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Research Article
(Araştırma Makalesi)

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Identifying the dynamics that make attractive the valley landscapes for hiking: Cappadocia Zemi Valley (Türkiye)

Doğa yürüyüşünde vadi peyzajlarını çekici kılan dinamiklerin belirlenmesi: Kapadokya Zemi Vadisi (Türkiye)

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ABSTRACT

Objective: The changing living conditions of today's society due to rapid urbanization have brought about the need for physical and spiritual renewal. In this context, people who want to socialize, discover new places, and escape their daily routines are increasingly inclined toward tourism and recreation activities. Among these, nature walks stand out as a popular option. This study aims to identify the distinguishing characteristics of Zemi Valley, one of the valleys in the Cappadocia, by determining its natural and cultural landscape features and examining visitors' perceptions and emotions regarding these features during nature walks.

Material and Methods: The main material of the study is the Zemi Valley. The method of the study consists of literature review, field study to determine natural and cultural landscape features, observation of participant behaviors by participating in a hiking activity in the valley, survey study to determine the perceptions and feelings of participants about the hiking experience, and statistical analysis of the surveys.

Results: Participants have different motivations for hiking, which can differ based on gender. The results indicate that the valley possesses unique landscape features that evoke positive emotions and enhance the hiking experience.

Conclusion: Based on the findings, recommendations are provided to contribute to planning studies aimed at promoting, conserving, and ensuring the sustainable use of the valley's unique qualities.

Keywords: Nature walking, Nevşehir, protected areas, recreation, tourism

ÖZ

Amaç: Günümüz toplumunun hızlı kentleşmeyle birlikte değişen yaşam koşulları, fiziksel ve ruhsal olarak yenilenme ihtiyacını beraberinde getirmiştir. Özellikle kentlerde doğayla etkileşimi azalan insanlar bu bağı kurmak için doğaya dayalı aktivitelere yönelmektedir. Bunlar içerisinde de doğa yürüyüşleri popüler bir seçenek olarak öne çıkmaktadır. Bu çalışmada Kapadokya Bölgesi vadilerinden biri olan Zemi Vadisi'nin doğal ve kültürel peyzaj özelliklerinin, ziyaretçilerin doğa yürüyüşü sırasında bu özelliklere ilişkin algılarının ve duygularının belirlenerek vadiyi farklı kılan karakteristik özelliklerin ortaya konulması amaçlanmıştır.

Materyal ve Yöntem: Çalışmanın ana materyalini Zemi Vadisi oluşturmaktadır. Çalışmanın yöntemi literatür taraması, doğal ve kültürel peyzaj özelliklerini belirlemeye yönelik arazi çalışması, vadide yürüyüş etkinliğine katılarak katılımcı davranışlarının gözlemlenmesi, katılımcıların yürüyüş deneyimine ilişkin algı ve duygularını belirlemeye yönelik anket çalışması ve anketlerin istatistiksel analizi aşamalarından oluşmaktadır.

Araştırma Bulguları: Katılımcılar doğa yürüyüşü yapmada cinsiyete göre değişiklik gösterebilen farklı motivasyonlara sahiptir. Vadinin, doğa yürüyüşünde katılımcılar üzerinde farklı pozitif duyguları uyandıran ve yürüyüş deneyimini zenginleştiren karakteristik peyzaj özelliklerinin olduğu belirlenmiştir.

Sonuç: Elde edilen bulgular sonucunda vadinin özgün niteliklerinin tanıtılması, korunması ve sürdürülebilir kullanımına yönelik bölgede yapılacak planlama çalışmalarına katkı sağlayacağı düşünülen öneriler sunulmuştur.

Anahtar sözcükler: Doğa yürüyüşü, Nevşehir, korunan alanlar, rekreasyon, turizm

INTRODUCTION

Today, urbanization and rapid population growth have considerably altered people's lifestyles and daily routines. City dwellers spend most of their time in enclosed environments such as homes, workplaces, and schools. This fast-paced and monotonous urban lifestyle leads to physical and mental fatigue. In response, people increasingly seek opportunities to escape daily stress, reconnect with nature, and rejuvenate through recreational and tourism activities. Rural areas, with their tranquil environments and natural beauty, have become prominent destinations for nature-based recreational activities, which continue to increase and diversify in type and scope (Aklıbaşında et al., 2012; Çelik Çanga & Şenay, 2023). Among these diverse activities, nature walking -including both trekking and hiking- has gained widespread popularity as a form of active engagement with the environment.

In the literature, "trekking" is defined as walks organized in accordance with age groups and with limited time in natural conditions that show certain difficulties and characteristics (Kasalak & Sarı, 2023; Topay, 2003). Trekking involves moving from one point to another in nature and is generally a light-paced walk; however, the duration and intensity may vary depending on the difficulty level of the designated route (Şenel, 2023). The main purpose of trekking is to enjoy nature, closely interact with the environment and reach certain places such as mountain peaks, lakes, or natural valleys (Nugroho & Winarto, 2024). Conversely, "hiking" refers to shorter, single-day nature walks conducted on forest roads, in wild but safe areas, or within designated natural sites (Ardahan & Mert, 2013). Hiking, which means daily nature walks/nature trips that start in the morning and end in the evening, is intertwined with tourism (Akkuş & Gül, 2022). Being a low-level adventure activity makes it popular and offers significant tourism value worldwide (Molokač et al., 2022).

According to Aydıngün (1997); nature walk is a nature sport that can be done only for walking purposes or as a means to do another nature-based sport (Ergüven, 2022). An important feature of hiking is the discovery of natural beauties and monuments. The focus of nature exploration is the topographic and hydrological features of the landscape, flora and fauna, geological development of the area, special geological formations, and nature protection (Molokač et al., 2022).

Nature walks offer individuals the opportunity to be in touch with nature, while also providing physical activity opportunities, thus promoting a healthy life. While allowing individuals to relax mentally and physically, they also provide an opportunity to escape from the mechanical and congested lifestyle brought by modernity (Atari & Feldman, 2023). Studies have demonstrated that nature experiences reduce stress levels, enhance mental health, improve cognitive performance, strengthens psychological resilience, and increase overall life satisfaction (Ardahan, 2012; Bratman et al., 2012; Stier-Jarmer et al., 2021; Karabulut, 2024). In addition, nature walks help people feeling happier and more peaceful by providing opportunities for social interaction and in-group communication (Marselle et al., 2019; Huber et al., 2023).

In this context, tourism activities and movements focused on trekking, hiking and mountain climbing are becoming widespread worldwide. Türkiye has serious opportunities in this field due to its cultural heritage and diverse geographical resources (Döner & Doğan, 2022). One of Türkiye's most renowned regions in this regard is Cappadocia, distinguished by its extraordinary geological formations, fairy chimneys, rock-carved churches, and deep-rooted cultural history. Cappadocia Region is the area covered by the provinces of Nevşehir, Aksaray, Niğde, Kayseri and Kırşehir. The narrower area, which is called the Core Cappadocia Region, consists of Göreme, Uçhisar, Ürgüp, Avanos, Derinkuyu, Kaymaklı, Ihlara and its surroundings (Anonymous, 2024a; Belber & Erdoğan, 2019). Located within the Rocky Cappadocia subregion, Göreme stands out as the focal point for nature and cultural tourism. Its unique landscape, which is recognized by UNESCO, offers various valleys ideal for nature walks, one of which is Zemi Valley.

Despite the growing interest in nature-based tourism in Cappadocia, there is a significant lack of academic research focusing on the natural and cultural landscape features of valleys, particularly the Zemi Valley. This study aims to fill this gap by providing a comprehensive analysis of the valley's features and visitor experiences, thus contributing to the literature on sustainable nature-based tourism and landscape assessment. In line with these goals, the study seeks to answer the following research questions:

- What are the distinctive natural and cultural features of Zemi Valley that support nature-based recreation?
- How do visitors perceive the landscape qualities and recreational value of the valley?
- What recommendations can be made to ensure the sustainable use and conservation of Zemi Valley within the tourism context?

By integrating landscape assessment with visitor perceptions, this study provides valuable insights for policymakers, planners, and tourism professionals aiming to balance conservation with recreational use in nature-sensitive areas like Cappadocia.

MATERIALS and METHODS

Study area

This research was approved by Nevşehir Hacı Bektaş Veli University Scientific Research and Publication Ethics Committee on 05.02.2025 with document number 2025.01.24. The main material of the study is the Zemi Valley located in Göreme, one of the important tourism centers of the Cappadocia Region (Figure 1). Göreme is a town in the Central District of Nevşehir and is 12 km away from the city center. The Zemi Valley spans an approximate length of 5.8 km and can be accessed from a section of the Nevşehir-Ürgüp Highway between Uçhisar and Ortahisar, as well as from Museum Street in central Göreme.

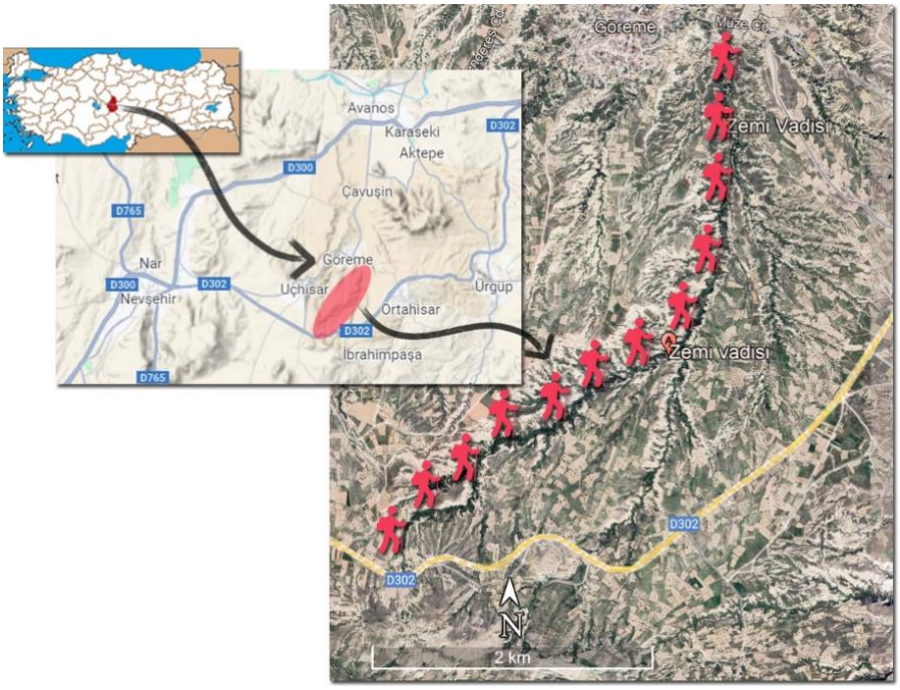

Figure 1. Location map of Zemi Valley.

Şekil 1. *Zemi Vadisi konum haritası.*

Methods and stages of the study

Given the high intensity of tourism and recreation activities in the region, valley landscapes draw attention with their unique ecological and visual features. This study consists of four stages to analyze the elements that make Zemi Valley attractive for nature walks, based on user impressions and experiences:

In the first stage of the study, participation was ensured in a group hiking event organized in the Zemi Valley in June. The natural and cultural landscape features of Zemi Valley were determined in detail through on-site examinations. The observations focused on the valley's topographic structure, surface formations, floristic elements (dominant and remarkable species), fauna, hydrological features, microclimatic characteristics, landscape beauty and difficulty level of the trail (slope, surface condition, walking comfort). In order to document all these features, notes were recorded, and photographs were taken systematically along the walking route. During this event, the activity was directly experienced, and participant behaviors were observed.

In the second stage, following the field activity, office-based analyses were conducted to evaluate the observational notes and photographs. Based on these evaluations, a structured questionnaire form was developed to assess participants' experiences and impressions of the valley. The form consists of three parts: (1) questions aiming to determine the demographic characteristics of the participants, (2) their nature walk tendencies and the factors affecting these tendencies, (3) their perceptions and feelings about their walks in Zemi Valley. The survey questions were prepared in a multiple-choice, open-ended and 5-point Likert-type grading format in accordance with the information desired to be obtained. In addition, in order to determine the areas that the participants liked the most on the walking route, 30 photographs with different qualities were selected from 300 photographs taken with a semi-professional camera during the event and the participants were asked to choose the ones they liked the most. Then, the survey was conducted with 30 volunteers among the people who participated in the hiking event.

In the third stage, the collected data were transferred to the SPSS 21.0 program and the percentages of the answers to the options of the multiple-choice questions and the frequency, percentage and score averages of the graded questions were analyzed.

Finally, in the fourth stage, the Chi-Square test was applied to examine the relationships between the gender, age and education status of the individuals and their reasons for hiking, the emotions they felt during hiking and the factors that affected them during hiking.

In the light of the findings, the landscape character of the valley, its ecological and recreational importance were revealed, and planning suggestions based on the sustainability of the valley within the balance of protection and use were presented.

RESULTS

Natural and cultural landscape characteristics of Zemi Valley

Cappadocia is home to some of the most distinctive surface formations in the world, shaped by volcanism, tectonic activity, and erosion (Dirik, 2009). Göreme is located in a volcanic region between Erciyes and Hasan Mountains in the Central Anatolia Region. Göreme, known as the capital of Cappadocia, has a geography consisting of plateaus, high hills, valleys and high plains separated by these valleys (Anonymous, 2024b). As a result of the erosion of the soils formed by volcano tuffs by surface waters, narrow and deep valleys have formed. The deep side valleys in this region covered with volcanic tuffs, opening to the Kızılırmak Valley from the south and north; constitute the main recreational areas of the region with their rich vegetation and water resources as well as their geological, geomorphological and archaeological values (Anonymous, 2024c).

Zemi Valley is entered from Uçhisar from a steep slope formed by tuff layers. The slopes surrounding the valley have an undulating geomorphological structure shaped by erosion processes caused by surface waters. These unique characteristics provide an aesthetic contribution to the natural landscape of the region and create attractive views for visitors (Figure 2).

Figure 2. Views from the entrance of the Zemi Valley on the Uçhisar side.

Şekil 2. *Zemi Vadisi'nin Uçhisar tarafındaki girişinden görünümler.*

The valley surroundings and the upper part of the slopes are dominated by steppe vegetation. However, the microclimate characteristics of the valley differentiate the flora in the valley and create a dense green texture, providing a rich vegetation (Figure 3). In the valley, where broad-leaved trees are dominant, fruit trees such as *Malus* sp., *Prunus* sp., *Pyrus* sp., *Cydonia* sp., *Crataegus* sp., *Juglans* sp., *Amygdalus* sp. and *Elaeagnus* sp., as well as species such as *Populus* sp., *Salix* sp., *Rhus* sp. and *Tilia* sp., are also found.

Along the hiking route, flowering shrub species such as *Colutea cilicica, Viburnum opulus*, *Berberis crataegina* and *Rosa canina*, as well as *Vitis* sp., which plays an important role in the region's agricultural activities, are noteworthy. *Iris* sp. flowers planted in various parts of the valley offer impressive views to the visitors who are hiking. In addition, the majority of the plants detected in the valley consist of species that also attract attention with their autumn leaf coloration. This gives the valley rich and impressive appearances in terms of color at different periods of the year.

Figure 3. Views from the vegetation of Zemi Valley.

Şekil 3. *Zemi Vadisi'nin bitki örtüsünden görünümler.*

In addition to the vegetation that makes the valley different, the geomorphological shapes of the slopes that form the backdrop behind the plants offer impressive views specific to the region. Passing through rocks shaped by volcanic tuffs and natural rock tunnels in places adds a unique excitement to the hiking experience.

The hiking trail is narrow and uneven, with a moderate difficulty level. The path has a rolling structure in some areas and wooden bridges have been placed at some points to facilitate the passage. Streams form in the valley from time to time due to rainfall, while, in drier periods, only puddles or thin water channels are observed along the route. Since no source has been reached in the literature regarding the animal species in the Zemi Valley, no scientific determination has been made regarding the fauna. However, the different bird sounds heard throughout the hike indicate that the region may have a rich bird fauna.

Survey findings of valley hiking

Among the 30 survey participants, 60% were female and 40% male. The ages of the participants ranged from 25 to 60, of which 23.3% between the ages of 25-34, 53.4% between the ages of 35-44, 13.3% between the ages of 45-54, and 10% over the age of 55. The majority held undergraduate (56.7%) and postgraduate (36.7%) degrees.

According to the question asked to the participants residing in Nevşehir to determine their interest in nature walks, it was determined that 70% of the participants walk in nature when they find the opportunity in their free time. Participants generally prefer the valleys in the Göreme, Uçhisar, Ortahisar, Ürgüp regions, but they also go on nature walks in areas of natural, historical or cultural importance such as the banks of the Kızılırmak River in Avanos and the Cappadocia region.

When the participants were asked "What are your reasons for hiking?", it was determined that the most important factors in hiking were stress relief and relaxation ($\bar{X}$=3.87; 73.3%). In addition, valuing being in touch with nature ($\bar{X}$=3.80; 70%) and desire to discover new places ($\bar{X}$=3.77; 70%) stand out as strong sources of motivation in performing this activity. In addition, it was determined that hiking activities were done as a social activity for purposes such as spending time with relatives ($\bar{X}$=3.70; 70%), observing nature ($\bar{X}$=3.70; 66.7%) and healthy living ($\bar{X}$=3.57; 66.7%) (Table 1, Figure 4).

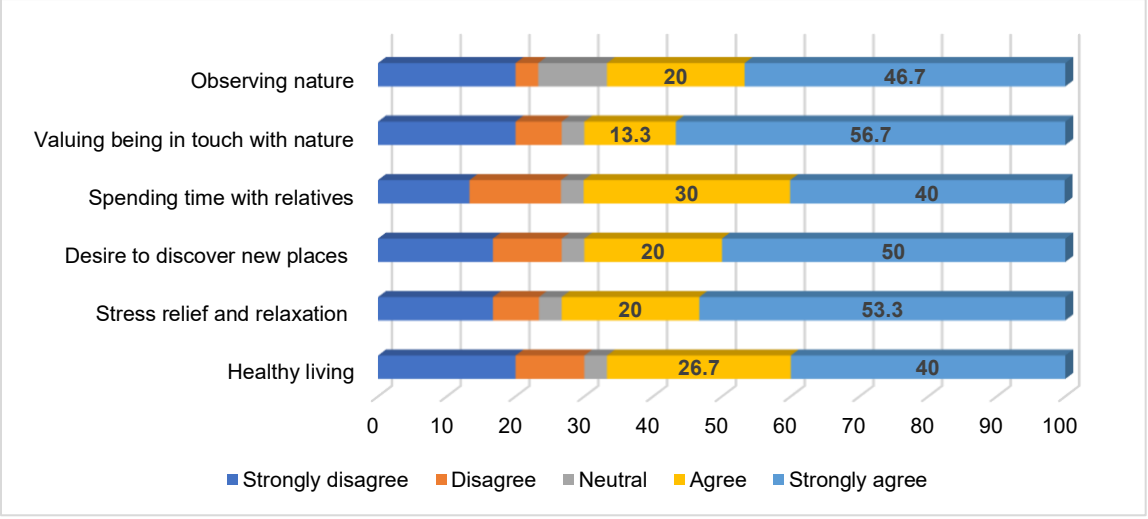

Figure 4. Percentages of participants' responses to the factors that influence their nature walks.

