asetat (CA), selüloz nitrat (CN) ve selüloz eter (CE) olarak üçe ayrılmaktır.

Selüloz asetat (CA), selülozun asetik anhidrit ve asetik asit ile sülfürik asidin varlığında reaksiyonuyla elde edilmektedir (Erinç ve ark., 2021). Kararlı hidrolitik özelliklere sahiptir, bozunabilir ve toksik değildir. Relatif olarak düşük maliyetli olup, ısıya dayanıklı, mükemmel film oluşturma özelliğine sahiptir ve yüksek kimyasal ve mekanik stabilite göstermektedir. CA, bir membran olarak, atık su arıtma, gaz ayırma, enerji üretimi, su tuzunu uzaklaştırma, yara pansumanı, biyomedikal amaçlar ve gıda ve ilaç endüstrilerinde yaygın olarak kullanılmaktadır (Jain & Garg, 2021).

Selüloz nitrat (CN), ticari olarak selülozun nitrik asitle reaksiyonu sonucunda selüloz hidroksil gruplarının nitrat gruplarıyla değiştirilmesi/ikame edilmesi yoluyla üretilmektedir. Yüksek mekanik mukavemet, iyi çözünürlük ve plastikleştiricilerle uyumluluk gibi özelliklere sahip olduğundan patlayıcı, plastik, kaplama ve mürekkep endüstrilerinde sıklıkla kullanılmaktadır (Seddiqi ve ark., 2021).

Selüloz eterleri (CE), genellikle selüloz hidroksil gruplarının alkil halojenler veya epoksitler gibi elektrofillerle nükleofilik reaksiyonuyla hazırlanan polimerlerdir. Gıda, ilaç ve kişisel bakım ürünleri, petrol sahası kimyasalları, inşaat, kâğıt, yapıştırıcılar, piller ve tekstil gibi birçok endüstride kalınlaştırıcılar, bağlayıcılar, yağlayıcılar, emülsifiye ediciler, reoloji değiştiriciler ve film oluşturucular olarak geniş bir kullanım alanı bulurlar. Selüloz eterleri ve selüloz esterleri gibi ticari ürünler, örneğin salata soslarının, diyet gıdaların, kızarmış yiyeceklerin, unlu mamullerin, süt içermeyen çırpılmış sosların, ısıtılmış hazır gıdaların, ekstrüde ve şekillendirilmiş gıdaların, dondurulmuş tatlıların, içecekler ve şekerleme ürünlerinin formülasyonlarında önemli bir kullanım alanına sahiptir (Moradian ve ark., 2021).

3. Ambalaj Malzemelerinin Üretim Teknikleri

Ambalaj malzemelerinin üretiminde amaca yönelik olarak çeşitli yöntemler kullanılmaktadır. Bu yöntemler, kullanılan hammaddenin özelliklerine, ürünün kullanım amacına ve endüstriyel uygulamaya bağlı olarak değişebilmektedir. Genellikle kullanılan yöntemler; ekstrüzyon, kalıplama, döküm, laminasyon ve kaplama olarak sıralanabilir (Reichert ve ark., 2020). Ancak bu yöntemler arasında ekstrüzyon ve kalıplama, yüksek verimlilik, maliyet etkinliği ve geniş uygulama alanları sayesinde öne çıkmaktadır. Ekstrüzyon, özellikle plastik ve metal bazlı ambalaj malzemelerinin üretiminde en yaygın tercih edilen yöntemlerden biridir. Sürekli üretime olanak tanıması, hızlı üretim süreci ve çeşitli form ve boyutlarda ürün elde edilebilmesi gibi avantajları sayesinde diğer üretim tekniklerine kıyasla daha ekonomik ve verimli bir çözüm sunmaktadır. Bununla birlikte, kalınlık

kontrolünün zorluğu ve karmaşık geometrik formlar için ek işlem gereksinimi dezavantajlar arasında yer almaktadır (Altıparmak ve ark., 2022). Kalıplama, enjeksiyon, termoform ve sıkıştırma gibi alt yöntemlerle uygulanabilen ve yüksek hassasiyet gerektiren ambalajların üretiminde üstünlük sağlayan bir tekniktir. Detaylı ve kompleks tasarımların elde edilebilmesi, yüksek mekanik dayanım sunması ve farklı hammaddelere uyum sağlaması gibi avantajları bulunmaktadır. Bununla birlikte, kalıp maliyetlerinin yüksek olması ve üretim sürecinin nispeten daha uzun sürmesi, bu yöntemin sınırlamaları arasında yer almaktadır (Fu ve ark., 2020; Tatara, 2024).