Şekil 4. *Katılımcıların doğa yürüyüşü yapmalarındaki etkenlere verdiği cevap yüzdeleri.*

Table 1. Factors contributing to participants' nature walks

Çizelge 1. *Katılımcıların doğa yürüyüşü yapmalarındaki etkenler*

What are your reasons for hiking?	*Frequency*					
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	$\bar{X}$
Healthy living	6	3	1	8	12	3.57
Stress relief and relaxation	5	2	1	6	16	3.87
Desire to discover new places	5	3	1	6	15	3.77
Spending time with relatives	4	4	1	9	12	3.70
Valuing being in touch with nature	6	2	1	4	17	3.80
Observing nature	6	1	3	6	14	3.70

A survey was applied to participants; 53.3% of them were hiking in Zemi Valley for the first time, while 46.7% had hiked in the valley before. When the participants were asked about the feelings they felt while hiking in the valley, the highest scores were given to the options of spiritually relaxing ($\bar{X}$=3.97; 76.7%) and pleasing ($\bar{X}$=3.97; 76.6%). The mean scores of the other answers were also quite high, and the participants found the valley to be refreshing ($\bar{X}$=3.90), interesting ($\bar{X}$=3.80), quiet/calm ($\bar{X}$=3.80), exciting ($\bar{X}$=3.70), funny ($\bar{X}$=3.67) and mysterious ($\bar{X}$=3.27), respectively (Table 2).

Table 2. Emotions felt by participants during the Zemi Valley walk

Çizelge 2. *Zemi Vadisi yürüyüşünde katılımcıların hissettiği duygular*

What did you feel while hiking in the Zemi Valley?	*Frequency*					
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	$\bar{X}$
It was spiritually relaxing.	7	0	0	3	20	3.97
It was interesting.	6	2	1	4	17	3.80
It was pleasing.	6	1	0	4	19	3.97
It was exciting.	5	3	2	6	14	3.70
It was refreshing.	7	0	0	5	18	3.90
It was calm.	4	2	3	8	13	3.80
It was exhausting.	7	10	6	3	4	2.57
It was funny.	7	0	1	10	12	3.67
It was mysterious.	3	8	5	6	8	3.27

Among the options, the parameter of finding the hiking experience exhausting received a score of 2.57. However, it was observed that the rate of those who answered 'agree' and 'strongly agree' to this question was low (23.3%) (Figure 5).

In order to determine the observations of the participants who walked in the Zelve Valley, which has different characteristics from the regional landscape character, the question 'What caught your attention or impressed you while walking in the Zemi Valley?' was asked. According to the survey results, the landscape features that attracted the participants' attention the most were the shapes of the hills surrounding the valley and the tuff formations ($\bar{X}$=3.93) and the floristic features ($\bar{X}$=3.89) (Table 3).

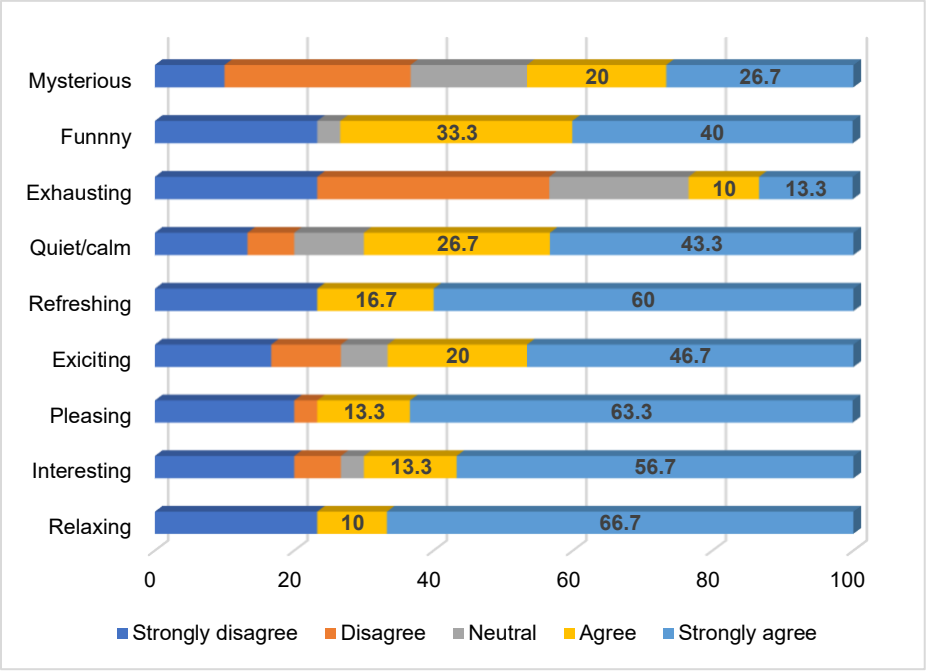

Figure 5. The acceptance rate of participants' emotional options in the Zemi Valley walk.

Şekil 5. *Zemi Vadisi yürüyüşünde katılımcıların duygulara yönelik seçeneklere katılma oranı.*

Table 3. Natural landscape features that attract the attention of walkers in Zemi Valley

Çizelge 3. *Zemi Vadisi'nde yürüyüş yapanların dikkatini çeken doğal peyzaj özellikleri*

What caught your attention or impressed you while walking in the Zemi Valley?		*Frequency*					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree	$\bar{X}$
Fauna	Bird sounds	5	3	2	3	17	3.80
Flora	Flowering plants	5	2	2	4	17	3.87
	Grapevines	2	5	2	5	16	3.93
	Fruit trees	5	3	2	4	16	3.77
	Dense vegetation	4	1	4	4	17	3.97
	Vegetation diversity	5	1	2	6	16	3.90
Hydrological Characteristics	Water resources	4	4	1	9	12	3.70
Geological and Geomorphological Features	Tuff formations and surface features	2	4	3	6	15	3.93
	Dynamic topography	3	4	1	10	12	3.80
Climate	Microclimatic features	3	2	2	12	11	3.87

The remarkable floristic features of the valley were listed as follows; dense vegetation ($\bar{X}$=3.97), grapevine plants ($\bar{X}$=3.93), vegetation diversity ($\bar{X}$=3.90), flowering plants ($\bar{X}$=3.87) and fruit trees ($\bar{X}$=3.77). It was observed that all parameters related to natural landscape features received high scores and that the valley was generally quite striking and impressive (Figure 6).

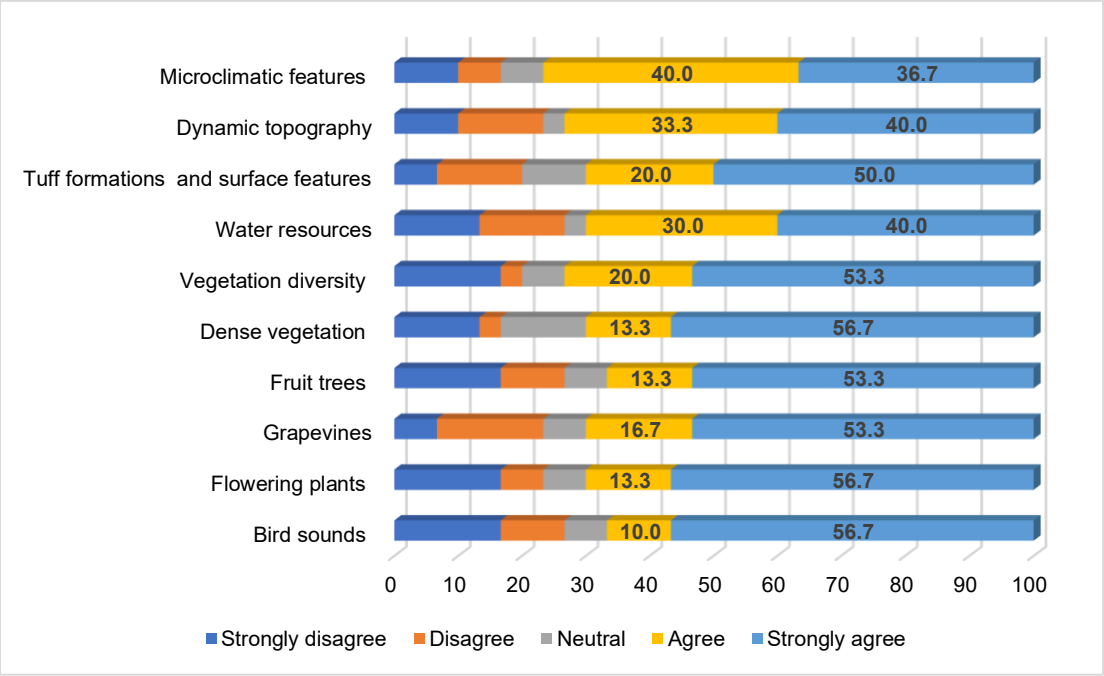

Figure 6. The rate of influence of natural landscape features of Zemi Valley on participants.

Şekil 6. *Zemi Vadisi doğal peyzaj özelliklerinin katılımcıları etkileme oranı.*

At the same time, the microclimatic features of the valley had a positive effect on the hikers. When the participants were asked about their general satisfaction level with the valley hike, 93.3% said they were “very satisfied” and 6.7% said they were “satisfied”.

In order to evaluate the general experience of the walk, participants were asked to evaluate the valley by giving a score between 1 and 5. 83.3% of the participants described the view of the valley as "very beautiful" and 16.7% as "beautiful". In addition, 30 photographs reflecting different landscape features of the valley were presented to the participants and they were asked to choose the ones they liked the most. In this selection, photographs showing characteristic geomorphological formations and flowering plants in the region were among the most liked images (Figure 7).

Figure 7. Participants' most liked images from the landscapes formed by natural and cultural landscape elements of Zemi Valley.

Şekil 7. *Zemi Vadisi doğal ve kültürel peyzaj elemanlarının oluşturduğu manzaralaradan katılımcıların en beğendiği görüntüler.*

Findings regarding Chi-Square analysis

When the relationship between the demographic characteristics of the individuals participating in the walk in Zemi Valley and the reasons for walking in nature, the emotions they felt during the walk and the factors that attracted their attention in the valley was examined, significant relationships were found between gender and some options (p<0.05) (Table 4). However, no significant relationship was found between the age and education status.

Among the reasons for the participants to walk in nature, the motivations of healthy living (X^2=10.492; p=0.014), valuing being in touch with nature (X^2=9.174; p=0.019) and observing nature (X^2=11.755; p=0.005) were found to be higher in female participants than in male participants. In addition, female participants stated that they felt happier during the valley walk experience compared to male participants (X^2=7.359; p=0.038). Flowering plants, one of the natural landscape elements of the valley, attracted the attention of women more than men (X^2=9.028; p=0.025).

Table 4. Options with significant relationships with gender from the demographic characteristics of the individuals participating in the survey

Çizelge 4. *Ankete katılan bireylerin demografik özelliklerinden cinsiyet ile anlamlı ilişkiler bulunan seçenekler*

Factor	Sub-factor	Gender	
		X^2	P
Reasons for hiking	Healthy living	10.492	0.014*
	Stress relief and relaxation	6.490	0.124
	Desire to discover new places	6.087	0.149
	Spending time with relatives	7.695	0.060
	Valuing being in touch with nature	9.174	0.019*
	Observing nature	11.755	0.005*
Emotions while hiking in Zemi Valley	Relaxing	3.674	0.148
	Interesting	4.569	0.336
	Pleasing	7.359	0.038*
	Exciting	7.660	0.077
	Refreshing	3.719	0.216
	Quiet/calm	5.343	0.250
	Exhausting	3.061	0.617
	Funny	4.416	0.174
	Mysterious	4.201	0.414
Attractive and influencing factors in Zemi Valley	Bird sounds	5.041	0.275
	Flowering plants	9.028	0.025*
	Grapevines	5.322	0.203
	Fruit trees	3.964	0.420
	Dense vegetation	6.639	0.101
	Vegetation diversity	4.446	0.343
	Water resources	6.447	0.137
	Tuff formations and surface features	8.005	0.056
	Dynamic topography	6.994	0.101
	Microclimatic features	5.994	0.152
* Statistically significant relationship at 0.05 level			

DISCUSSION and CONCLUSION

The Cappadocia Region is a globally recognized destination on the UNESCO World Heritage List due to its unique natural and cultural features. Its unique geomorphological structures shaped by volcanic eruptions, fairy chimneys, underground cities and rich cultural texture that has hosted various civilizations throughout history, make the region special in both visual and

To preserve these unique features and pass them on to future generations, it is crucial to adopt sustainable tourism and recreation approaches. In this context, research studies addressing the natural and cultural heritage of the region in a multidimensional manner both contribute to the scientific literature on tourism and recreation activities in protected areas and provide a scientific basis for regional planning.

This study examined Zemi Valley, one of the valleys in the Cappadocia Region, from the perspective of nature walking as a nature-based tourism and recreation activity. The landscape features of the valley were analyzed through observations and how these features were perceived by users walking in the valley was assessed. The results show that the natural landscape elements of the Zemi Valley were found highly impressive by visitors. Participants described their hiking experiences in the valley with positive emotions such as "relaxing" and "pleasing" and also perceived the valley as refreshing, calm, interesting,

exciting, fun, and mysterious. This situation reveals that the valley offers a dynamic and multidimensional experience. Studies by Bratman et al. (2012) and Stier-Jarmer et al. (2021) emphasize that nature walks reduce stress levels and improve mental health, and the hiking experiences in Zemi Valley confirm this effect.

Another aspect of nature walks such as trekking and hiking is the increase in individuals' interaction with the environment and the discovery of nature (Molokač et al., 2022). Among the landscape features of the Zemi Valley, the 'geomorphological formations' attracted the participants' attention the most. Nature walks in the valley with different surface shapes not only provide physical benefits but also increase the participants' desire to discover and learn about nature.

Another feature that attracts the attention of hikers in Zemi Valley is the ‘dense green texture’. Within this texture, grape plants (grapevines), fruit trees and other flowering plants with cultural characteristics are watched with interest by hikers. Studies have also shown that dense and diverse vegetation provides aesthetic value and recreational appeal (Harris et al., 2017), and the presence of flowering plants that create a color effect by covering an area increases visual preference (Aklıbaşında & Bulut, 2018).

In nature walks where participants are on the move, the climatic characteristics of the environment are important in terms of walking comfort. Valleys are microclimatic areas that direct wind movements, limit solar radiation and provide moisture balance due to their natural structure. In addition, studies show that plants increase thermal comfort by lowering the temperature through shading and evaporation (Bowler et al., 2010; Shashua-Bar et al., 2011; Fujiwara et al., 2024). In this regard, the microclimate characteristics of Zemi Valley create a cool and tranquil atmosphere, providing participants with both physical and emotional relaxation.

Individuals may have different motivations for engaging in nature walks based on factors such as gender. In general, nature walks stand out as an important recreational activity in line with the desire of people who love to be in touch with nature to evaluate their free time and relieve stress. Chai-allah et al. (2023) emphasized the health and well-being benefits of physical activities in natural landscapes by associating outdoor physical activities of hikers with a sense of pleasure, renewal, and physical effort. The results obtained show that Zemi Valley has significant potential in this regard. Although the valley has a dynamic topography, its moderate difficulty level makes it accessible to a broad range of visitors. When the emotions felt by the participants while hiking in the Zemi Valley are analyzed, it is seen that the nature walk in the valley offers a multidimensional and positive experience. These findings are in line with Ardahan (2012), who points out that nature walks increase the psychological well-being of individuals.

The number of local and foreign visitors is increasing every day in Zemi Valley, which is seen to have important visual, sensory, perceptual, and physical qualities in terms of nature walks in the Cappadocia Region. In this respect, the protection and promotion of the natural and cultural characteristics of the valley and the organization of planned and controlled walks by determining the carrying capacity are important in terms of sustainability.

There are information boards at the entrances and exits of the valley for nature walks and guiding signs within the valley. However, in line with the findings obtained from visitor experiences, integrating promotional content on landscape elements and natural-cultural features that increase the attractiveness of the valley into these areas will both enrich the experiences of visitors and contribute to the promotion of the valley. In addition, within the scope of tourism diversification studies in the region, it should be ensured that the walks are carried out with a guide who knows the area well and has received training in nature protection and use in the mass walking activities to be organized for tourists. During the walk, introducing the geomorphological formations and flora features, which are the most striking features of the valley, will make the walking experience more efficient for the participants who want to explore and learn. In this regard, it will be useful to conduct more comprehensive scientific studies and create promotional documents and train the guides. At the same time, in the studies to be carried out, it is necessary to determine the endemic species and take measures to prevent them from being harmed during nature walks.

Developing planning and management strategies that consider the region's sensitive ecological balance, historical values, and tourism potential will ensure both the protection and sustainable use of the valley. Effectively managing an area within the conservation-utilization balance requires a comprehensive analysis of its natural and cultural landscape features, as well as user profiles, trends, demands, and behaviors. Such holistic approaches will provide a sustainable management model that accommodates visitor needs while minimizing potential environmental and social impacts associated with tourism and recreation.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: MA; sample collection: MA; analysis and interpretation of data: MA; statistical analysis: MA; visualization: MA; writing manuscript: MA.

Ethical Statement

This research was approved by Nevşehir Hacı Bektaş Veli University Scientific Research and Publication Ethics Committee on 05.02.2025 with document number 2025.01.24.

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Research Article
(Araştırma Makalesi)

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Investigation of local pressure losses in reducers for sprinkler irrigation systems: Experimental, analytical and CFD approaches

Yağmurlama sulama sistemlerinde kullanılan redüksiyonlarda basınç kayıplarının incelenmesi: Deneysel, sayısal ve CFD yaklaşımlarıyla

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ABSTRACT

Objective: This study aims to investigate the local pressure losses for conical reducers used in sprinkler irrigation systems using experimental, analytical, and Computational Fluid Dynamics (CFD) methods.