3.1. Ekstrüzyon

Ekstrüzyon, polimerin basınç altında eritildikten sonra bir başlıktan geçirilip zorlanarak şekillendirildiği bir işlemdir. Termoplastik granüller, ekstrüderin içerisinde bir vida sistemi yardımıyla homojen bir şekilde eritilir ve ekstrüder çıkışında bulunan bir kalıba basılır. Ekstrüder, farklı ısı bölgeleri, ısı kontrol panelleri ve filtre gibi sistemlerle donatılmıştır. Erimiş plastik, kalıba basıldıktan sonra soğuyarak sertleşir ve ardından kalıp açılarak malzeme çıkarılır. Bu süreçte kimyasal bir reaksiyon gerçekleşmez. Ekstrüderler, tek vidalı ekstrüderler ve çift vidalı ekstrüderler olmak üzere iki gruba ayrılmaktadır. Tek vidalı ekstrüderler malzemeyi yalnızca eritip şekillendirirken, çift vidalı ekstrüderler besleme, eritme, karıştırma ve gaz giderme gibi özelliklere sahiptir (Büyükyazı & Tavman, 2020; Şahin & Sayaslan, 2023).

3.2. Kalıplama

Kalıplama, enjeksiyon ve şişirme ile kalıplama olarak ikiye ayrılmaktadır. Enjeksiyon kalıplama farklı şekillerde, düzgün yüzeylere sahip ürünler üretmek için termoplastik malzemelerin şekillendirilmesinde kullanılan en eski ve en yaygın yöntemdir. Bu işlem sırasında polimerler yüksek sıcaklıklara kadar ısıtılmakta ve istenen şekli elde etmek için yüksek bir basınçla kalıp boşluğuna itilmektedir. Sıkıştırma, enjeksiyon, soğutma ve çıkarma işlemleri kalıplamanın önemli adımlarıdır (Sam ve ark., 2016). Ambalaj endüstrilerinde ön kalıplar, plastik şişeler, kutular, kapaklar, kavanozlar ve kaplar üretmek amacıyla yaygın olarak enjeksiyon ile kalıplanmaktadır (Stanley ve ark., 2023).

Şişirme ile kalıplama, şişirmeli ekstrüzyonun bir türüdür ve bir enjeksiyon işlemiyle gerçekleştirilir. Bu yöntem, iki aşamadan oluşur. İlk aşamada, eritilmiş plastik malzeme enjeksiyon kalıbına enjekte edilir ve nihai ürün haline getirilecek olan küçük bir plastik parça elde edilir. Preform adı verilen bu plastik parça tüp şekline sahiptir ve boyun kısmı bu aşamada şekillenir. Ardından, preform şişirme çubuğuna yerleştirilerek şişirme işlemine geçilir ve kalıbın şeklini alır (Sam ve ark., 2016).

4. Gıda Ambalajlama Uygulamaları

Gıdaların kalitesinin ve güvenliğinin korunması amacıyla modifiye atmosferde ambalajlama teknolojisi (MAP), akıllı ambalajlama teknolojisi ve aktif ambalajlama teknolojisi gibi çeşitli uygulamalar geliştirilmiştir. Bu uygulamalar sayesinde ürünlerin tüketiciye ulaştırılması sırasında ürünlerde gerçekleşen değişimlerin izlenmesi veya ambalaj materyalinde/ortamında çeşitli değişiklikler yapılarak ürünlerin raf ömrünün artırılması ve kalitesinin ilk günkü gibi korunması hedeflenmektedir (Erdem ve ark., 2022).

4.1. Modifiye atmosferde ambalajlama teknolojisi (MAP)

MAP, ambalajdaki gıdayı çevreleyen havanın bileşimini değiştirerek taze veya minimum işlenmiş gıdaların raf ömrünü uzatmak için kullanılan bir tekniktir. MAP kullanımı, böceklerin veya mikroorganizmaların solunum hızını ve aktivitesini azaltmakta, meyve ve sebzelerde olgunlaşma kontrolü sağlamakta, kesilen ürünlerde olgunlaşmayı veya esmerleşmeyi geciktirmekte ve dolayısıyla raf ömrünü uzatmaktadır (Karagöz & Demirdöven, 2017). MAP tasarımının amacı, belirli bir ürünün uzun süre depolanması için en uygun atmosferi yaratacak koşulları belirlemek ve o atmosferi elde etmek için gereken süreyi en aza indirmektir. Yani, ürün ambalajı ile dış atmosfer arasındaki etkileşimler nedeniyle ambalaj içindeki istenen oksijen ve karbondioksit konsantrasyonunun dengeye en kısa sürede gelmesi ve bu atmosfer bileşiminin, ürünün maksimum sürede depolanabilmesi için gerekli seviyelerde

tutulmasıdır (Safaei ve ark., 2022). Modifiye atmosferde ambalajlama teknolojisi, aktif ve pasif olmak üzere iki şekilde uygulanabilmektedir (Mulla ve ark., 2025).