Material and Methods: Eight different reducers with nominal outer diameters of 90-75, 110-90, and 110-75 mm were considered. In the experiments, the pressure losses in the reducers were measured at different water flow rates. The CFD analysis was carried out using the Realizable k-ε, SST k-ω, and RSM turbulence models. The pressure loss coefficients were determined by measurements, analytically, and CFD analysis and were compared with each other.

Results: Taking the experimental data into account, the local loss coefficients for the $R1_{90-75}$, $R2_{90-75}$, $R4_{110-90}$, and $R5_{110-90}$, reducers were determined to be values between 0.5 and 1.0. The $R6_{110-75}$, and $R7_{110-75}$, $R8_{110-75}$ reducers local loss coefficients between 0.8 and 1.5 were determined. The local loss coefficients determined using the SST k-ω turbulence model considered in the CFD analysis were in better agreement with the experimental results.

Conclusion: It can be said that the pressure losses in the newly designed reducers could be determined by the CFD analysis at the design stage, and it would be useful to use these values in the system design.

ÖZ

Amaç: Çalışmada, yağmurlama sulama sistemlerinde kullanılan redüksiyonlar için yerel basınç kayıplarının deneysel, analitik ve Hesaplamalı Akışkanlar Dinamiği (CFD) yöntemleri ile incelenmesi amaçlanmıştır.

Materyal ve Yöntem: Çalışmada, nominal dış çapları 90-75, 110-90 ve 110-75 mm olan sekiz farklı redüksiyon dikkate alınmıştır. Denemelerde, redüksiyonlardaki basınç kayıpları farklı su geçiş debilerinde ölçülmüştür. Redüksiyonlardaki basınç kayıpları, teorik eşitliklerle ve Reliazable k-ε, SST k-ω ve RSM türbülans modelleri dikkate alınarak CFD analiz yöntemiyle incelenmiştir.

Araştırma Bulguları: Deneysel veriler dikkate alındığında yerel kayıp katsayıları, $R1_{90-75}$, $R2_{90-75}$, $R4_{110-90}$, $R5_{110-90}$ redüksiyonları için 0.5 ile 1.0 arasında ve $R6_{110-75}$, $R7_{110-75}$, $R8_{110-75}$ redüksiyonları için ise 0.8 ile 1.5 arasında belirlenmiştir. Sayısal analiz yönteminde SST k-ω türbülans modeli kullanılarak belirlenen yerel kayıp katsayıları, deneysel sonuçlar ile en iyi uyumu göstermiştir.

Sonuç: Yeni tasarlanan redüksiyonlardaki basınç kayıplarının tasarım aşamasında sayısal analiz yöntemi ile belirlenebileceği ve sistem tasarımında kullanılmasının uygun olacağı söylenebilir.

INTRODUCTION

Sprinkler irrigation is a method of controlled application of water similar to rainfall. The water is distributed under pressure through a network that can consist of pumps, valves, main and/or sub-main pipes, laterals, and sprinklers. The success of a sprinkler irrigation system depends on the selection of the appropriate sprinkler type and its components, the hydraulic design of the system, and its operation at suitable operating pressures.

Pressure loss due to friction is important parameters in the hydraulic design of the sprinkler irrigation system. The main factors affecting pressure losses are the type of pipe, the type of flow in the pipe, and its geometric dimensions that cause a change in the direction or cross-section of the flow in the pipeline. Reducers, which are usually made of polyethylene (PE), are used to connect pipes with different diameters in sprinkler irrigation systems. These conical contraction parts interrupt a uniform flow, causing turbulence and thus additional losses. These additional losses are generally lower than the pressure losses in long pipe networks. However, the local losses in irrigation networks consisting of short pipes and many fittings can be higher than the losses in straight pipes. Therefore it is important to take local losses into account when designing the system (Idel'chik, 1960; Daugherty & Franzini, 1965; Cengel & Cimbala, 2006).

The pressure losses in the flow at the fittings can be calculated using the coefficients given in the literature. However, these coefficients are constant and cannot take into account the properties of the flow. Essentially, the pressure losses in the flow in pipes and fittings are a function of the Reynolds number. Therefore, parameters such as flow velocity, pipe diameter, and roughness have a direct effect on the loss coefficient. For instance: radius of curvature at elbows; and sudden or gradual contraction or expansion at reducers. Several experimental studies have been carried out on total friction and local losses for different types of irrigation parts. Most studies focus on the pipes and emitters used in drip irrigation systems (Howell & Barinas, 1980; Bagarello et al., 1997; Juana et al., 2002; Provenzano & Pumo, 2004; Demir et al., 2019). Experimental studies on components of sprinkler irrigation systems are quite limited.

Computational Fluid Dynamics (CFD) is a method of modeling flow patterns using advanced algorithms and computers. CFD enables engineers to make faster and better decisions to improve the quality, durability, and performance of their designs. The studies carried out using the CFD method for the fittings in the fluid lines mainly focused on valves and elbows (Cürebal, 2016). In addition, several studies have been conducted on the design of filters, emitters, and jet sprayers for micro irrigation systems around the world (Palau-Salvador et al., 2004; Wei et al., 2006; Zhang et al., 2007; Wang et al., 2009; Demir et al., 2020; Demir et al., 2022). Saldivia et al. (1990) modeled pressure losses using the finite element method with a similar approach for equivalent pipe lengths in different system components of sprinkler irrigation systems. Various researchers have conducted studies on the gradual expansion (Choi et al., 2019), and contraction (Deev et al., 2009; Satish et al., 2013; Tan et al., 2013; Narayane et al., 2014; Das et al., 2015; Jivani & Naik, 2019), particularly using the CFD approach. The researchers performed CFD analyses at specific velocities for constant expansion or contraction angles and used k-epsilon (k-ε), k-omega (k-ω), and Reynolds stress model (RSM) turbulence models for their analyses. The CFD results were compared with the results of the analytical method, and it was found that the local loss coefficients change depending on the Reynolds number. No experimental and/or simulation-based studies were found on reducers with diameters used in sprinkler irrigation systems.

This study aims to determine the local pressure losses for conical reducers used in sprinkler irrigation systems using experimental, analytical, and computational fluid dynamics (CFD) methods.

MATERIALS and METHODS

The study considered eight different PE (polyethylene) reducers from different companies that are widely used in sprinkler irrigation systems. The reducers were categorized into three groups; they were used in the flow transition between nominal diameters of 90 mm and 75 mm, 110 mm and 90 mm, and 110 mm and 75 mm. Details of the reducers are given in Figure 1 and Table 1.

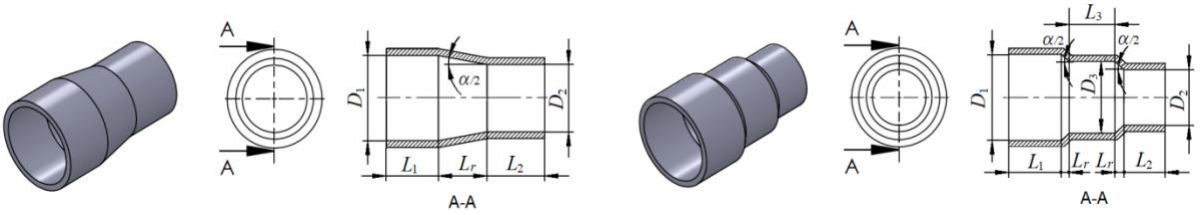

Figure 1. General view of the reducers used in the study.

Şekil 1. *Çalışmada ele alınan redüksiyonların genel görünüşleri.*

Table 1. Technical data of the reducers used in the study

Çizelge 1*. Çalışmada ele alınan redüksiyonların teknik özellikleri*

Types of reducers	D_1 (mm)	D_2 (mm)	D_3 (mm)	$\alpha/2$	L_r (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)
$R1_{90\text{-}75}$	75	63	-	7°	48.9	64	48	-
$R2_{90\text{-}75}$	77	63	-	17°	22.9	77	62	-
$R3_{90\text{-}75}$	69	65	-	15°	7.5	64	48	-
$R4_{110\text{-}90}$	94	75	-	10°	53.9	61	66	-
$R5_{110\text{-}90}$	95	75	-	18°	30.8	72	62	-
$R6_{110\text{-}75}$	96	63	-	20°	45.3	67	58	-
$R7_{110\text{-}75}$	94	64	-	35°	21.4	67	62	-
$R8_{110\text{-}75}$	96	62	80	41°	9.8	61	48	53

The study was carried out in three stages: experimental, analytical, and CFD analysis.

Experimental studies

In the first step of the study, experiments were carried out in the Pump and Irrigation Equipment Test Laboratory of the Department of Agricultural Engineering and Technologies at the Faculty of Agriculture at Ege University and the experimental setup was shown in Figure 1. The experimental apparatus was used to determine the pressure loss caused by the reducers with different diameters at different flow rates.

The water was supplied by a submersible pump, and the flow rate was controlled by a valve during the experiments. The flow rate was measured with an electromagnetic flow meter (Emd-C100F type DN100, Bass-Ela, Czech Republic) with an accuracy of ±0.5% (±0.4 L/s). The pressures at different flow rates were measured with two pressure sensors (PAA-21 SR type, Keller, Switzerland) with an accuracy of ±0.2% (±1.2 kPa) when the flow was stabilized.

As stated in various references when measuring pressure drops in the fittings, to minimize turbulence interaction, it is recommended that the pressure measurements at the inlet and outlet of the fitting should be far from at least 5 or 10 times the inner diameter of the pipe and not less than 1 m from the inlet and outlet of the fittings (ASAE, 2003; Cengel & Cimbala, 2006; Ntengwe et al., 2015; TS, 2019). In the study, the measuring distance for the reducer with the largest inner diameter is 10x96=960 mm. For this reason, the pressure sensors used in the study were placed 1 m before and after all the reducers to conduct the studies under the same conditions.

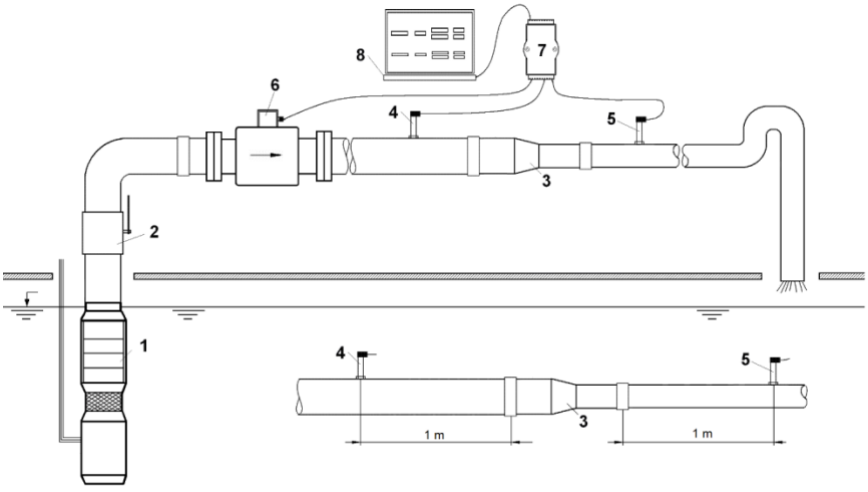

Figure 2. Schematic representation of the experimental apparatus: (1) submersible pump and water inlet pipe; (2) control valve; (3) reducer; (4) inlet pressure sensor; (5) outlet pressure sensor; (6) electromagnetic flow meter; (7) data acquisition system; (8) computer.

Şekil 2. *Deneme düzeninin şematik görünümü: (1) dalgıç pompa ve su giriş borusu; (2) kontrol vanaları; (3) redüksiyon; (4) giriş basınç sensörü; (5) çıkış basınç sensörü; (6) manyetik debimetre; (7) veri algılama-kayıt sistemi; (8) bilgisayar.*

Measurements were recorded by a data acquisition system (ADAM 4520 and ADAM 4017+, Advantech Automation Corp., USA) using GeniDAQ version 4.25 data acquisition software. The data acquisition system used in this study can record 6 data per second. The data was recorded for 15 seconds in the study. During the entire measurement period, 15x6=90 flow and pressure values were recorded separately and the average values were used for the study. During the experiments, the water temperature was measured with a digital thermometer, and it varied between 18 and 22°C. The pressure losses in straight PE pipes and reducers were measured repeatedly.

Analytical studies

In the second step of the study, comparative calculations were carried out using theoretical equations. The pressure loss (ΔP_f) in the straight PE pipes at the inlet and outlet of the reducer was calculated using the Darcy-Weisbach equation (White, 2001; Munson et al., 2002; Cengel & Cimbala, 2006).

$$\Delta P_f = f \frac{L}{D} \frac{\rho V^2}{2} \quad (1)$$

The Darcy-Weisbach friction factor (f) for a fully developed turbulent flow in a straight pipe was calculated taking into account the relative roughness (ε/D) and the Reynolds number (Re) and using the following equations (Cengel & Cimbala, 2006);

$$\frac{1}{\sqrt{f}} = -1.8\, log\left[\frac{6.9}{Re} + \left(\frac{\varepsilon/D}{3.7}\right)^{1.11}\right] \quad (2)$$

$$Re = \frac{VD}{\nu} \quad (3)$$

where: ΔP_f is the pressure loss in a straight pipe in Pa; V is the mean flow velocity in the pipe in ms^{-1}; D is the inner diameter of the pipe in m; L is the pipe length in m; ρ is the density of water in kgm^{-3}; f is the Darcy-Weisbach friction factor; ε is the roughness of the inner surface of a pipe in m; ν is the kinematic viscosity of water m^2s^{-1} (ν=1.01×10^{-6} m^2s^{-1} for 20°C).

The local pressure loss (ΔP_k) for each reducer was determined by subtracting the calculated pressure losses for the straight PE pipe from the measured total pressure losses. In addition, the local loss coefficients (k) at different flow velocities ($V=4Q/\pi D^2$) were calculated using Equation (4).

$$\Delta P_k = k\frac{\rho V^2}{2} \qquad \Rightarrow \qquad k = \frac{\Delta P_k}{\frac{1}{2}\rho V^2} \tag{4}$$

These data were used to determine the relationships between the flow rate and the pressure loss, as well as the flow velocity and the local loss coefficient. In addition, comparisons were made with the equations and coefficients given in the literature for conical contraction fittings. The theory used for this purpose is explained below.

The total local pressure loss in the tapered flow includes the losses in the transition region between the fully developed inlet and outlet flows (Figure 3). The equation for the local pressure loss in this region is expressed in Equation (5) (Rennels & Hudson, 2012).

$$hk = k\frac{V_2^2}{2g} = k_{acc}\frac{V_C^2}{2g} + \frac{(V_C - V_2)^2}{2g} \tag{5}$$

where: hk is the total local pressure loss in m; Vc is the mean flow velocity in the vena contracta region in ms^{-1}; V_2 is the mean flow velocity in the pipe outlet in ms^{-1}; k_{acc} is the local loss coefficient for the acceleration part of the flow in the conical region. In the equation, the first and second terms express the gradual acceleration of the flow towards the vena contracta region and the sudden expansion of the flow from the vena contracta to the outflow, respectively.

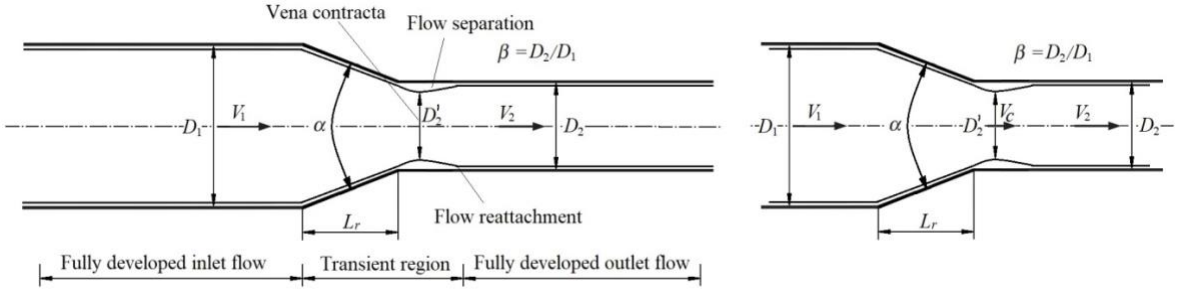

Figure 3. Flow in conical contraction (Rennels & Hudson, 2012).

Şekil 3. *Konik daralmada akış (Rennels & Hudson, 2012).*

Crane (1982) and Rennels & Hudson (2012) summarized the experimental data for the local loss coefficients of such conical pipe transitions and stated that they can be determined by semi-empirical equations. There is an acceleration in the transition region due to the contraction along the flow channel and a deceleration in the outlet pipe due to the expansion of the flow separation and confluence regions. The region with the smallest flow cross-section in the separation region of the outlet is called the vena contracta, and the velocity is highest in this region. Depending on these flow characteristics, the pressure losses in the transition region are expressed as the sum of the local pressure losses due to the surface friction in the conical contraction region and the contraction that occurs at the transition from the conical to the expansion region, Equation (6) (Roul & Dash, 2011; Rennels & Hudson, 2012).

$$hk = hk_{fr} + hk_{con} \tag{6}$$

where: hk_{fr} is the local pressure loss due to surface friction in the conical contraction region in m; hk_{con} is the contraction pressure loss that occurs at the transition from the conical to the expansion region in m. The researchers found that the pressure losses due to surface friction can be significant due to the increase in surface length at a small angle. The pressure losses for surface friction and conical contractions can be calculated using Equations (7) and (8) (Rennels & Hudson, 2012).

$$hk_{fr} = k_{fr}\frac{V_2^2}{2g} \quad (7)$$

$$hk_{con} = k_{con}\frac{V_2^2}{2g} \quad (8)$$

The local loss coefficients for surface friction (k_{fr}), conical contraction (k_{con}), and total coefficient (k) in the equations were calculated using the following equations:

$$k_{fr} = \frac{f\,(1-\beta^4)}{8\,sin\,(\alpha/2)} \quad (9)$$

$$k_{con} = 0.0696\,sin\,(\alpha/2)\,(1-\beta^5)\lambda^2 + (\lambda-1)^2 \quad (10)$$

$$\lambda = 1 + 0.622(\alpha/180)^{4/5}(1-0.215\beta^2-0.785\beta^5) \quad (11)$$

$$k = k_{fr} + k_{con} \quad (12)$$

where: $\beta=D_2/D_1$ diameter ratio; λ is the rate of velocity in the contraction jet; α is the conical contraction angle. The mean flow velocity (V_c) in the vena contracta region was calculated using the ratio of the velocity in the contraction jet according to Equation (13), and the local loss coefficient (k) was calculated according to Equation (14).

$$\lambda = \frac{V_c}{V_2} \quad \Rightarrow \quad V_c = \lambda \cdot V_2 \quad (13)$$

$$hk = k\frac{V_c^2}{2g} \quad \Rightarrow \quad k = \frac{2ghk}{V_c^2} = \frac{\Delta P}{\frac{1}{2}\rho V_c^2} \quad (14)$$

The friction factor (f) depends on the relative roughness of the conical surface, the hydraulic diameter at the cone outlet, and the Reynolds number. The local loss coefficient for conical contractions is a function of the diameter ratio ($\beta=D_2/D_1$), the cone contraction angle (α), and the ratio of velocity in the contraction jet (λ). Equations (15) and (16), which are often used as a function of the contraction angle (α) in the calculation of the local loss coefficients for conical contractions, were taken into account in the comparison (Crane, 1982).

$$k = \frac{0.8\,sin\,(\alpha/2)\,(1-\beta^2)}{\beta^4} \qquad \alpha \le 45^o \quad (15)$$

$$k = \frac{0.5\,(1-\beta^2)\sqrt{sin(\alpha/2)}}{\beta^4} \quad 45^o < \alpha \le 180^o \quad (16)$$

In addition to the measurement results for the reducers, the pressure losses and the local loss coefficients were calculated using the theoretical equations given by Rennels and Hudson (2012) and Crane (1982). Furthermore, the local loss coefficients were calculated as a function of the velocity in the region of the vena contracta, and their variations were shown for each reducer.

CFD analysis

In the third step of the study, the pressure losses in the reducers were investigated by CFD analysis using ANSYS Fluent 17.2 software (ANSYS, 2016). Each reducer was modeled and meshed for the flow analysis (Figure 4). The mesh structure was divided into three sections: Inlet pipe, outlet pipe, and reducer. In the preliminary studies conducted to determine the most appropriate number of elements

for the solution, different network structures and different numbers of elements were created in different regions. By increasing the number of elements, the optimal network structure were performed. The hexahedral mesh structure was used for the analysis. The maximum dimension of a grid in the mesh structure was set to be 2 mm in the reducer section and 5 mm in the inlet and outlet pipes. In addition, the pipe walls were provided with 10 layers. The number of nodes and elements in this mesh structure was more than 4.1×10^5 and 3.7×10^5, respectively.

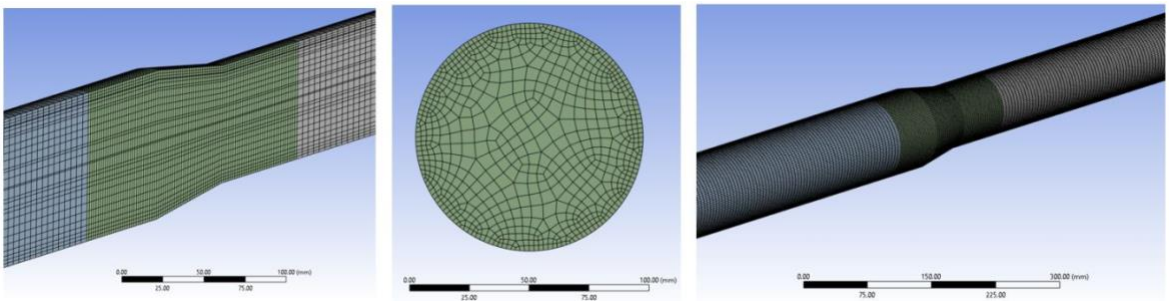

Figure 4 Geometry and mesh structure of the test pipes and the reducer.

Şekil 4. *Redüksiyon ve deneme borusunun geometrisi ve ağ yapısı.*

The turbulence models and options considered in the study are given below:

- Realizable k-ε turbulence model with standard wall and curvature correction options,
- SST k-ω turbulence model with low-Re corrections, corner flow correction, and production limiter options,
- LPS RSM (Reynolds Stress Model) turbulence model with wall BC from the k-equation, wall reflection effects, and standard wall options.

For the CFD analysis, water was chosen as the fluid. It was assumed that the fluid is steady, incompressible, viscous, and without gravity. Coupled algorithms and second-order discretization schemes were used for all solutions. The absolute roughness of PE pipes is often neglected or considered too low. However, since the reducers are friction-welded, the weld zones contain too much roughness. Therefore, the level of surface roughness was assumed to be 0.1 mm in the pipe section and 0.5 mm in the reducer.

The measured flow rates at the pipe inlet and the measured pressures at the pipe outlet were defined by the inlet and outlet boundary conditions, respectively. The convergence accuracy of the solution was assumed to be 1×10^{-10}.

Statistical analysis

The mean absolute error (MAE) and root mean square error (RMSE) were used to compare the differences between the experimental pressure loss data and the data predicted by CFD models (Willmott et al., 1985; Willmott & Matsuura, 2005).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\Delta P_{i,exp} - \Delta P_{i,CFD}\right| \quad (17)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\Delta P_{i,exp} - \Delta P_{i,CFD}\right)^2\right]^{1/2} \quad (18)$$

where: $\Delta P_{i,exp}$ is experimental and $\Delta P_{i,CFD}$ is the simulation values, n is the number of data.

The lowest value of these comparison criteria represents the highest estimate of the model.

RESULTS and DISCUSSION

The experimental results of the measured pressure loss at different flow rates for eight different reducers and the calculated Reynolds numbers and local loss coefficients for the outlet pipe are shown in Table 2. The variations of the local loss coefficient as a function of the outlet velocity are shown in Figure 5.

Table 2. Pressure losses and local loss coefficients in the reducers

Çizelge 2*. Redüksiyonlarda basınç kayıpları ve kayıp katsayıları*

Types of reducers	Flow rate Q (Ls^{-1})	Reynolds number Re^*	Pressure loss in reducer ΔP_k (kPa)	Local loss coefficient for reducer k^*
$R1_{90\text{-}75}$	6.8-15.7	162201-374055	2.26-8.60	0.68-0.95
$R2_{90\text{-}75}$	5.6-15.5	136959-380631	1.38-7.95	0.64-0.86
$R3_{90\text{-}75}$	6.7-15.7	138752-322993	1.32-5.29	0.47-0.64
$R4_{110\text{-}90}$	7.6-15.8	159836-333723	1.22-4.55	0.71-0.83
$R5_{110\text{-}90}$	5.2-15.8	110649-337274	0.72-4.58	0.71-1.05
$R6_{110\text{-}75}$	4.3-16.0	130926-488959	1.40-12.74	0.96-1.48
$R7_{110\text{-}75}$	4.8-15.9	139902-459907	1.53-12.14	0.99-1.35
$R8_{110\text{-}75}$	5.3-15.9	167120-500922	2.36-13.92	1.00-1.52

* The Reynolds numbers and local loss coefficients were calculated for the outlet pipe.

It can be seen that the pressure losses are between 0.72 and 8.6 kPa for single-stage reducers with nominal diameters of 90-75 and 110-90 mm and between 1.4 kPa and 13.92 kPa for two-stage reducers with nominal diameters of 110-75 mm (Table 2).

When Table 2 and Figure 5 are examined, it is seen that the local loss coefficients of all reducers used in the study vary depending on the velocity of the water in the pipeline. It can be seen that the local loss coefficients for single-stage reducers with different diameters are close to each other and that the local loss coefficients for two-stage reducers are higher than these values. The local loss coefficients were between 0.5 and 1.0 for single-stage reducers and between 1.0 and 1.5 for two-stage reducers.

The experimental results of the total pressure loss for all reducers were compared with the results of the CFD analysis performed with different turbulence models. The results are shown in Figure 6.

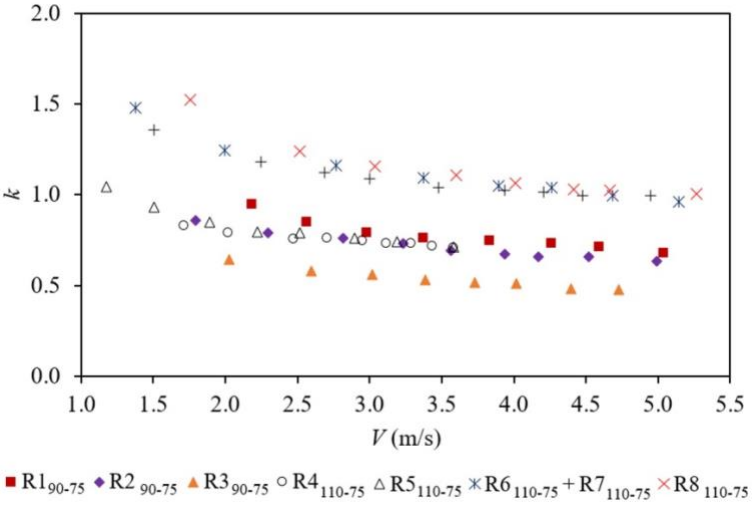

Figure 5. Variations of the coefficient of local loss as a function of the outlet velocity in the reducers.

Şekil 5. *Redüksiyonlarda kayıp katsayılarının çıkış hızına göre değişimleri.*

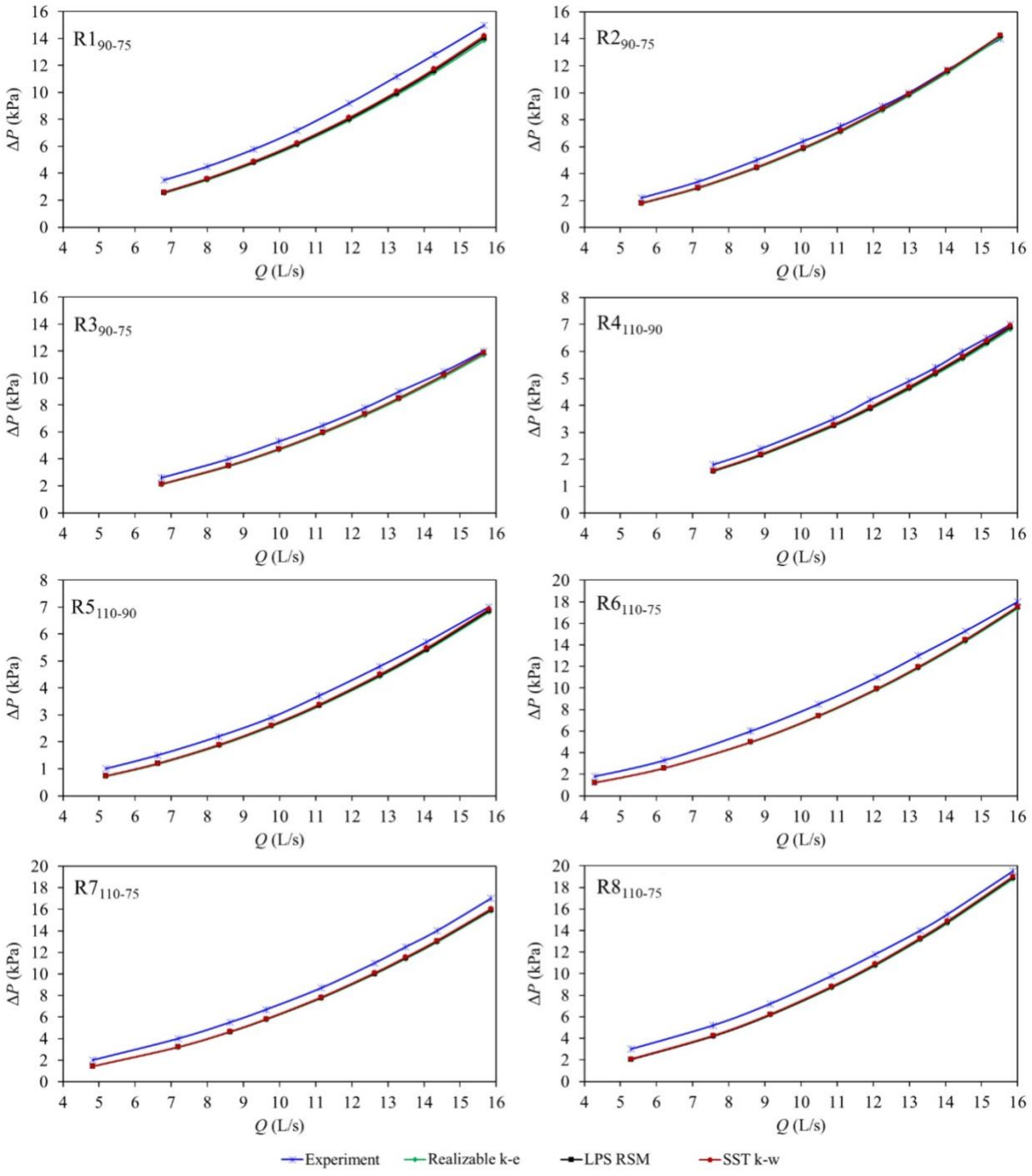

Figure 6. Comparison of the results of the total pressure loss with the experimental and the CFD analysis in reducers.

Şekil 6. *Redüksiyonlarda deneysel ve CFD analiz sonucu bulunan toplam basınç kaybı değerlerinin karşılaştırılması*

It was found that the local pressure losses for the reducers $R1_{90-75}$, $R2_{90-75}$, and $R3_{90-75}$ are quite close to each other (Figure 6). For the $R4_{110-90}$ and $R5_{110-90}$ reducers, the local pressure losses were close to each other but lower than for the 90-75 mm reducers. The enlargement of the cross-section at the same flow velocity leads to lower pressure losses. The local pressure losses in the two-stage reducers ($R6_{110-75}$, $R7_{110-75}$, and $R8_{110-75}$) were found to be similar.

The local pressure losses calculated with different turbulence models using CFD analysis were found to be quite close to each other (Figure 6). When comparing the measurement and simulation results, it can be seen that the results for some reducers (such as $R2_{90-75}$, $R4_{110-90}$, and $R5_{110-90}$) are very close to each other, while there are differences for some reducers (such as $R1_{90-75}$ and $R7_{110-75}$). The 3D models created for the simulation are very smooth. However, the reducers are manufactured by joining the pipe connection heads using the friction welding technique. Therefore, very high roughness occurs in the welding zones of the reducers. In addition, the water passages in the actual reducers could have gaps. These could also cause different vortices during the water passage in the experiments. The differences between the experimental and simulation data could be explained by the different roughness of the welding zones in the reducers and the surfaces of the water flow zone as well as by the additional pressure losses caused by the vortices in the pipe connections. The statistical evaluation of the measured and calculated pressure losses with different CFD turbulence models is given in Table 3.

Table 3. Comparison of the MAE and RMSE values between the measured values and the values calculated with CFD turbulence models

Çizelge 3. *Redüksiyonlar için ölçülen ve farklı CFD türbülans modelleri ile hesaplanan basınç kayıplarının istatiksel olarak MAE ve RMSE değerleri yönüyle karşılaştırılması*

Types of reducers	MAE*			RMSE**		
	SST k-ω	Realizable k-ε	LPS RSM	SST k-ω	Realizable k-ε	LPS RSM
$R1_{90-75}$	0.953	1.152	1.061	0.958	1.162	1.067
$R2_{90-75}$	0.298	0.372	0.322	0.341	0.408	0.361
$R3_{90-75}$	0.424	0.510	0.429	0.445	0.522	0.451
$R4_{110-90}$	0.178	0.261	0.217	0.189	0.265	0.224
$R5_{110-90}$	0.248	0.309	0.279	0.259	0.314	0.286
$R6_{110-75}$	0.824	0.927	0.848	0.854	0.954	0.877
$R7_{110-75}$	0.838	0.947	0.885	0.847	0.962	0.896
$R8_{110-75}$	0.812	0.950	0.866	0.831	0.958	0.881

* Mean Absolute Error (Equation 17)
** Root Mean Square Error (Equation 18)

As can be seen in Table 3, the lowest MAE and RMSE values between the measured and CFD simulation models were found for the SST k-ω turbulence model. Although the graphs in Figure 6 do not show much difference between the other models considered, it can be seen that the SST k-ω model statistically provides a better estimate than other models. It can be said that this turbulence model should be preferred for the estimation of pressure losses in reducers. Cürebal (2016), investigated the three-dimensional solution of turbulent flow in elbows with different diameters at different flow rates for air, natural gas, and water and found that the SST k-ω turbulence model showed better agreement with the experimental results.

In the study, the local loss coefficients were calculated using Equation (4) from the pressure losses measured experimentally and calculated with the SST k-ω turbulence model. In addition, the local loss coefficients were calculated using Equation (12) from Rennels and Hudson (2012), Equation (15) from Crane (1982), and Equation (14) as a function of velocity in the vena contracta region. The changes as a function of flow velocity for each reducer are shown in Figure 7.