Pasif modifikasyonda, gıda uygun bir ambalaj malzemesi ile ambalajlandıktan sonra, ambalaj içindeki atmosferik gaz bileşimi, gıdanın solunumu sonucunda otomatik olarak dengeye ulaşır. Pasif modifikasyonun amacı ortamdaki oksijen miktarını azaltarak ürünün solunum hızını yavaşlatmaktır. Pasif modifikasyonda, kimyasal kullanılmadan raf ömrünün uzatılması sağlandığından organik ürünler için ideal bir ambalajlama teknolojisidir (Kocamanlar, 2009).

Aktif modifikasyonda, istenen gaz bileşimi, pasif modifikasyonda olduğu gibi ambalaj içinde kendiliğinden değil, doğrudan enjekte edilerek sağlanır. MAP için eser gaz olarak karbon monoksit, azot ve nitrik oksitler, kükürt dioksit, etan ve klor gibi gazlar önerilir ancak bu eser gazların çoğu güvenlik sorunları, tüketici tepkisi, yasal kısıtlamalar ve maliyet nedeniyle kullanılmamaktadır. Bu nedenle MAP amaçlı ticari olarak kullanılan başlıca gazlar karbondioksit (CO_2), oksijen (O_2) ve azottur (N_2). Çoğu meyve ve sebze için, ürün ihtiyaçlarına bağlı olarak seçici olarak bu gazların iki veya üç farklı kombinasyonu kullanılır (Kocamanlar, 2009). Modifiye atmosfer ambalajlamada kullanılan koruyucu gaz veya gaz karışımları, gıdanın ihtiyaçları göz önünde bulundurularak gereken gaz konsantrasyonları belirlenerek hazırlanmaktadır (Czerwiński ve ark., 2021).

4.2. Akıllı ambalajlama teknolojisi

Bu teknoloji, ambalajlı gıdaların üretimden satışa kadar olan süreç boyunca dağıtımı ve depolanması sırasında sıcaklık değişimleri ve mikroorganizmalar gibi bozulmaya neden olan unsurların takibini sağlayan, ürün kalitesini ve tazeliğini izlemeye yardımcı olan, ambalaj içinde ve dışında kullanılabilen bir teknolojidir. Akıllı ambalajlama sisteminde kullanılan göstergeler, film üzerine yapıştırılabilir veya ambalaj içerisine entegre edilebilir. Bu şekilde tedarik zinciri boyunca ürün kalitesinin izlenmesi, kritik noktaların kontrol edilmesi ve daha ayrıntılı bilgi sağlanması için olanak sağlanır (Hepsağ & Varol, 2018). Akıllı ambalajlama sistemleri akıllı etiketler ve ambalaj indikatörleri olmak üzere iki grupta sınıflandırılmaktadır (Takma & Nadeem, 2019).

Akıllı etiketler hem üreticilere hem de tüketicilere çeşitli avantajlar sunar. Üreticiler açısından, bu etiketler gıda güvenliği risklerini azaltmaya yardımcı olurken; perakendeciler, sıcaklık dalgalanmaları nedeniyle oluşabilecek bozulmaları minimize ederek taze ve hassas gıda satışlarını artırabilir. Tüketicilere ise en taze ürünü seçme imkânı sunarak, soğuk zincir takibi yapmalarını sağlar ve gıda güvenliği konusundaki endişelerini hafifletir. Barkodlar ve radyo frekansı ile tanımlama (RFID) etiketleri bu akıllı etiketlerin örnekleri arasında yer alır (Yüceer & Caner, 2023).

Barkod, bir harf veya sayı biçiminde yazılarak bulunduğu nesne hakkındaki bilgileri temsil eder. Barkod bu bilgileri, depolandığı ve işlendiği sisteme ileten, optik barkod tarayıcı ile okunabilen bir sistemdir. Barkod, bir ürünün bulunduğu yeri, tedarik zincirinin herhangi bir noktasında takip etmeyi sağlar. Barkodlar mürekkeple basılan farklı genişlikteki çubuklar ve altlarındaki sayılardan oluşmaktadır. Bir barkod on iki haneden oluşmaktadır. İlk iki hane barkodun oluşturulduğu ülkeyi gösterirken takip eden dört rakam ise ürünü kimin ürettiğini belirtir. Son altı hane ise üretici tarafından belirlenen ürün kodudur. Bu sistem sayesinde, her ürün kendi bireysel koduna sahiptir ve her kod optik tarayıcı sistemleri ile okunabilir (Lee & Rahman, 2014).