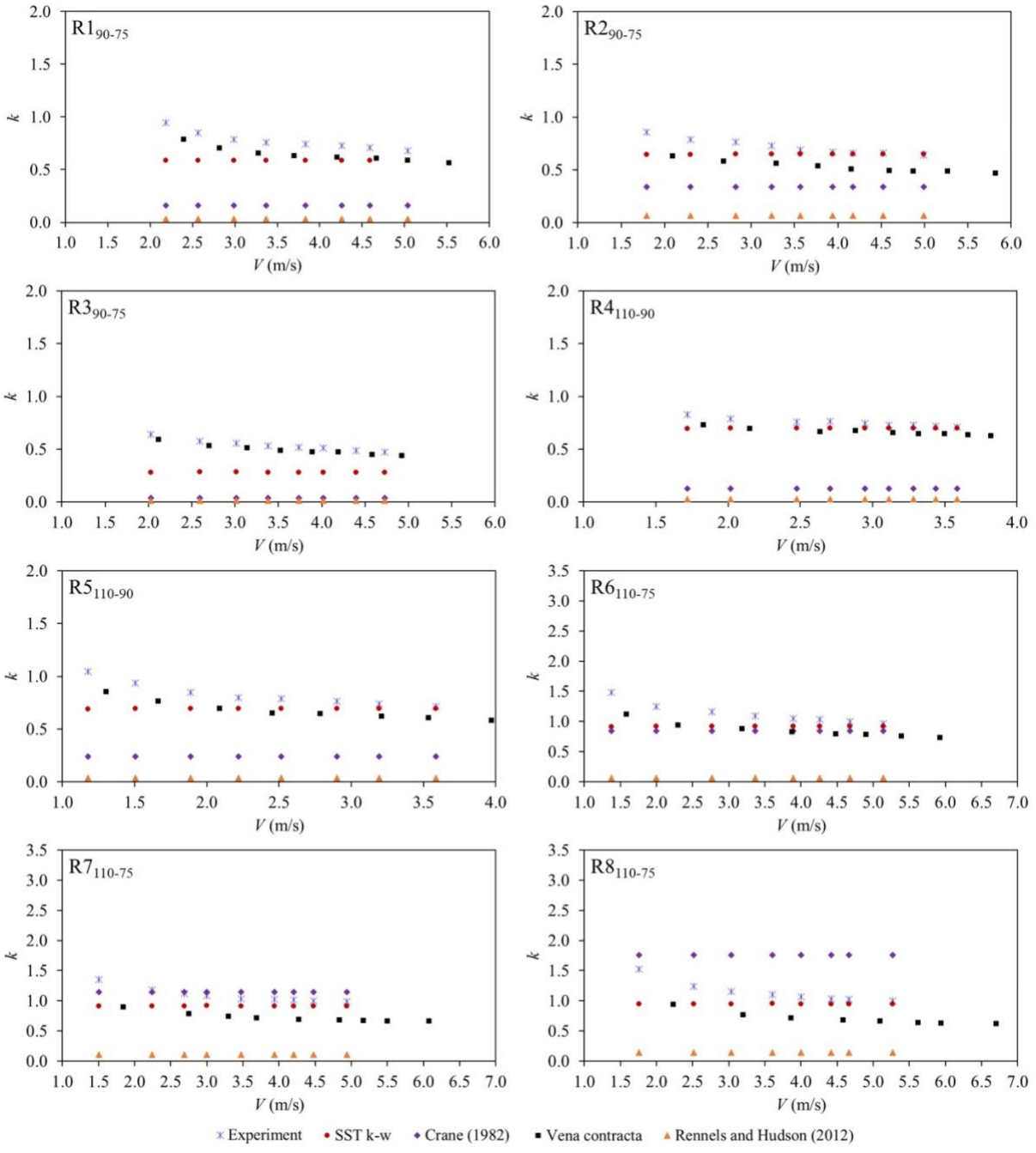

Figure 7. Comparison of the pressure loss coefficients in reducers determined by experimental and CFD analysis.

Şekil 7. *Redüksiyonlarda deneysel ve CFD analiz ile bulunan basınç kayıp katsayılarının karşılaştırılması.*

Figure 7 shows that the local loss coefficients calculated with the SST k-ω turbulence model and Equation (14) in the region of the vena contracta are close to each other for all reducers. The results of the CFD analysis of the reducers with different contraction angles using the SST k-ω turbulence model about the conical contraction and in particular, the flow in the region of the vena contracta are shown in Figure 8. The examination of Figure 8 shows that there are sudden pressure changes in the flow in the conical contraction of the reducers, and especially in the vena contracta, the pressure suddenly drops, and the turbulence intensity increases in this region.

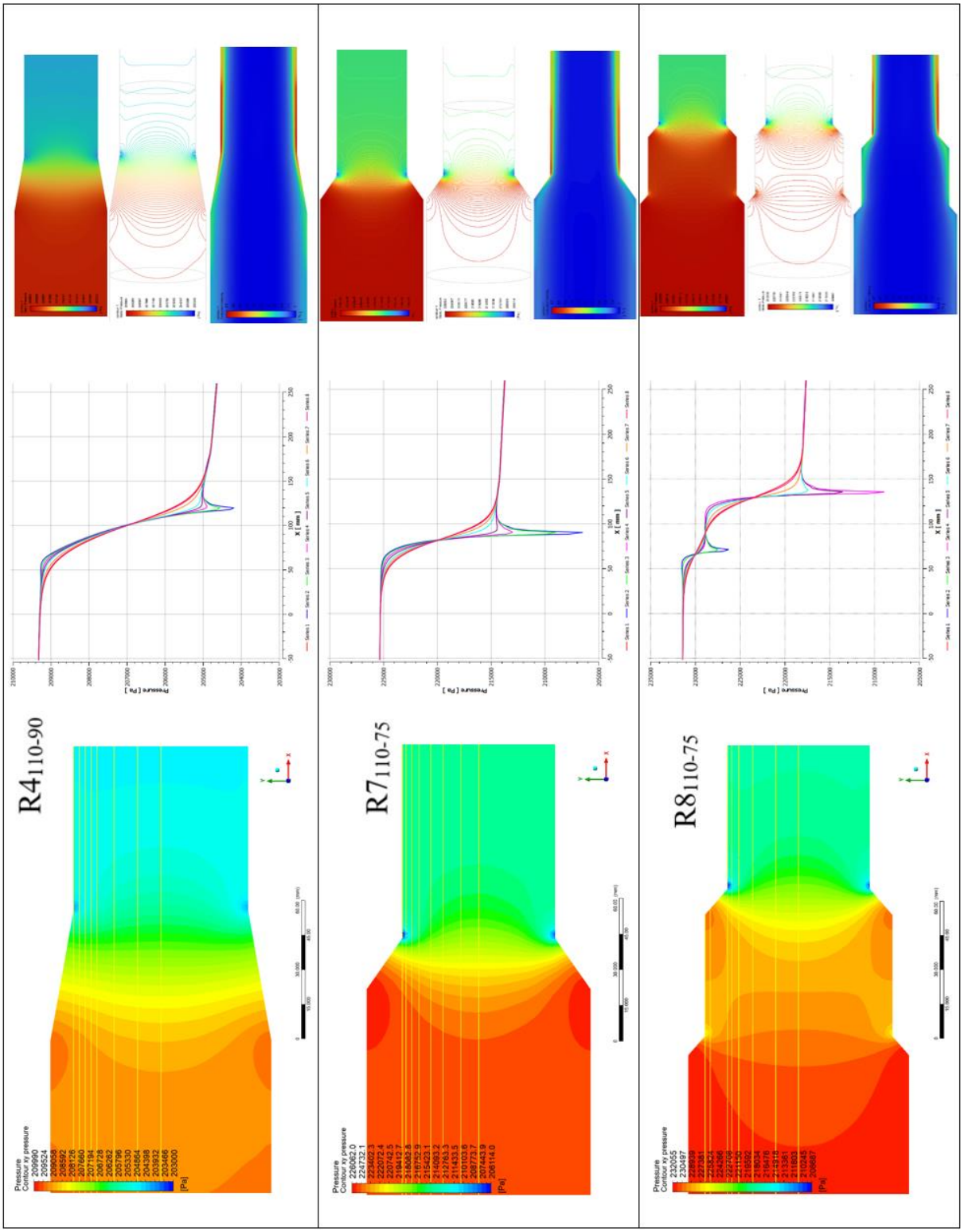

Figure 8. Flow analysis with the SST k-ω turbulence model in the region of the conical contraction and the vena contracta in reducers with different contraction angles.

Şekil 8. *Farklı* daralma *açılarına sahip redüksiyonlarda SST k-ω türbülans modeli ile konik daralma ve vena contracta bölgesinde akışın analizi*

When examining Figure 7, it is seen that the results obtained in the literature using the equations of Rennels and Hudson (2012) and Crane (1982) are different for the various reducers. In particular, the results calculated using the equation by Rennels and Hudson (2012) differ greatly from the measurement results. The results calculated using the equation by Crane (1982) show great variability from reducer to reducer. For example, while very low k-values were calculated for $R1_{90\text{-}75}$ and $R4_{110\text{-}90}$, very high k-values were calculated for $R8_{110\text{-}75}$. The reason for this could be that the k equation is calculated directly as a function of the contraction angle and other factors are not taken into account. For these reasons, it is clear that taking these two equations into account when calculating the pressure loss of the reducers used in irrigation systems could lead to errors for these nominal sizes. It can be seen that the equations (15 and 16) expressed by Crane (1982) for the local pressure loss coefficient are independent of the friction factor (*f*) and the Reynolds number (*Re*). Cengel and Cimbala (2006), stated that the local pressure loss coefficient calculated with these equations can be corrected with a coefficient of 1.05 for fully turbulent flows and 2.0 for fully developed laminar flows. However, as can be seen in Figure 7, the use of these coefficients for the turbulent flow region gave very different results from the experimental data for many of the reducers considered in the study.

The experimental results show that the local pressure loss coefficients in the single-stage reducers $R1_{90\text{-}75}$, $R2_{90\text{-}75}$, $R4_{110\text{-}90}$, and $R5_{110\text{-}90}$ are between 0.5 and 1.0, where 0.8 can be used as the average value for the calculations. For the two-stage reducers of types $R6_{110\text{-}75}$, $R7_{110\text{-}75}$, and $R8_{110\text{-}75}$ the local pressure loss coefficients vary between 0.8 and 1.5, whereby 1.2 can be used as an average value for the calculations.

CONCLUSION

The aim of this study is to determine the local pressure losses for conical reducers used in sprinkler irrigation systems using experimental, analytical, and CFD methods. Considering the experimental results, it was found that the local pressure loss coefficients for single-stage reducers with different diameters were close to each other. The local pressure loss coefficients were found between 0.5 and 1.0 for the single-stage reducers and between 0.8 and 1.5 for the two-stage reducers.

Realizable k-ε, SST k-ω, and LPS RSM turbulence models were considered in the study. It was found that the pressure losses calculated with all turbulence models were quite close to each other. The experimental local pressure losses were found to be slightly higher than the simulation results. This difference could be explained by the weld roughness in the manufacture of the reducer and the additional pressure losses caused by the vortices in the pipe connections.

The local pressure loss coefficients calculated with the theoretical equations for the reducers in the study were found to be quite different from the experimental and CFD simulation results. It was found that the local pressure loss coefficients calculated using the equation of Rennels and Hudson (2012) were quite different from the experimental results, while the equation of Crane (1982) showed a large variability from reducer to reducer. For these reasons, it can be said that using these two equations to calculate the local pressure loss coefficients for reducers can cause errors. When calculating the local pressure loss in the reducers with different CFD simulation models, it was found that the SST k-ω turbulence model was statistically closest to the experimental results.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: VD, HY; sample collection: VD, HY; analysis and interpretation of data: VD, HY; statistical analysis: VD, HY; visualization: VD, HY; writing manuscript: VD, HY.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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Research Article
(Araştırma Makalesi)

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Soluble green tea production and determination of changes during the *in vitro* gastrointestinal system*

Çözünebilir yeşil çay üretimi ve *in vitro* gastrointestinal süreçteki değişikliklerin belirlenmesi

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ABSTRACT

Objective: This study investigated the transformations and bio-accessibility of soluble green tea components throughout the digestive process by utilizing an *in vitro* gastrointestinal system simulation.

Material and Methods: Green tea was obtained from a local market considering the expiration date. In preliminary experiments, it was determined that the highest phenolic content was reached when 2% infusions were brewed at 80ºC for 60 seconds. The prepared infusions were filtered, maltodextrin was added and freeze-dried at -59.5ºC, 33 Pa for 48 hours. Color, total phenolic substance and antioxidant activity analyses were performed on green tea infusion (GT) and maltodextrin-coated green tea (SGT). In addition, changes in phenolic substance during the *in vitro* gastrointestinal process were investigated by HPLC.

Results: In the initial condition, only catechin and epicatechin contents were statistically significant ($p<0.01$) when comparing GT and SGT. Phenolic acid content, antioxidant activity, and phenolic compounds showed statistically significant differences in different regions of the gastrointestinal system. Additionally, changes in both green tea samples throughout the digestive process were statistically significant ($p<0.01$).

Conclusion: Significant alterations in phenolic content, antioxidant capacity, and polyphenolic composition were observed in GT and SGT samples; co-application of maltodextrin with other materials may enhance green tea phenolic stability and bioavailability.

ÖZ

Amaç: Bu çalışma, çözünebilir yeşil çay bileşenlerinin sindirim sürecindeki dönüşümlerini ve biyoyararlanımını in vitro gastrointestinal sistem simülasyonu ile incelemiştir.

Materyal ve Yöntem: Yeşil çay, son kullanma tarihi dikkate alınarak yerel bir marketten temin edilmiştir. Ön deneylerde, 2% infüzyonların 80ºC'de 60 saniye demlendiğinde en yüksek fenolik içeriğe ulaştığı belirlenmiştir. Hazırlanan infüzyonlar süzülerek maltodekstrin eklenmiş ve -59,5ºC, 33 Pa'da 48 saat boyunca dondurarak kurutulmuştur. Yeşil çay infüzyonu (YÇ) ve maltodekstrin kaplı yeşil çayın (MYÇ) renk, toplam fenolik madde ve antioksidan aktivite analizleri yapılmıştır. Ayrıca, fenolik madde değişimi HPLC ile değerlendirilmiştir.

Araştırma Bulguları: Başlangıçta, YÇ ve MYÇ arasındaki kateşin ve epikateşin içerikleri istatistiksel olarak anlamlı bulunmuştur ($p<0.01$). Gastrointestinal sistemin farklı bölgelerinde fenolik asit içeriği, antioksidan aktivite ve fenolik bileşiklerde önemli farklılıklar gözlenmiştir. Sindirim sürecinde her iki çay örneğinde de belirgin değişimler meydana gelmiştir ($p<0.01$).

Sonuç: YÇ ve MYÇ örneklerinde fenolik içerik, antioksidan kapasite ve polifenolik bileşimde önemli değişiklikler gözlemlendi; maltodekstrinin diğer materyallerle birlikte uygulanması yeşil çay fenolik stabilitesini ve biyoyararlanımını iyileştirebilir.

INTRODUCTION

Tea, one of the most widely consumed beverages in the world after water, is commercially grown in more than 30 countries, especially in China, India, Kenya, Sri Lanka, and Türkiye (Akbulut et al., 2020). Tea is widely consumed worldwide for its unique color, taste, and health benefits derived from its bioactive components. The leaves of the tea plant, called *Camellia sinensis* L., are green in all seasons. Its high antioxidant activity is attributed to its phenolic compounds (Şatır, 2023). Among all major tea varieties, green tea has been associated with the most significant health benefits. It is one of the most widely consumed types of tea globally and has been steadily gaining popularity, currently accounting for approximately 20% of the 3 million tons of annual global tea production (Radeva-Ilieva et al., 2025). The most important of green tea polyphenols are classified into the 4 types: epigallocatechin-3-gallate (EGCG), epicatechin-3-gallate (ECG), epigallocatechin (EGC) and epicatechin (EC) (Llczbínski & Bukowska, 2022). Green tea contains bioactive components such as flavonoids, tannins, methylxanthine alkaloids (caffeine, theophylline), and linoleic acid, as well as minerals such as calcium, magnesium, zinc, and selenium (Khatoon, 2023). EGCG supports the immune system by neutralizing free radicals and preventing cell damage. Green tea, which is obtained from the *Camellia sinensis* L. plant, contains more than 2000 active ingredients, including phenolic compounds, proteins, catechins, flavonoids, and volatile compounds. It is a functional beverage due to its health benefits (Singh et al., 2022a). Green tea, an unfermented tea, is produced by enzyme inactivation, which preserves the catechins in fresh leaves. Green tea's phenolic content and antioxidant capacity are higher than black tea (Akbulut et al., 2020). Catechins and polyphenols mainly attract attention with their potential health benefits, such as metabolic syndrome, protection against cancer, and prevention of obesity and diabetes (Singh et al., 2022a). In addition, green tea's anticarcinogenic and antioxidant properties may provide protective effects against cardiovascular diseases (Taş et al., 2005; Prasanth et al., 2019). Scientific studies have shown that green tea has many positive effects, such as weight control, improved physical performance, oral and bone health, and protection against ultraviolet radiation (Zhao et al., 2019). Green tea is consumed by brewing or straining bags in different cultures, and its health benefits increase with regular consumption (Taş et al., 2005). With all these features, green tea is a natural source that contributes to health beyond just a daily drink. Bioactive compounds such as phenolic substances can be significantly reduced during thermal processing and storage. In fact, the unsaturated bonds in the molecular structure of phenolic compounds can easily lead to degradation and loss of fragile components during storage, due to external factors such as heat, pH, exposure to oxygen and light (Medfai et al., 2023). Maltodextrin is one of the most widely utilized wall materials for preserving phenolic chemicals because of its low cost, ease of acquisition, film-forming capabilities, high water solubility, and low viscosity at significant concentrations (Navaro-Flores et al., 2020; Medfai et al., 2023). Maltodextrin has been found to be effective in formulating stable green tea extract microparticles through spray drying. These microparticles maintain their size, shape and antioxidant capacity over 60 days of storage at different pH values (Cruz-Molina et al., 2021). Silva et al. (2023) evaluated the physicochemical properties, antimicrobial activity, and toxicological safety of microcapsules obtained by spray-drying green tea extract with cashew gum and maltodextrin using the Zebrafish model. Chuysinuan et al. (2021) encapsulated green tea extract with cyclodextrin to form an inclusion complex, which was subsequently incorporated into a chitosan/polyvinyl alcohol (CS/PVA)-based hydrogel matrix. They assessed the physicochemical characteristics and antioxidant capacity of the resulting system.

The digestive system is a complex network responsible for digestion, absorption, and waste excretion (Kızıl, 2019). Digestion involves the physical and chemical breakdown of food, allowing the release of beneficial components to the body. The food matrix affects the release of nutrients and their transportation to target areas during digestion (Sensoy, 2021). The digestive system is controlled by a network of nerves and hormones that regulate digestion, secretion, absorption, and motility along a canal extending from the mouth to the anus (Baş, 2019). While digestion and absorption occur in the stomach and small intestine,

nutrients are separated, passed into the blood, and used for energy and growth in the body. Digestive enzymes and fluids support this process, and contractions provide motility and transport nutrients to target organs (Saka et al., 2016). Since in vivo studies are complex, expensive, and ethically limited, *in vitro* digestion models have been developed since the 1990s (Sensoy, 2021). *In vitro* digestion models are essential for designing and evaluating new food products. While static *in vitro* models simplify digestion and mimic biochemical conditions, these models have limitations. For example, differences in digestion parameters make it difficult to compare research results (Brodkorb et al., 2019). In addition, these models fail to simulate the dynamic aspects of the digestive process, especially mechanical forces and fluid dynamics (Li et al., 2020). Dynamic *in vitro* models provide more realistic digestion simulations. These models simulate the stomach and small intestine compartments and consider dynamic factors such as pH changes, enzyme secretion, and peristaltic forces (Minekus et al., 2014; Li et al., 2020). However, these models cannot mimic all physiological conditions of the digestive system (Sensoy, 2021). In general, dynamic digestion models aim to mimic all gastrointestinal tract compartments by providing a complete digestion simulation (Singh et al., 2022b). These models more accurately simulate the digestive process of nutrients while also considering the constant changes in environmental conditions (Fusco et al., 2022).

Upon examining the literature, it becomes apparent that studies conducted using in vitro gastrointestinal systems primarily focus on probiotic microorganisms and microbiological evaluations. For example, İnce-Palamutoğlu et al. (2023) evaluated the viability of lactic acid bacteria in the dynamic in vitro gastrointestinal system in home-type and industrial kefir samples. Similarly, Çomak-Göçer et al. (2024) examined the rheological, microbiological, and in vitro digestive properties of kefirs produced with different kefir grains and commercial starter cultures. These studies provide essential findings for evaluating the microbiological and digestive properties of fermented products. On the other hand, studies on green tea generally focus on issues such as component stability, antioxidant capacity, and encapsulation technologies; structural changes during the digestive process and bioavailability levels are addressed to a limited extent. It is noteworthy that comprehensive studies on the chemical and biological transformations of green tea components during the digestive process, particularly using an in vitro gastrointestinal system model, are lacking. In this context, the study conducted is one of the pioneering studies that systematically evaluate the chemical and biological changes that natural and maltodextrin-coated green tea extracts undergo during the digestive process, providing original and scientifically valuable contributions to the literature on the understanding of the gastrointestinal behavior of functional ingredients.

The main objective is to evaluate the transformations and bioavailability of soluble green tea components during the stages of an in vitro gastrointestinal digestion simulation.

MATERIALS and METHODS

Materials

The study was conducted in the Food Chemistry Laboratory of the Department of Nutrition and Dietetics, Faculty of Health Sciences, Afyonkarahisar Health Sciences University. Green tea was obtained from the local market in Afyonkarahisar, Türkiye. The chemicals used for the analysis were analytical grade. This research has been approved by the Afyonkarahisar Health Sciences University Non-Interventional Scientific Research Ethics Committee with document number 2023/401 dated 1 September 2023.

Soluble Green Tea Production

Preliminary experiments showed that green tea (GT) prepared using 2% aqueous green tea infusions at 80ºC of water for 60 seconds had the highest phenolic content. Green tea extracts obtained from the infusions were filtered through filter paper. Then, 2.5% maltodextrin was added and homogenized at 8000 rpm for 5 min. The samples were then freeze-dried for 48 hours at -59,5ºC and 33 pa (INOFD-10S, Innova, China) (Figure 1).

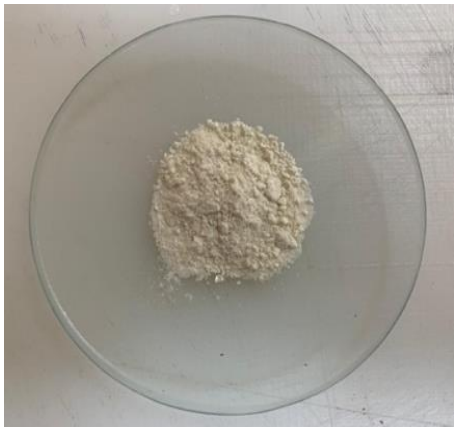

Figure 1. Maltodextrin-coated green tea.

Şekil 1. *Maltodekstrin kaplı yeşil çay.*

Methods

Establishment of *in vitro* gastrointestinal model

This *in vitro* digestive model simulates the mouth, stomach, and small intestine sections. A temperature-controlled water bath was used for the mouth section, and a double-jacketed reaction vessel kept at 37ºC was used for the stomach and small intestine sections. Temperature and pH were continuously monitored. Digestion time was determined as 5 minutes in the mouth section, 2 hours in the stomach section, and 2 hours in the small intestine section. Secretion flow rates were controlled with adjustable peristaltic pumps. The pH balance of the stomach and small intestine sections was provided with 1 M Sodium Hydroxide (NaOH) and 1 M Hydrochloric Acid (HCl).

Mucin, α-amylase, and a 40% NaOH solution were used to simulate salivary secretion. Simulated saliva (0.05 mL/g sample) was added to the oral environment at a flow rate of 5 mL/min, and all reagents were incubated at 37ºC for 5 minutes. Gastric fluid simulation involved mucin and pepsin enzymes to promote acid denaturation of digested foods, with hydrochloric acid used to activate pepsin. Simulated gastric secretion (0.05 mL/g sample) was added to the stomach reactor at 0.25 mL/min. After digestion in the oral phase at pH 6.9, samples entered the stomach reactor at a 100 mL/min flow rate. Gradual acidification to pH 2.5 was achieved by adding 0.2 mL of 1 M HCl and 0.695 mL of water, with the HCl flow adjusted to 3.5 mL/min until reaching pH 2.5 and then reduced to 0.9 mL/min to simulate gastrin inhibition. Gastric digestion was maintained for 2 hours at 37ºC. A double-jacketed reactor integrated with a circulating water bath ensured constant temperature. Pancreatin and bile salts were used to simulate small intestinal fluid. Simulated intestinal secretion (0.25 mL/g sample) was introduced at a 3 mL/min flow rate. Samples were transferred from the stomach (pH 2.5) to the small intestine reactor at 100 mL/min over 20 minutes. pH was gradually increased to 6.9 by adding 1 M NaOH at 0.65 mL/min. Intestinal digestion was maintained for 2 hours at 37ºC. Temperature, digestion times, secretion compositions, and flow rates were set based on established gastrointestinal simulation protocols from the literature (Minekus et al., 2014; Çomak Gökçer et al., 2021).

Total phenolic content

Tea samples were diluted 10-fold to determine the total phenolic content, and 0.1 ml of Folin-Ciocalteau reagent was diluted 1:2 with distilled water. Then, 0.3 ml of 2% Na_2CO_3 solution was added. The tubes were vortex-mixed and incubated in the dark and at room temperature for 2 hours. A blank solution was prepared by adding distilled water instead of 0.1 ml of tea sample. At the end of two hours, the absorbance of the resulting blue-green solutions was measured at 760 nm against the blank (Singleton & Rossi, 1965). The total phenolic content of the samples was expressed in mg gallic acid

equivalent (GAE)/g dry tea sample using a standard calibration curve (r^2>0.99) based on the gallic acid standard. The equation of the calibration curve is given below;

$$y = 0.0004x + 0.0009$$

$$r^2 = 0.9955$$

Color determination

In the study, infusion color was measured using an X-Rite Ci64x portable color spectrophotometer. Spectrophotometry is the best way to obtain data for color formulation and ensure quality by filtering light into very narrow color bands and analyzing their return signals. In addition, the spectrophotometer quantifies the red, green, and blue components of each measurement and determines the location of color in color space using *L*, a*, b** metrics (HunterLab, 2001; Schanda, 2018).

Antioxidant activity determination

Antioxidant activity was analyzed using the DPPH (2,2-Diphenyl-1-picrylhydrazyl) radical inhibition method (Brand-Williams et al., 1995). A DPPH solution was prepared by dissolving it in methanol at a concentration of 20 mg/L. 1.5 ml of DPPH radical was taken, 0.75 ml of tea samples were added to it, and the absorbance values at 517 nm at 0 and 30 minutes were read using a spectrophotometer (Klab Optızen Pop UV, Korea).

Antioxidant activity was calculated according to the formula.

Antioxidant Activity (%) = $(A_0 - A)/ A_0) \times 100$

Absorbance value at 0 minutes = (A_0); Absorbance value at 30 minutes = (A)

Determination of catechin composition in High-Performance Liquid Chromatography (HPLC)

Catechin composition of samples was determined according to the method applied by Wang et al. (2000). For this purpose, 1 mL samples were collected from the mouth (at 0 and 5 minutes), stomach (at 60 and 120 minutes), and small intestine (at 60 and 120 minutes) during the *in vitro* gastrointestinal system. The samples were centrifuged at 10000xg at 4ºC for 1 hour. At the end of centrifugation, the extracts were filtered through a 0.45 µm membrane filter in the clear part, and the catechin composition was analyzed using HPLC (Thermoscientific). After mixing the brewed tea with the mobile phase 1:1 v/v and filtering the mixture through a 0.2 µm PVDF acrodisc syringe filter (Gelman, Ann Arbor, MI), tea flavanols were analyzed using HPLC. The filter discs were washed with 200 µl methanol, and the wash solution was also analyzed for flavanols with HPLC. The flavanol content separated from the filter disc was added to the data obtained from the tea analyses. Mobile phase A comprised acetonitrile, while mobile phase B comprised 960 ml of 0.1% acetic acid (pH 3.5) + 20 ml of acetonitrile + 20 ml of tetrahydrofuran. Flavanols were eluted and equilibrated with a gradient of 100% B at 0 min, 40% B at 45 min, and 100% B at 47 min. Final concentrations were calculated by comparing them with a known standard response. Detection was performed at 280 nm wavelength. An external standard method was used for the identification process, and catechin was used as a standard for this purpose. The amount of catechin in the samples was calculated with the help of the curve created with five different concentration standard solutions injected into the device under the same conditions as the samples (Henning et al., 2003).

Statistical analyses

The study was conducted with two replicates, and two parallel analyses were performed on each sample taken from each replicate. The results were evaluated with a one-way analysis of variance (ANOVA) using the statistical program IBM SPSS Statistics (Version 26). The Shapiro-Wilk test was used to determine whether the distribution of the analysis results was homogeneous. In cases where the distribution was homogeneous, the Tukey multiple comparison test was used to determine the difference between the means. In cases where it was not homogeneous, Dunnett's T_3 test was used (IBM Corp., 2019).

RESULTS and DISCUSSION

Color

The *L*, a*, b** values of GT and SGT samples used in the study were found to be 22.09±0.11, 1.85±0.35, 4.74±0.26 and 23.2±0.25, 2.70±0.14, 3.07±0.16, respectively. The differences between them were statistically significant ($p<0.05$). In accordance with Parvez et al. (2022), tea powders in the nanoencapsulation are lighter than tea extract, and the L* value increases as the maltodextrin content increases by 5% to 15%. This suggests that maltodextrin contributes to the increased L* values in encapsulated tea extracts (Zorzenon et al., 2020). Additionally, Parvez et al. (2022) showed that samples showing a tendency for red and yellow exhibited positive a* and b* values. The b value decreased with the concentration of 1:10. Similarly, in the present study, encapsulated green tea powders exhibited higher L values, while b values showed a decreasing tendency, consistent with the literature.

Total phenolic content

Green tea is essential for healthy nutrition due to its rich polyphenolic components and strong antioxidant properties. However, it has not been fully clarified how beneficial products such as green tea change throughout the digestive system. Gastrointestinal conditions such as stomach acids and bile can affect the phenolic compound values in green tea. Although human studies are ideal for determining changes, their applicability is limited due to technical, financial, and ethical limitations. On the other hand, animal studies offer an alternative solution, but they are generally not preferred due to the difficulty of methods such as surgical intervention. *In vitro*, gastrointestinal system models have become increasingly popular because they offer reproducibility and flexibility. These models are particularly important in determining how the phenolic substance content in green tea coated with green tea continues throughout the digestive system.

The total phenolic content values throughout the gastrointestinal system are given in Table 1. At the beginning of digestion, the total phenolic content in the mouth region of the GT sample was 112.19±2.02 mg GAE/100mL while in the SGT sample, it was, it 106.74±1.34 mg GAE/100mL at 0 minutes. It was determined that the difference between the total phenolic substance amount of these two tea samples at the beginning was not statistically significant. It was observed that the differences between the total phenolic substance amounts in the two tea samples were statistically significant only in the minor intestine at 0 and 120 minutes ($p<0.05$). The change in the total phenolic substance amount of the GT and SGT throughout the gastrointestinal system was statistically significant ($p<0.001$).

Tengse et al. (2017) conducted a study to optimize green tea extract and maltodextrin by spray drying at several percentages, yielding values of phenolic compounds between 33.48 and 58.19 mg EAG/g dry tea. Our phenolic content results are comparable to those of their study. Navarro-Flores et al. (2020) reported in their study that phenolic compounds were rapidly released for 5 minutes, and after 10 minutes, the release stabilized, and the microcapsules showed a complete phenol release of close to 97% for all treatments. They reported that the gum maltodextrin complex wall material provided a stronger phenolic compound interaction than the maltodextrin and protein complex, and there was a statistical difference between them. However, no significant difference was observed after 5 minutes. They reported that these results could be explained by the dispersion of the microcapsules in water, where the encapsulation agents are highly soluble.

Table 1. Total phenolic substance amount of tea samples throughout the *in vitro* gastrointestinal system

Çizelge 1. *İn vitro* gastrointestinal sistem boyunca çay örneklerinin toplam fenolik madde miktarı

GIS Tract	Total Phenolic Content (mg GAE/100mL)		
	GT	SGT	Sig.
Mouth 0. min	112.19±2.02^{b}	106.74±1.34^{de}	ns
Mouth 5. min	106.44±2.26^{bc}	102.12±0.17^{e}	ns
Stomach 0. min	109.58±3.68^{b}	105.43±3.18^{de}	ns
Stomach 60. min	130.66±3.35^{a}	112.96±5.11^{c}	ns
Stomach 120. min	126.40±4.36^{a}	131.32±0.25^{a}	ns
Small Intestine 0. min	99.99±3.18^{cd}	122.26±3.51^{b}	*
Small Intestine 60. min	98.09±2.52^{d}	102.83±1.51^{de}	ns
Small Intestine 120. min	113.61±0.33^{b}	109.11±0.67^{cd}	*
	***	***	

GIS: Gastrointestinal System
a-e: The difference between the means given with different letters in the same column is statistically significant
*p<0.05, ***p<0.001, ns: non-significant

Antioxidant activity

Antioxidant activity (%) values of the samples are given in Table 2. At 0 minutes, the antioxidant activity of the GT sample in the mouth region was 78.83±2.36, while it was 75.07±1.38 for the SGT sample. It was determined that the difference between the antioxidant activity values of these two tea samples at the beginning was not statistically significant. However, statistically significant differences were observed only in the stomach at 60 and 120 minutes (p<0.05). The overall change in antioxidant activity of the GT and SGT samples throughout the gastrointestinal system was found to be statistically significant (p<0.001).

Tengse et al. (2017), reported that the DPPH activity was higher at low temperature, while antioxidant activity decreased as the temperature increased due to a reduced interaction between antioxidants and free radicals. Results showed that total antioxidant activity, as measured by DPPH method, varied between 47.15% and 73.46%. In the experimental design, the highest DPPH scavenging activity was observed at 120ºC with 25% green tea extract concentration at 1:2 core-wall ratio. Parez et al. (2022) *in vitro* antioxidant assays such as DPPH, reducing power, and metal chelating activity under a simulated gastrointestinal system demonstrated the bioactivity of the encapsulated with much higher values than the encapsulated form. Therefore, it can be predicted and concluded that the best way to improve the antioxidant potential of green tea extracts under simulated gastrointestinal conditions is to nano-encapsulate it using maltodextrin. The use of this nanotechnology may offer promising possibilities for the possible application of green tea extract as a new nutraceutical.

Table 2. Antioxidant activity of tea samples throughout the *in vitro* gastrointestinal system

Çizelge 2. *In vitro* gastrointestinal sistem boyunca çay örneklerinin antioksidan aktivitesi

GIS Tract	Antioxidant Activity (%)		
	GT	SGT	Sig.
Mouth 0. min	78.83±2.36^{a}	75.07±1.38^{b}	ns
Mouth 5. min	84.40±0.79^{a}	80.15±5.81^{a}	ns
Stomach 0. min	79.46±7.97^{a}	82.31±1.77^{a}	ns
Stomach 60. min	51.18±0.10^{b}	25.28±1.86^{d}	**
Stomach 120. min	55.92±2.27^{b}	21.38±1.08^{d}	**
Small Intestine 0. min	53.13±5.61^{b}	58.57±2.07^{c}	ns
Small Intestine 60. min	23.96±0.98^{c}	25.07±0.99^{d}	ns
Small Intestine 120. min	22.14±2.76^{c}	25.35±4.14^{d}	ns
	***	***	

GIS: Gastrointestinal System
a-d: The difference between the means given with different letters in the same column is statistically significant
*p<0.05, **p<0.01, ***p<0.001, ns: non-significant

Gallic Acid, Catechin, Epicatechin, Epigallocatechin Gallat and Narginin

Table 3 presents data on the concentrations of gallic acid and naringin phenolic compounds along the *in vitro* gastrointestinal tract of GT and SGT samples. While the gallic acid amount was determined as 0.96±0.01 mg/100 mL in the mouth region of the GT sample at minute 0, while it was 0.94±0.01 mg/100 mL in the SGT sample. No significant difference was found between the initial gallic acid amounts of the two tea samples ($p>0.05$). However, an important difference was observed in the measurements at minute 5 in the mouth region ($p<0.05$). Gallic acid concentration varied significantly between tea types across all gastrointestinal tract regions ($p<0.001$). Regarding naringin amounts, the initial concentration of the GT sample in the mouth region was 0.50±0.01 mg/100 mL, while it was 0.51±0.02 mg/100 mL in the SGT sample. There was no significant difference between these two samples at the initial measurement ($p>0.05$). However, the differences between the naringin amounts at all measurement points (0, 60, and 120 minutes) in the stomach region and the small intestine region were found to be statistically significant ($p<0.05$). Most of the changes in phenolic compound concentrations along the *in vitro* gastrointestinal tract of GT and SGT samples were statistically significant ($p<0.001$).