RFID etiketi, radyo dalgalarını kullanarak etiket okumayı sağlayan ve ürünü uzaktan izleme imkânı veren bir teknolojidir. Çalışma prensibi; mikroçiplerin ürünlere yerleştirilerek, fiziksel etkileşim yerine, ürünlerin kimliklerinin radyo dalgalarıyla okunabilmesidir. Gıda endüstrisinde bu sistem genellikle tedarik zinciri yönetimi, gıda izlenebilirliği ve geri çağırma gibi gıda güvenliğini artıran alanlarda kullanılır. Kullanılan sistemde depoya gelen paletlere RFID'li akıllı etiketler yapıştırılmaktadır. Depo giriş ve çıkışlarına kurulan RFID antenler, depo içerisinde bir palet okunduğunda tüm bilgileri otomatik olarak sisteme göndermektedir. Bu, ürünlerin yeterli miktarda uygun raflara yerleştirilmesini ve sevkiyat ve yerleştirme işlemlerinin zamanında tamamlanmasını sağlamaktadır (Yüksel & Zaim, 2009).

Ambalaj indikatörleri, genellikle karakteristik bir renk değişimi ile bir hedef maddenin varlığını, yokluğunu veya iki ya da daha fazla madde arasındaki reaksiyonun derecesini gösteren materyallerdir (Lee & Rahman, 2014). Bu indikatörler, ambalajın içine veya dışına yerleştirilebilir ve çevresel koşullara, gaz içeriğine bağlı olarak gıdanın kalitesi hakkında bilgi sağlar. Gıdanın ambalajda bulunduğu süre boyunca sıcaklık, mikrobiyal bozulma, ambalajın bütünlüğü, fiziksel hasar ve orijinallik gibi

özelliklerin izlenmesinde farklı indikatörler kullanılır. Bazı indikatörler gıdayla doğrudan reaksiyona girerken, bazıları ise herhangi bir etkileşim olmaksızın bilgi sağlar (Sürengil & Öztürk, 2017). Ambalaj indikatörleri arasında sıcaklık-süre indikatörleri, sızıntı (O_2 ve CO_2 indikatörleri), tazelik indikatörleri ve biyosensörler yer almaktadır (Kadağan & Gürbüz, 2022).

Gıda ambalajlarında kullanılan sensörler, ürünlerin tazeliğini izlemenin yanı sıra mikrobiyal bozulma, oksidatif acılaşma ve sıcaklıkla ilişkili değişiklikleri tespit etmek amacıyla kullanılır (Kokangül & Fenercioğlu, 2012). Biyosensörler, hücrelerde ve moleküllerde meydana gelen değişiklikleri algılayarak analiz edilecek maddeyi ölçmek ve tanımlamak için kullanılır. Bu sensörler, çok düşük konsantrasyonlardaki maddeleri bile etkili bir şekilde tespit edebilir. Biyosensör, malzemenin biyolojik bileşene bağlanmasıyla orantılı bir sinyal üretir. Örneğin, bir yiyecekte bakteri konsantrasyonu yüksekse, biyosensör güçlü bir sinyal üreterek yiyeceğin güvenli olmadığını işaret eder (Naresh & Lee, 2021).

Zaman-sıcaklık indikatörleri (Time-Temprature Indicators/TTI) renk değiştirerek tüketicileri bilgilendirme amacıyla kullanılmaktadır. Bu indikatörler çevresel faktörlere duyarlıdır, ürünün maruz kaldığı ısı ve nem gibi dış etmenler sonucunda üründe meydana gelen kimyasal, enzimsel, mikrobiyal ve mekanik değişimleri renk değiştirerek belirtmektedir. Bu nedenle de yaygın bir kullanım alanı bulunmaktadır (Şahin Nadeem & Konuk Takma, 2019).

Tazelik indikatörleri, gıdalarda mikrobiyal faaliyet sonucu oluşan metabolitler (örneğin asetik asit, laktik asit, glikoz, etanol, uçucu azot bileşikleri, biyojenik aminler, karbondioksit, ATP bozunma ürünleri ve sülfür bileşikleri) genellikle gıda tazeliğinin değerlendirilmesinde öncelikli olarak ele alınır (Yüceer & Caner, 2023). Tazelik göstergesi, sadece sıcaklığa bağlı biyokimyasal değişiklikleri veya ambalaj sızıntılarını belirtmek yerine, mikrobiyal metabolizma sonucu oluşan ürünleri kullanarak gıda ürünlerinde meydana gelen değişiklikleri gösteren, doğrudan ürün kalite bilgisi sağlamak için geliştirilen bir ambalaj sistemi olarak tanımlanmaktadır (Şahin Nadeem & Konuk Takma, 2019; Yüceer & Caner, 2023).

Sızıntı indikatörleri, modifiye atmosferle ambalajlanan ürünlerde kullanılan bazı gazların varlığını veya yokluğunu tespit eden ve ambalajın bütünlüğü ile olası sızıntılar hakkında bilgi sağlayan sistemlerdir. Ambalajdaki bir sızıntı, koruyucu atmosferi bozarak dış ortamdan mikroorganizmaların içeriye girmesine yol açar. Bu durum mikrobiyal büyümeyi hızlandırır ve ürünün daha kısa sürede bozulmasına neden olur. Sızıntı indikatörleri, kimyasal veya enzimatik reaksiyonlar sonucunda renk değişimi gösterir. Oksijen ve karbondioksit indikatörleri olmak üzere iki tür sızıntı indikatörü yaygın olarak kullanılmaktadır (Özçandır & Yetim, 2010).

4.3. Aktif ambalajlama teknolojisi

Aktif ambalajlama, "Ambalajlı gıdanın kalitesini göz önünde bulundurarak, gıdanın raf ömrünü uzatmak veya güvenliğini ve duyusal özelliklerini geliştirmek amacıyla ambalajlı gıdanın ortamını değiştirmektir." şeklinde tanımlanmaktadır.

Aktif ambalajlama teknolojisindeki temel ilkeler, ambalaj malzemesi olarak kullanılan polimerin kendine özgü özelliklerine veya polimerin içine belirli maddelerin eklenmesine dayanmaktadır. Bu maddelere, organik asitler, enzimler, bakteriyosinler, fungusitler, doğal özler, iyonlar ve etanol örnek verilebilir. Aynı zamanda bu etken maddelerin dahil edilebilmesi amacıyla kâğıt, plastik, metal veya bu malzemelerin karışımlarından elde edilen ambalaj materyalleri kullanılabilir (Tuncalı, 2015).

Aktif ambalajlama teknolojisi, iki ana türde sınıflandırılabilir: istenmeyen maddelerin uzaklaştırılması ve kontrollü salınım (Karagöz & Demirdöven, 2017). İstenmeyen maddeler arasında oksijen, karbondioksit, etilen ve nem yer alır; bu gazların ortamdaki dengesi, gıdaların tazeliği ve raf ömrü için önemlidir (Çelik & Tümer, 2016). Bu gazları tutmak için ambalaj içerisine tablet veya kesecikler şeklinde aktif bileşenler eklenir (Vasile & Baican, 2021). Etilen, oksijen ve karbondioksit tutucular, bu amaçla geliştirilen en önemli aktif ambalajlama sistemleridir (Karagöz & Demirdöven, 2017).

Kontrollü salınımda, gıdaların bozulmalara karşı korunmasında antioksidanlar ve antimikrobiyaller gibi maddelerin kullanımı, aktif ambalajlama sistemleri ile daha etkili hale getirilmektedir (Piergiovanni ve Limbo, 2010). Bu sistemler, uçucu antimikrobiyal ajanların ambalaj filmine veya polimerine entegre edilmesi ya da antimikrobiyal özellik taşıyan polimerlerin kullanılması

ile uygulanır (Kapetanakou & Skandamis, 2016). Yaygın olarak kullanılan antimikrobiyaller arasında doğal uçucu yağlar, etanol, kükürt dioksit, klordioksit, bakteriyosinler, gümüş iyonları ve organik asitler bulunmaktadır (Akgün, 2017).

5. Gıda Endüstrisindeki Uygulamalar

Meyve ve sebzelerde bulunan ve bir bitki hormonu olan etilen, bitkilerde solunum hızını ve olgunlaşmayı desteklemektedir (Sezer & Ayhan, 2017). Etilen gazının ortamda bulunması sebebiyle solunum hızında meydana gelen artış, birçok meyve ve sebzenin olgunlaşmasına ve yumuşamasına sebep olmaktadır. Doku yumuşaması, ürünlerin mikroorganizmalara karşı daha dirençsiz hale gelmesine neden olmaktadır (Tiribolulu, 2019). Dolayısıyla, meyve ve sebzelerin raf ömrünü artırmak ve tazeliğini korumak amacıyla, ambalaj atmosferinde bulunan etilen gazının ortamdan uzaklaştırılması gerekmektedir (Sezer & Ayhan, 2017). Etilen tutucu aktif ambalajlama sistemleri, meyve sebzelerdeki etilenin kontrolü için geliştirilmiş sistemlerden biridir (Aday, 2021).