Table 3. Amount of gallic acid and naringin in tea samples throughout *in vitro* gastrointestinal system

Çizelge 3. *In vitro* gastrointestinal sistem boyunca çay örneklerindeki gallik asit ve naringin miktarı

GIS Tract	Gallic Acid Amount (mg/100mL)			Naringin Amount (mg/100mL)		
	GT	SGT	sig.	GT	SGT	Sig.
Mouth 0. min.	0.96±0.01^{a}	0.94±0.01^{a}	ns	0.50±0.01^{a}	0.51±0.01^{a}	ns
Mouth 5. min.	0.85±0.01^{b}	0.75±0.00^{c}	*	0.47±0.01^{b}	0.46±0.00^{b}	ns
Stomach 0. min	0.80±0.02^{c}	0.80±0.02^{b}	ns	0.45±0.01^{bc}	0.36±0.01^{e}	ns
Stomach 60. min	0.84±0.02^{b}	0.82±0.04^{b}	ns	0.36±0.01^{d}	0.47±0.02^{b}	ns
Stomach 120. min	0.84±0.03^{b}	0.80±0.01^{b}	ns	0.43±0.01^{c}	0.39±0.00^{cd}	**
Small Intestine 0. min	0.54±0.01^{d}	0.53±0.01^{d}	ns	0.15±0.00^{e}	0.36±0.01^{e}	*
Small Intestine 60. min	0.06±0.00^{e}	0.70±0.00^{e}	ns	0.45±0.01^{bc}	0.38±0.01^{de}	*
Small Intestine 120. min	0.02±0.00^{f}	0.03±0.00^{f}	ns	0.36±0.00^{d}	0.42±0.01^{c}	**
	***	***		***	***	

GIS: Gastrointestinal System

a-f: Differences between means given with different letters in the same row are statistically significant

*p<0.05, **p<0.01, ***p<0.001, ns: non-significant

Table 4 presents data on the concentrations of catechin, epicatechin, and epigallocatechin gallate (EGCG) phenolic compounds along the in vitro gastrointestinal tract of GT and SGT samples. Catechin levels, it was determined that the mouth region of the GT sample contained 1.02±0.02 mg/100 mL catechin at minute 0. In contrast, this amount was 0.53±0.00 mg/100 mL in the SGT. The difference between the initial catechin amounts of these two samples was statistically significant ($p<0.01$). However, the difference between the catechin concentrations in the stomach region at minute 60 was not significant ($p>0.05$). In all other regions, the amounts of catechin showed significant differences between tea types ($p<0.05$). The epicatechin amounts in the mouth region of the GT sample and SGT at minute 0 were determined as 0.12±0.00 mg/100 mL and 0.23±0.01 mg/100 mL, respectively. The difference between the initial epicatechin amounts was statistically significant ($p<0.01$). Except for the measurements at the 120th minute of the small intestine region, significant differences were found between the epicatechin amounts in all other regions ($p<0.05$). When evaluated in terms of EGCG concentration, the GT sample was determined as 10.62±0.19 mg/100 mL at minute 0 in the mouth region, and the SGT sample as 10.05±0.02 mg/100 mL. No significant difference was observed between these two samples at the beginning ($p>0.05$). However, the differences between the EGCG amounts measured at the 5th minute of the mouth region and the 120th minute of the small intestine region were statistically significant ($p<0.05$). Epigallocatechin gallate (EGCG) has been found to be partially degraded in stomach acid but exhibited higher bioactivity in the small intestine.

Table 4. Amount of catechin, epicatechin, and epigallocatechin gallate in tea samples throughout *in vitro* gastrointestinal system

Çizelge 4. *In vitro* gastrointestinal sistem boyunca çay örneklerindeki kateşin, epikateşin ve epigallokateşin gallat miktarı

GIS Tract	Catechin Amount (mg/100mL)			Epicatechin Amount (mg/100mL)			Epigallocatechin Gallate Amount (mg/100 mL)		
	GT	SGT	Sig	GT	SGT	Sig	GT	SGT	Sig
Mouth 0. min.	1.02±0.02 ^{a}	0.53±0.00 ^{c}	**	0.12±0.00 ^{c}	0.23±0.01 ^{c}	**	10.62±0.19^{a}	10.01±0.13 ^{a}	ns
Mouth 5. min.	0.64±0.01 ^{c}	0.48±0.00 ^{d}	**	0.25±0.01 ^{a}	0.30±0.00 ^{a}	**	10.89±0.23^{a}	10.05±0.02 ^{a}	*
Stomach 0. min	0.68±0.02 ^{c}	0.55±0.01 ^{c}	*	0.22±0.01 ^{b}	0.11±0.00 ^{e}	**	10.25±0.35^{a} ^{b}	9.78±0.29^{a}	ns
Stomach 60. min	0.54±0.01 ^{d}	0.44±0.02 ^{e}	*	0.11±0.01 ^{d}	0.26±0.01 ^{b}	**	9.87±0.25^{bc}	9.73±0.44^{a}	ns
Stomach 120. min	0.92±0.03 ^{b}	0.85±0.00 ^{b}	ns	0.21±0.01 ^{b}	0.03±0.00 ^{g}	**	9.87±0.35^{bc}	9.72±0.02^{a}	ns
Small Intestine 0. min	0.03±0.00 ^{g}	1.06±0.04 ^{a}	**	0.05±0.00 ^{e}	0.17±0.00 ^{d}	**	10.68±0.34^{a}	9.78±0.28^{a}	ns
Small Intestine 60. min	0.18±0.00 ^{e}	0.36±0.00^{f}	***	0.03±0.00^{f}	0.09±0.00^{f}	*	9.52±0.25^{c}	8.95±0.13^{b}	ns
Small Intestine 120. min	0.12±0.00^{f}	0.48±0.00 ^{d}	***	0.02±0.00^{f}	0.02±0.00 ^{g}	ns	9.55±0.03^{c}	8.63±0.06^{b}	**
	***	***		***	***		**	**	

GIS: Gastrointestinal System

a-g: Differences between means given with different letters in the same row are statistically significant

*p<0.05, **p<0.01, ***p<0.001, ns: non-significant

As shown in Figure 2, the loss rates of antioxidant activity and analyzed polyphenol compounds were compared between the oral (0 min) and small intestine (120 min) digestion stages for GT and SGT samples. The findings revealed that the digestion stability of the compounds varied among the formulations. In terms of antioxidant activity, approximately 71.9% loss was observed in the GT sample, while 66.2% was observed in the SGT sample. These results indicate that both green tea samples were unable to retain their antioxidant activities to a great extent during in vitro digestion; however, the SGT sample showed slightly higher activity. Gallic acid exhibited a very high loss rate (approximately 98%) in both samples, indicating that it was degraded under digestive conditions. In contrast, the level of decrease in naringin levels was approximately 28.0% for the GT sample and 17.6% for the SGT sample. These low values indicate that naringin was significantly resistant during the digestion process. Catechin was lost by 82.4% in the GT sample, while it was only about 9.4% in the SGT sample. This remarkable difference suggests that SGT formulation may increase catechin stability during digestion. Epicatechin was lost by 83% in the GT sample and 91% in the SGT sample. This indicates that both tea samples are labile for Epicatechin, and Epicatechin is largely degraded under simulated gastrointestinal conditions. EGCG was found to be highly stable in digestive conditions in both samples, losing 10.1% in GT and 13.8% in SGT. As a result, the loss of antioxidant activity and polyphenol compounds during digestion varied depending on the compound and formulation. EGCG showed the highest stability, while Gallic acid showed a high loss. SGT showed lower loss rates except for Gallic acid and Epicatechin. These findings suggest that polyphenol stability during digestion is influenced not only by digestion conditions but also by formulation strategies and the type of carrier system employed.

Cruz-Molina et al. (2021) analyzed the content of phenolic compounds in the free extract at pH 6 was primarily epicatechin (68.12%), followed by epigallocatechin gallate (12.38%) and catechin (9.42%), based on the phenolic profiles of free and encapsulated green tea extracts during storage at various pHs. It was reported that no EGC was found at the 30-day storage end. A phenolic molecule may not be useful as an antioxidant or antibacterial agent if it is shown to be unstable during food processing conditions like heating, frying, or microwaving, or if it is present in foods exposed to high pH. For instance, the tea polyphenol epigallocatechin gallate, an ester of gallic acid, should be unstable as epigallocatechin is stable at high pH values while gallic acid is not (Friedman and Jürgens, 2000).

Green tea is an essential component of a healthy lifestyle due to its potent antioxidants and concentration of polyphenolic content. However, the transformation of these beneficial compounds throughout the digestive system has not yet been fully elucidated. Gastrointestinal conditions such as stomach acidity and bile may affect the structure and activity of phenolic substances in green tea. Although human studies are ideal for determining these changes, they are often impractical due to technical, financial and ethical limitations. Although animal models offer an alternative approach, they are generally not preferred due to the difficulty of methods such as surgical interventions. To overcome these challenges, *in vitro* gastrointestinal system models have become increasingly popular because they offer reproducibility and flexibility. The *in vitro* gastrointestinal system model is important in determining how the phenolic content of green tea coated with green tea changes throughout the digestive system. This study aims to understand the chemical transformation of green tea and maltodextrin coated green tea during the digestive process and to use this information to develop more effective consumption strategies for individuals seeking a healthy life. In parallel, recent studies have shown that EGCG, one of the major catechins in green tea, inhibits coronavirus replication by interfering with 3CL-protease activity (Jang et al., 2021). Therefore, understanding its stability and transformation during digestion is crucial for evaluating its biological effectiveness beyond antioxidant capacity.

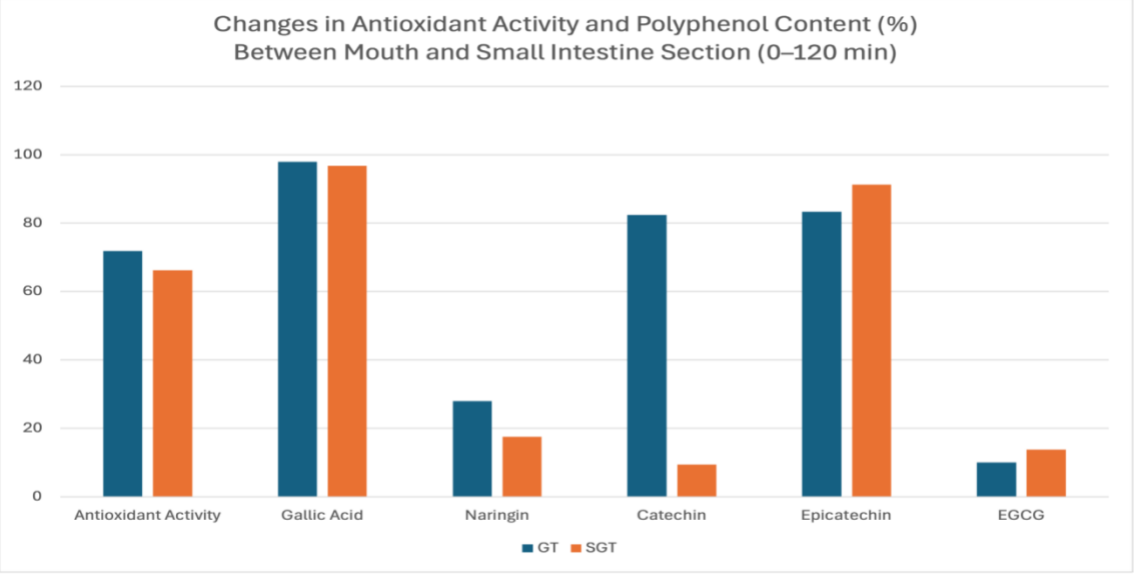

Figure 2. Changes in antioxidant activity and polyphenol content (%) between mouth and small intestine section (0-120 min)

Şekil 2. Ağız ve ince bağırsak bölümü arasında antioksidan aktivite ve polifenol içeriğindeki (%) değişiklikler (0-120 dk)

Results showed that green tea and maltodextrin coated green tea samples showed differences in total phenolic content, antioxidant activity and polyphenolic components throughout the *in vitro* gastrointestinal tract. Although the initial values were generally not statistically significant in both samples, significant changes were observed in different regions of the gastrointestinal tract. Especially in the small intestine stage, total phenolic content and antioxidant activity showed significant changes ($p<0.05$). In addition, statistically significant changes were found in the amounts of components such as catechin, epicatechin, epigallocatechin gallate and naringin ($p<0.001$). These findings suggest that maltodextrin coating may influence polyphenol stability and bioavailability and that their behavior in the gastrointestinal tract may differ. Liu et al. (2022) demonstrated that phenolic extracts isolated from tea seed oil exhibited significant antioxidant capacity in both in vitro and in vivo models. They emphasized that the antioxidant activity was closely related to the structural characteristics and concentration of phenolic compounds. This supports the notion that not only digestive conditions but also the physical form and protective matrices of phenolics (such as maltodextrin coating) can significantly influence their stability and

biological potential during gastrointestinal transit. Moreover, Ma et al. (2022) investigated Pu-erh tea, a fermented dark tea, and found that solid-state fermentation significantly altered the levels of phenolic compounds. While catechins, such as EGCG and EC, decreased markedly after fermentation, compounds like quercetin and kaempferol increased, thereby impacting the antioxidant capacity. These results support the idea that not only digestion conditions but also tea type and processing (fermentation vs. non-fermentation) can substantially affect the chemical stability and biological potential of tea polyphenols throughout the digestive process. This cross-validation highlights the importance of understanding tea matrix transformations under various physiological and processing conditions.

The chemical composition of green tea samples used as raw materials in the studies will vary depending on environmental factors such as the region where it is grown, climate, soil structure and harvest time, which will be a challenge in standardized product production. In addition, the changes that occur throughout the gastrointestinal system do not follow a linear decrease but instead fluctuate. Therefore, further research is needed with different coating materials and/or coating materials that can be used together in a mixture with maltodextrin.

CONCLUSIONS

This study reveals how the changes in the phenolic compound profiles of GT and SGT samples differ throughout the *in vitro* gastrointestinal system. The results show that the maltodextrin coating process may affect the stability and bioavailability of phenolic compounds. When examined for phenolic compounds such as total phenolic acid, gallic acid, catechin, epicatechin, epigallocatechin gallate, and naringin, it is observed that the coating process may be beneficial in preserving some compounds. Nevertheless, their initial concentrations and behavior in the gastrointestinal system may vary significantly with the coating material.

However, the effects of the coating process are particularly pronounced in the stomach and small intestine, highlighting the need to optimize the coating materials to increase the bioavailability of phenolic compounds. Furthermore, the variations in the behavior of different compounds emphasize the importance of understanding the dynamics of individual phenolic compounds in such biological systems.

In conclusion, the effects of maltodextrin coating on polyphenol stability and bioavailability of GT are apparent. This suggests that the behavior of GT in the gastrointestinal system is more complex than expected. The nonlinearity of the changes occurring during the digestive process emphasize the need for further in-depth research in this field. Therefore, future studies should explore a broader range of coating materials and maltodextrin combinations to gain a more comprehensive understanding of green tea component. Such studies will be critical for increasing the bioavailability and more effective use of essential nutrients such as green tea.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: MİP, RP; analysis and interpretation of data: MİP, RP, CK; statistical analysis: RP; visualization: MİP, RP; writing manuscript: MİP, RP, CK.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

Ethics approval was obtained from the Afyonkarahisar Health Sciences University Non-Interventional Scientific Research Ethics Committee (dated 1 September 2023 and no. 2023/401).

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Research Article
(Araştırma Makalesi)

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A simulation model for estimating 2D wetting patterns in drip irrigation systems

Damla sulama sistemlerinde 2B ıslatma desenlerinin tahmini için bir simulasyon modeli

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ABSTRACT

Objective: The aim of this study is to develop a model that allows the 2D wetting pattern that occurs in drip irrigation systems to be analytically defined.

Material and Methods: In the model, the wetting pattern is simulated as a truncated ellipse. Wetting radius at the soil surface, the maximum wetting depth and width in the soil profile, and the depth of this maximum wetting width from the soil surface were taken into account. The experiments were carried out under uniform profile conditions and on soil samples with a loamy sand texture. The investigation was carried out for different emitter discharges.

Results: The wetting radius, maximum wetting depth, and cross-sectional area of the wetting pattern occurring at any time t of the water application period under each emitter discharge are estimated with the determination coefficients of 0.961, 0.947 and 0.995, respectively, by the numerical models developed in this study. The results show that the values of 2D cross-sectional area also increase as the emitter discharge increases.

Conclusion: The results of this study indicate that the proposed model defines the overall shape of the wetting pattern and can be used to determine the cross-sectional area of the pattern.

ÖZ

Amaç: Bu çalışmanın amacı, damla sulama sistemlerinde oluşan 2 boyutlu ıslatma deseninin analitik olarak tanımlanmasına olanak tanıyan bir model geliştirmektir.

Materyal ve Yöntem: Modelde ıslatma deseni kesik elips olarak simüle edilmiştir. Toprak yüzeyindeki ıslatma yarıçapı, toprak profilindeki maksimum ıslatma derinliği ve genişliği ve bu maksimum ıslatma genişliğinin toprak yüzeyinden itibaren derinliği dikkate alınmıştır. Denemeler, uniform toprak profili koşullarında ve tınlı kum bünyeye sahip toprakta gerçekleştirilmiştir. Araştırma, farklı damlatıcı debilerinde gerçekleştirilmiştir.

Araştırma Bulguları: Bu çalışmada geliştirilen sayısal modeller, farklı damlatıcı debilerinde herhangi bir t anında oluşan ıslatma yarıçapı, maksimum ıslatma derinliği ve ıslak kesit alanını sırasıyla 0.961, 0.947 ve 0.995 belirleme katsayıları ile tahmin etmektedir. Sonuçlar, damlatıcı debisi arttıkça 2B kesit alanının da arttığını göstermektedir.

Sonuç: Bu çalışmanın sonuçları, önerilen modelin ıslatma deseninin genel şeklini tanımladığını ve desenin ıslatma yarıçapı, maksimum ıslatma derinliği ve kesit alanını belirlemek için kullanılabileceğini göstermiştir.

INTRODUCTION

Drip irrigation is considered worldwide as a way to sustainably utilize deficit resources in irrigation applications. On the other hand, emitter discharge, irrigation time and soil hydraulic properties are not sufficiently considered in the design and management of drip irrigation systems. Several studies have been conducted for analytical (Philip, 1984; Chu, 1994), numerical (Lazarovitch et al., 2007) or empirical (Zur, 1996; Sepaskhah & Chitsaz, 2004; Amin & Ekhmaj, 2006; Elmaloglou & Malamos, 2006; Molai et al., 2008; Thabet & Zayani, 2008; Dabral et al., 2012) formulations to describe the shape of the wetting pattern and to estimate its components.

The wetting pattern is one of the main variables in the design and management of a drip irrigation system. The dimensions of the pattern are critical for choosing the appropriate spacing between the laterals and for choosing the correct spacing between emitters. Elmaloglou & Diamantopoulos (2007) carried out a study on a cylindrical flow model. In this study, two types of soils and two discharges were used. The vertical component of the wetting pattern was studied for pulse irrigation and continuous irrigation. The difference between the irrigation applications was eliminated for longer time. Bhatnagar & Chauhan (2008) devised a numerical model in order to to estimate the wetting pattern under an emitter. The spheroidal coordinate system was considered in the modeling. The results were evaluated comparatively with different solution approaches. Tian et al. (2011) devised a numerical model for the two-dimensional movement of water in a drip irrigation system. The 2D Richards equation was used to describe the movement of water in soil. The model was evaluated for the simulation of water movement in soil for the long-term water application conditions.