Gıda sektörü içerisinde yer alan et ve et ürünleri, uygun şekilde işlenmediği, ambalajlanmadığı ve satışa sunulmadığı sürece kısa sürede bozulabilen gıdalardır. Yüksek oranda su ve yine oransal olarak yüksek oranda yağ içeren et ve et ürünleri, lipit oksidasyonuna ve mikrobiyal kontaminasyona duyarlı ürünlerdir (Doğanlar & Ceritoğlu, 2023). Et ve et ürünleri gibi çabuk bozulan gıdaların soğukta muhafazası sırasında mikroorganizma gelişimini kontrol altına alarak raf ömrünü uzatmak amacıyla vakum, modifiye atmosfer (MAP), aktif ve akıllı ambalajlama gibi teknikler kullanılmaktadır (Bağdatlı & Kayaardı, 2010).

Fırıncılık ürünlerinde önemli bir mikrobiyal bozulma türü olan küflenmenin önlenmesi, koku ve renk gibi duyusal kalite özelliklerinin korunabilmesi ve besin değerindeki azalmanın engellenebilmesi için ortamdaki oksijenin uzaklaştırılması gerekmektedir. Oksijenin ortamdan uzaklaştırılabilmesi için kullanılan en yaygın aktif ambalajlama sistemi, oksijen tutuculardır. Bunun yanı sıra, et ürünlerinde olduğu gibi neme duyarlı gıdalardan olan hububat ürünlerinde de nem düzenleyiciler kullanılmaktadır (Postoğlu, 2018).

Çeşitli gıdalarda yapılan çalışmalarda aktif ambalajlama teknolojilerinin kullanıldığı ürünlerde, raf ömrünün ve kalitenin önemli ölçüde korunduğu belirlenmiştir (Çizelge 1).

Çizelge 1. Farklı ambalajlama teknolojilerinin gıda uygulamaları ve raf ömrüne etkileri

Gıda Örneği	Kullanılan Teknoloji	Çalışılan Materyal	Deney Süresi/Ortamı	Sonuç
Çin hünnabı	Etilen tutucu	Nano-Ag, nano-TiO_2, kaolin ve polietilen esaslı nano malzeme	4 °C'de 12 gün	Nano ambalajlı örneklerde, meyve yumuşaklığı, ağırlık kaybı ve esmerleşmenin kontrol örneklerine göre önemli derecede azaldığı tespit edilmiştir (Li ve ark., 2011).
Etilene maruz bırakılmış kivi	Etilen Tutucu	Nano-gümüş, nano-TiO_2 ve montmorillonit esaslı ambalaj materyali	4 °C'de 42 gün	Nanokompozit bazlı ambalajın polietilen ambalajlı kontrol örneğine göre kalite özelliklerini daha yüksek oranda koruduğu belirlenmiştir (Li ve ark., 2011).
Patojen inoküle edilmiş parçalanmış tavuk eti	Antimikrobiyal ambalajlama	%4 gümüş-bakır nanoparçacıklarını ve %50 tarçın esansiyel yağını içeren lineer alçak yoğunluklu polietilen	4 °C'de 21 gün	Depolama esnasında *Salmonella typhimurium* ve *Campylobacter jejuni*'nin gelişiminin tamamen engellendiği ve *Listeria monocytogenes*'in ise gelişiminin büyük ölçüde yavaşlatıldığı belirlenmiştir (Ahmed ve ark., 2018a; 2018b).
Frankfurter sosis	Antimikrobiyal ambalajlama	Nisin içeren metil ve hidroksi metil selüloz ile kaplanmış düşük yoğunluklu polietilen film (LDPE)	4 °C'de 60 gün	156.3 IU/ml düzeylerindeki nisin frankfurter sosislerin yüzeyine inoküle edilen *L. monocytogenes* seviyesinde önemli bir değişme sağlamazken; 7500 ve 10 000 IU/ml düzeylerindeki nisinin yaklaşık 4 log'luk azalma sağladığı bulunmuştur (Çelebi Sezer & Bozkurt, 2021).
3 günlük fermantasyon ve ısıl işlemden geçirilmiş sucuk	Antimikrobiyal ambalajlama	Kitosan ve gümüş katkılı zeolit (AgZeo) ile formüle edilmiş kılıf	4 °C'de 12 gün	Aktif kılıfların kullanımının toplam aerobik bakteri ve LAB sayısını azalttığı belirlenmiştir (Çelebi Sezer & Bozkurt, 2019).

Çizelge 1. Farklı ambalajlama teknolojilerinin gıda uygulamaları ve raf ömrüne etkileri (devam)

Gıda Örneği	Kullanılan Teknoloji	Çalışılan Materyal	Deney Süresi/Ortamı	Sonuç
Kiraz domates (*Lycopersicon esculentum L.*)	Etilen Tutucu ve MAP	Yapısında etilen tutucu katkı içeren düşük yoğunluklu polietilen (LDPE) ambalajda Katkısız LDPE ambalajda pasif MAP altında	4 ºC ve 10 ºC'de %60 bağıl nemde 32 gün	En az etilen üretimi 4 ºC'de etilen tutucu içeren aktif ambalajlarda gerçekleşmiş ve fiziksel, kimyasal ve duyusal analiz sonuçları da dikkate alındığında etilen tutucu içeren aktif ambalajlarda kiraz domatesin 4 ºC'de 32 gün raf ömrüne sahip olduğu tespit edilmiştir (Tiribolulu & Ayhan, 2023).
Mantar (*Agaricus bisporus*)	Etilen Tutucu ve pasif MAP	Pasif MAP altında yapısında Zeolit bulunan düşük yoğunluklu polietilen (LDPE) Pasif MAP altında düşük yoğunluklu polietilen (LDPE)	4 °C'de %50 bağıl nemde 16 gün	Ambalajsız mantarlarda %20'ye yakın bir ağırlık kaybı görülürken Zeolit içeren ve içermeyen LDPE ambalajlarda ağırlık kaybı açısından önemli bir değişim gözlenmemiştir. Ambalajsız mantarların 4 günlük kabul edilebilirliği zeolit içeren ve içermeyen LDPE ambalajlar sayesinde 8 güne çıkarılmıştır (Kütahneci ve ark., 2020).
Ön kurutma işlemi (180°C'de 4 dakika) ile nem değeri %34'e düşürülmüş mantı	MAP	%80 CO_2 + %20 N_2 %60 CO_2 + %40 N_2 %40 CO_2 + %60 N_2 %20 O_2 + %40 CO_2 %40 N_2	4 °C'de 90 gün	Depolama süresince hiçbir mantı örneğinde *Escherichia coli*, sülfit redükte eden anaerob bakteri ve *Salmonella spp*. tespit edilmemiştir. %80 CO_2 içeren ambalajdaki toplam aerobik mezofilik mikroorganizma ve küf-maya sayısı diğer ambalajlara göre daha düşük seviyede seyretmiştir. Kontrol örneğinde yüksek mikroorganizma sayısı ve lipid oksidasyonu görülmüş olup, bu durum ürünlerin 60.günden itibaren ürünlerin duyusal kabul edilebilirlik sınırının altında kalmasına yol açmıştır. MAP uygulamasında ambalaj içerisindeki CO_2 miktarının artışı mantılardaki tekstürün ve lezzetin ilk güne yakın değerlerde olmasına katkıda bulunmuştur (Akkaya, 2024).
Hatay peyniri	MAP	Modifiye atmosfer (%50 CO_2 ve %50 N_2) Hava (%21 O_2 ve %79 N_2) Vakum altında farklı ambalaj materyalleri ile Koekstrude PA/PE OPET/OPA/CPP PP/PA/EVOH/PE	4 °C'de 60 gün	Ambalajsız muhafaza edilen Hatay peynirinin raf ömrü kuruma, ufalanma, sararma, tat bozulması gibi sebeplerden dolayı 5 gün olarak belirlenirken ambalajlı uygulamalardaki ürünlerin tüm duyusal özellikleri 60 gün süresince kabul edilebilir bulunmuştur. En düşük gaz geçirgenliğine sahip malzeme (PP/PA/EVOH/PE) ile ambalajlanmış ve vakum uygulanmış ürünün başlangıç kalitesini 60 gün boyunca en iyi şekilde koruduğu belirlenmiştir (Toplu ve ark., 2023).
Levrek (*Dicentrarchus labrax*) filetosu	Antimikrobiyal ve vakum ambalajlama	Farklı konsantrasyonlarda (%0,2, %0.4 ve %0.8) nisine daldırılmış levrekler polyamid bazlı poşetler ile vakum ambalajlama	4±2 °C'de 18 gün	Nisin uygulanarak vakum ambalajlanmış levrek örneklerindeki lipid oksidasyonunun kontrol örneğine kıyasla daha düşük olduğu belirlenmiş ve en yüksek çoklu doymamış yağ asidi içeriğinin %8 nisin ile muamele edilmiş levrekte bulunduğu belirlenmiştir. Doymamış yağ asitlerinde görülen oto-oksidasyonun üründe kimyasal bozulmalara sebep olduğu bilindiğinden, nisin uygulamasının oto-oksidasyon reaksiyonlarını geciktirdiği, dolayısıyla ürünün raf ömrüne katkıda bulunduğu düşünülmektedir (Uçar ve ark., 2020).

Çizelge 1. Farklı ambalajlama teknolojilerinin gıda uygulamaları ve raf ömrüne etkileri (devam)

Gıda Örneği	Kullanılan Teknoloji	Çalışılan Materyal	Deney Süresi/Ortamı	Sonuç
Pandispanya kek	MAP	%50 CO_2: %50 N_2, %100 N_2	15-20 °C, %53-61 bağıl nem	Kontrol grubunun raf ömrü 3 gün olup 6.günün sonunda küf gelişimi gözlendiği bildirilmiştir. %100N_2 ile ambalajlanmış üründe 13 güne kadar herhangi bir küf gelişimi gözlenmezken %50CO_2: %50N_2 ile ambalajlanmış ürünlerin %60'ında küf gelişimi gözlenmiştir. %100N_2 ile ambalajlanmış üründeki mezofilik aerobik bakteri sayısının %50CO_2: %50N_2 ile ambalajlanmış ürüne göre daha az olduğu belirlenmiştir. %50CO_2: %50N_2 ile modifiye atmosferde ambalajlanmış kek örneklerinin raf ömrünün kontrol grubu örneklerine göre 2-3 gün daha uzun olduğu belirlenmiştir (Uçar & Hayta, 2012).
Dilimlenmiş buğday unu ekmeği	Etanol tutucu ve Oksijen tutucu	PET-SiOx//LDPE ambalajlama materyali ile ambalajlanmış kimyasal ticari koruyucu içeren, etanol tutucu içeren ve hem etanol hem de oksijen tutucu içeren olmak üzere dört farklı örnek	20 °C'de 30 gün	Bu örneklerde 30 günlük depolama sonunda küf ve maya sayımı sırasıyla şöyledir: 5.1; 3.8; 2.0 ve 2.0 kob/g. *Bacillus cereus* sayısı ise: 4,7; 2.5; 2.3 ve 2.0 kob/g'dır. Lipid oksidasyonu ve uçucu bileşenlerin kaybından dolayı koruyucu içermeyen ve kimyasal ticari koruyucu içeren örneklerde depolama süresince aroma kayıpları meydana gelmiştir. Ne etanol tutucu içeren örneklerde ne de hem etanol hem de oksijen tutucu içeren örneklerde koku, tat ve tekstür açısından olumsuz bir etki tespit edilmemiştir. Duyusal (tekstürel) ve mikrobiyolojik verilere dayanarak, koruyucu içermeyen örnekler için raf ömrünün 4 gün, kimyasal ticari koruyucu içeren örnekler için 6 gün, etanol tutucu içeren örnekler için 24 gün ve hem etanol hem de oksijen tutucu içeren örnekler için en az 30 gün olarak belirlenmiştir (Latou ve ark., 2010).

6. Sonuç

Aktif ambalajlama uygulamaları, gıdaların raf ömrünü uzatmada dikkate değer bir etki göstermektedir. Bu yöntem hem üreticiler hem de tüketiciler için önemli avantajlar sunarak gıda tedarik zincirinde önemli iyileştirmeler sağlamaktadır. Yapılan çalışmalar, meyve ve sebzelerde yaygın olarak kullanılan etilen tutucuların meyve yumuşaklığı, ağırlık kaybı ve esmerleşme gibi parametreleri önemli ölçüde azalttığını göstermektedir. Et ürünlerinde kullanılan antimikrobiyal ambalajlama uygulamalarının bazı mikroorganizmaların gelişimini tamamen engellediği, bazılarının ise üremesini ciddi derecede yavaşlattığı görülmektedir. Ayrıca, et ürünlerinde kullanılan nem tutucuların, üründeki su aktivitesini düşürerek bazı mikroorganizmaların büyümesini önemli ölçüde yavaşlattığı ifade edilmektedir. Hububat ürünlerinde yaygın kullanılan oksijen tutucular ise aerobik mikroorganizmaların gelişimini geciktirmekte ve ürünlerin korunmasına katkı sağlamaktadır. Bu bağlamda, aktif ambalajlama teknikleri, gıdaların raf ömrünü uzatmanın yanı sıra, kalite, tazelik ve güvenilirliği yüksek düzeyde muhafaza etmektedir.

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