Drip irrigation is used in many arid and semi-arid regions. If the system is well designed and properly operated, high efficiency of water application and high crop yields can be achieved. Soil moisture distribution patterns were predicted by using the neutron scattering technique for the surface and subsurface drip irrigation conditions in the investigation carried out by Badr & Abuarab (2013). Soil moisture distribution was evaluated as a function of variation in the distance between the distributors and lateral pipes. A neutron moisture meter was used to measure soil moisture. The results indicate that the distribution of soil moisture and its uniformity under the surface emitters was highly influenced by the distance between the emitters and less by the lateral pipes. Kuklik & Dai Hoang (2014) determined the geometry of wetted soil volume under surface drip irrigation. The infiltration of water under an emitter and the spatial distribution of water in the soil profile are the main components of the model. The experiments were carried out for different emitter discharges and irrigation periods. The width and depth of the wetting pattern were determined. However, most of the evaluations were carried out using the plots for different conditions rather than the mathematical formulation. The equidistant line sources were used by Elmaloglou et al. (2013) for the simulation of soil water dynamics under surface drip irrigation. In this model, the two-dimensional distribution process was considered. The soil water distribution patterns were investigated for two soil types and two different emitter discharge. The results of the numerical model showed that the soil water dynamics mainly depend on the hydraulic properties of the soil, the distance between the drip lines and the irrigation depth.

The infiltrated water in the soil under a surface emitter forms a wetted zone whose shape resembles a semi-ellipse or a truncated sphere, depending on the total amount of applied water, emitter discharge and the hydraulic properties of the soil. Moncef & Khemaies (2016) devised an approach to estimate the wetted soil volume for a drip irrigation system. It was assumed that the wetting pattern has a semi-elliptical shape whose diagonals are merged with the soil surface and the axis of symmetry. The initial water content, the hydraulic conductivity of the soil and the water content in the wetting pattern are some of the components of the model. The study was conducted on three soil types. It was found that the

predicted values were close to the results of the Healy & Warrick (1988) model. Kilic (2020) developed a model that enabled the prediction of the 3D volume wetting pattern under an emitter. The wetted soil volume was modeled. Al-Ogaidi et al. (2016) carried out an investigation for drip irrigation with two discharge rates and two soil textures. The vertical and horizontal progress of the wetting pattern was estimated by an empirical model for different application times. The depth of the wetting pattern and the wetting radius at the soil surface were estimated. The same procedure was used to estimate the shape of the wetting pattern.

The aim of this study is to develop models that determine the 2D cross-sectional area of the wetting pattern, the wetting radius and maximum wetting depth that occur under a surface emitter with different discharges at each time t of the water application period.

MATERIALS and METHODS

Experimental procedures

This research was conducted in the Department of Agricultural Engineering and Technologies at Faculty of Agriculture at Ege University. Details of the emitter discharge experiments were described in the investigation carried out by Demir et al. (2019). Emitters with discharges of 1.2, 1.7, 2.6, 3.0 and 4.0 L h^{-1} at a working pressure of 1.0 bar were used in the experiments.

The properties of the soil used for the experiment are listed in Table 1. The initial moisture content of the soil was 4-6%, as indicated by the pre-irrigation analysis.

Table 1. The properties of the soil used for the experiments

Çizelge 1*. Denemelerde kullanılan toprak özellikleri*

Texture	Loamy sand
pH	7.72
Salt (%)	0.015
Lime (%)	3.3
Organic material (%)	0.81
Sand (%)	77.12
Silt (%)	16
Clay (%)	6.88
Moisture holding capacity (%)	30.11

Transparent Plexiglas containers 60x60x10 cm were used to determine the water distribution in the soil. Grid lines were drawn at 10 cm intervals on the outside of the boxes so that water movement in the soil could be easily observed. During the experiments, the dried soil samples were homogeneously filled into the Plexiglas containers and the top of the soil samples were smoothed. The water was applied through the emitters in the center of the top of the containers and the water movement was observed during the experiments.

Development of models to estimate the parameters of the wetting pattern

The real-time video recordings were recorded for each experiment during the period of water application (Figure 1a). The video recordings were converted to images with an interval of five minutes. It can be seen that the soil profile wetted by the emitters was fitted to an ellipse. This output was used to measure the baseline data associated with an ellipse on the images of the soil profiles wetted by each emitter (Figure 1b).

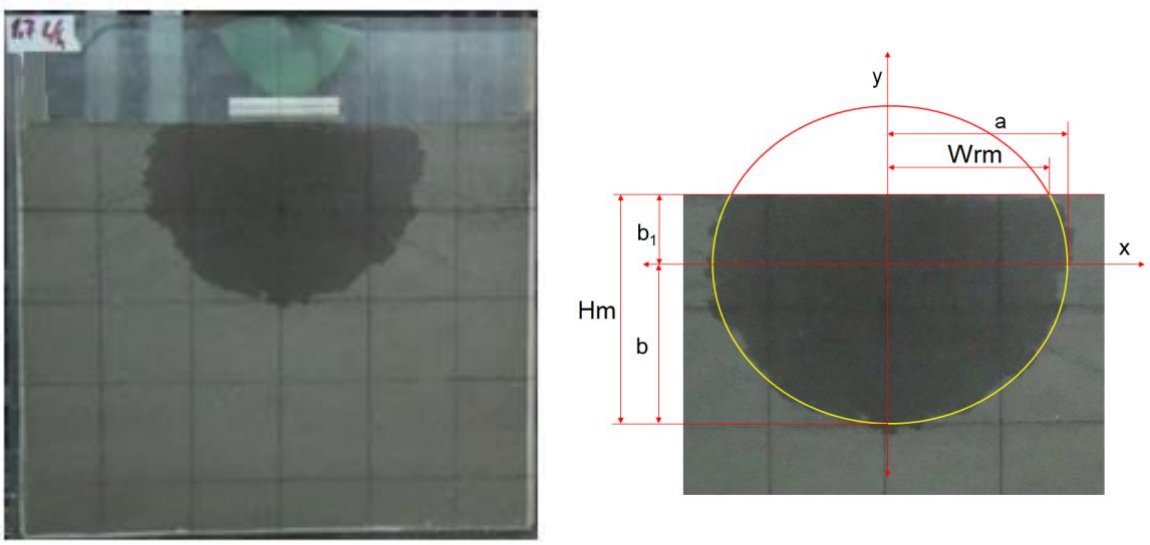

Figure 1. a) Observation of the wetting pattern, b) Main parameters of the wetting pattern.

Şekil 1. *a) Islatma deseninin gözlenmesi, b) Islatma deseninin ana parametreleri.*

In this study, four main parameters were considered in defining the 2D pattern that occurs under an emitter. These are the wetting radius, the wetting depth and width and their distance from the soil surface. These parameters define the overall pattern that occurs in a drip irrigation system.

The 2D pattern under a surface emitter is simulated as a truncated ellipse (Figure 1b). The reason for this is that the maximum wetting width almost always occurs below the soil surface. Apart from this, the shape of the ellipse has a practical use in the application. This is another reason why the wetting pattern was simulated in this shape.

The main general shape representing the wetting patterns occurring in the experiments is shown schematically in Figure 2.

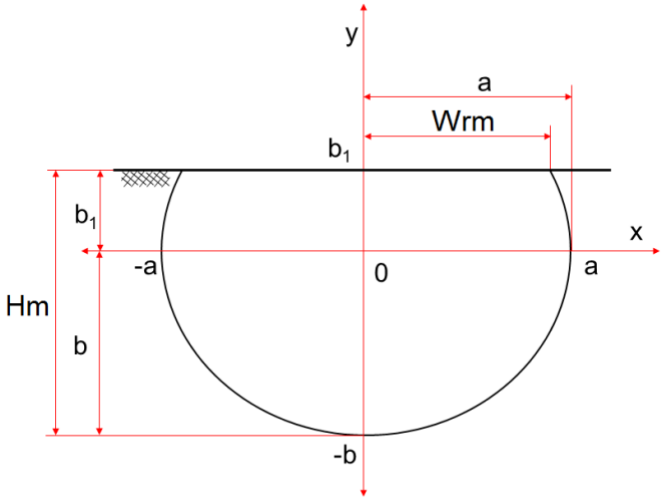

Figure 2. Simulation of the 2D wetting pattern, which becomes a truncated ellipse under a surface emitter.

Şekil 2. *Damlatıcı altında oluşan ıslatma deseninin kesik elips şeklinde 2B simülasyonu.*

The center of the ellipse in Figure 1 is the origin and the major axis is the x-axis. If you set up the equation for the central ellipse, you get equation (1).

$$x^2 = a^2\left(1 - \frac{1}{b^2}y^2\right) \quad (1)$$

In Figure 1, the area surrounded by the points –b, b1, Wr and a forms the cross-section. The cross-sectional area surrounded by these points is given by equation (2).

$$A = \int_{-b}^{b1} a\sqrt{\left(1 - \frac{y^2}{b^2}\right)}dy \quad (2)$$

If equation (2) is rearranged, the cross-sectional area of the pattern is obtained by carrying out equation (3) as follows.

$$A = a\left(\frac{b^2 \arcsin\left(\frac{b_1}{b}\right) + b_1\sqrt{b^2 - b_1^2}}{2b} + \frac{\pi b}{4}\right) \quad (3)$$

Y is also the symmetry axis of the 2D wetting pattern (Figure 2). The area of the entire 2D wetting pattern under an emitter can be determined by equation (4).

$$Ae = 2xA \quad (4)$$

The meaning of the symbols used in the equations and shown in Figure 2 is as follows. a is the maximum wetting radius (cm); b is the distance between the maximum wetting radius and the depth (cm); b1 is the distance from the maximum wetting radius to the soil surface (cm); A is the cross-sectional area of the right side of the wetting pattern with respect to the symmetry axis (cm^2); Ae is the experimental cross-sectional area of the entire pattern under an emitter (cm^2), Wrm is the measured wetting radius on the soil surface (cm) and Hm is the measured maximum wetting depth from the soil surface (cm).

Equation (3) and equation (4) provide a solution for the case where the value of the parameter b1 is zero. In this condition, the maximum wetted width corresponds to the diameter at the soil surface.

In the next step of the investigation, the sizes of the cross-sectional areas of the wetting patterns are defined as a function of time and the emitter discharge. In addition, the wetting radius and the maximum wetting depth that occur under a surface emitter with different discharges at each time t of the irrigation period are estimated by the numerical models developed in this study (equations 4, 6 and 7).

RESULTS and DISCUSSION

The temporal variations of wetting radius and maximum wetting depth with five different emitter discharges are shown in Figure 3.

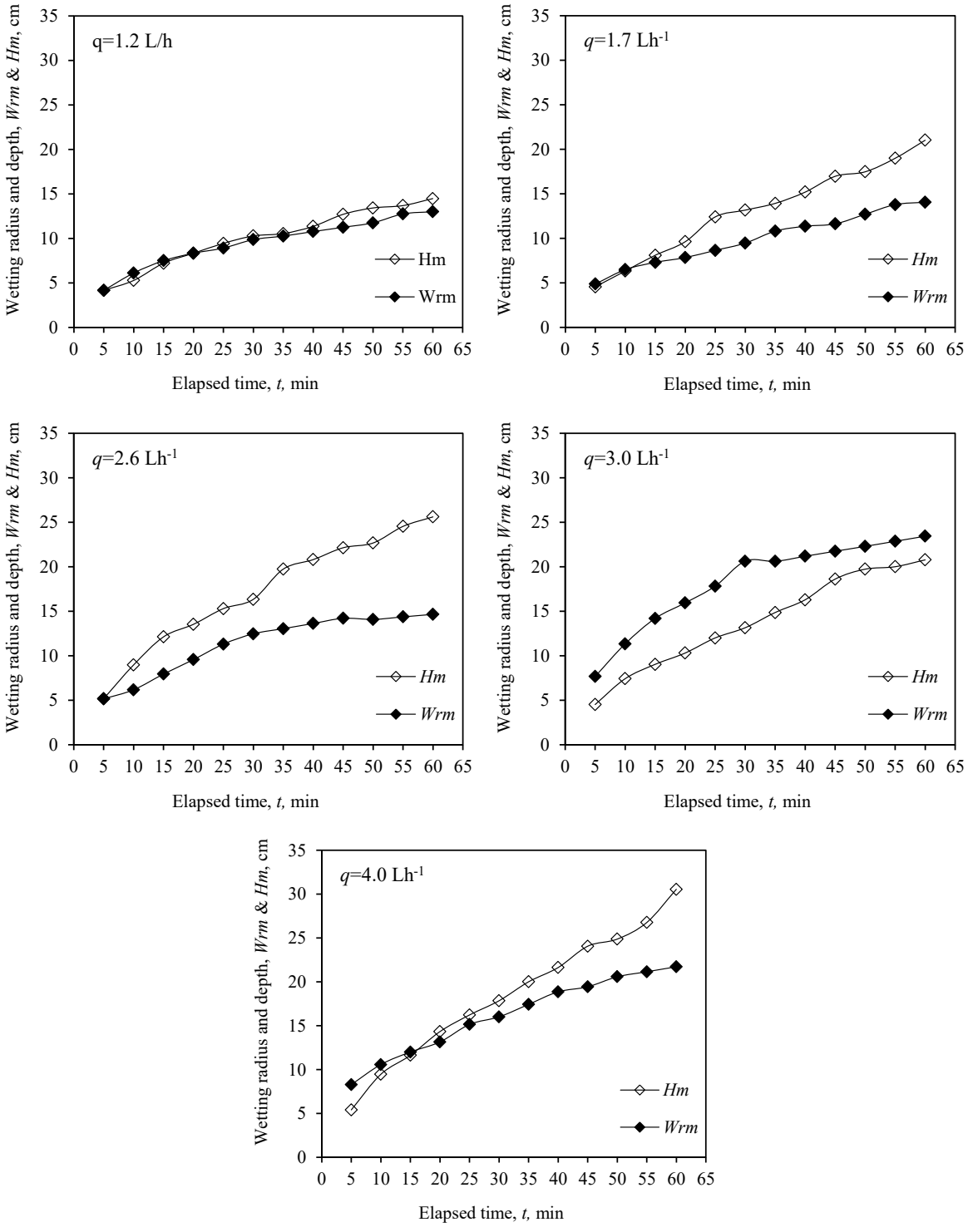

Figure 3. Temporal variations of the wetting radius and maximum wetting depth of the 2D wetting patterns occurring under different emitter discharges.

Şekil 3. *Farklı damlatıcı debilerinde meydana gelen 2B ıslatma desenlerinde ıslatma yarıçapı ve maksimum ıslatma derinliğinin zamansal değişimi.*

The wetting radius and maximum wetting depth show an increase as a function of time of water application in 2D wetting patterns occurring under different emitter discharges (Figure 3). The cross-sectional areas of the wetting patterns under different emitter discharges according to equation (4) are shown in Figure 4.

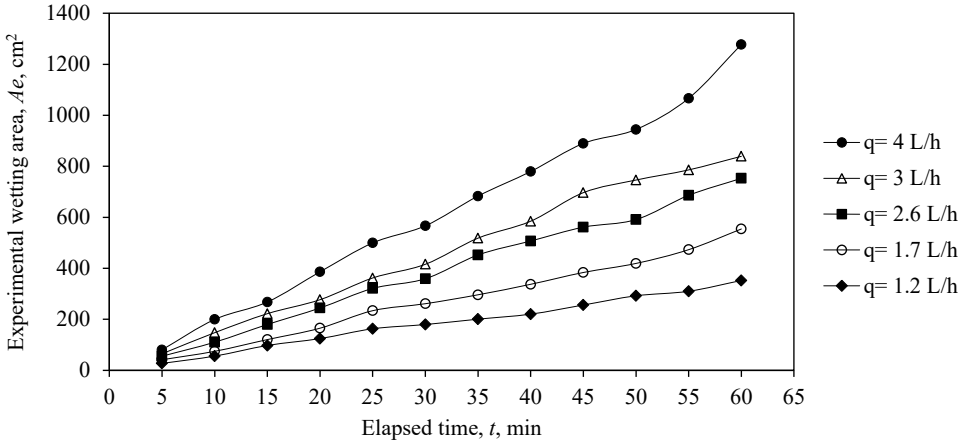

Figure 4. Temporal variations of the experimental cross-sectional areas of the wetting patterns occurring under different emitter discharges according to equation (4).

Şekil 4. *Eşitlik (4)'e göre farklı damlatıcı debilerinde meydana gelen ıslatma desenlerinde deneysel kesit alanlarının zamansal değişimi.*

The experimental cross-sectional areas of the wetting patterns occurring under the emitter discharges of 1.2, 1.7, 2.6, 3.0 and 4.0 L h^{-1} took the values of 352.35 cm^2, 554.29 cm^2, 752.91 cm^2, 839.30 cm^2 and 1278.02 cm^2 at the end of the 60 min water application, respectively (Figure 4). The increase in emitter discharge also increases the cross-sectional areas of the wetting patterns (Figure 4). These results are consistent with the findings of Al-Ogaidi et al. (2016).

Equation (5) applies to the total emitter discharges and the water application periods in this study. The equation is given below;

$$Ap = 4.3188\ q^{1.0045}\ t^{1.0316} \qquad R^2 = 0.995 \qquad (5)$$

In equation (5), Ap is the predicted area of the pattern (cm^2) occurring at time t of the water application period. q is the emitter discharge (L h^{-1}). t is an arbitrary time (min) during the water application period for estimating the area of the pattern.

Comparison between the experimental and predicted cross-sectional area of the wetting pattern occurring at any time t are shown in Figure 5.

The experimental and predicted areas of the pattern (Ae and Ap) were compared. The model provides satisfactory results within the range of operating and emitter discharges used in the experiments. As can be seen in Figure 5, a good agreement between Ae and Ap is obtained with a coefficient of determination of 0.995 between 5 and 60 minutes. The results show that the model given in equation (5) can be used to estimate the areas of the wetting patterns that occur at different emitter discharges at each time t of the water application period. In this way, an water application period compatible with the cross-section of the wetting pattern and the root zone of the plants can be determined. This also allows optimal planning of the irrigation timing.

In addition, the radius of wetting at the soil surface is predicted using the following equation (6).

$$Wrp = -132.3 + 273.6\ q - 198.2\ q^2 + 59.8\ q^3 - 6.29\ q^4 + 0.388\ t - 0.003\ t^2 \qquad (6)$$

R^2=0.961

Good agreement was obtained between the measured and predicted values of the wetting radius with the coefficient of determination 0.961 between 5 and 60 minutes (Figure 6). The results show that the solution approach developed in this study can be used to estimate the wetting radius that occurs at any time t during the water application period.

Furthermore, the maximum wetting depth that occurs under a surface emitter with different discharges is predicted by applying equation (7).

$$Hp = 90.34 - 198.82\,q + 149.39\,q^2 - 45.18\,q^3 + 4.74\,q^4 + 0.435\,t - 0.002\,t^2 \qquad (7)$$

R^2=0.947

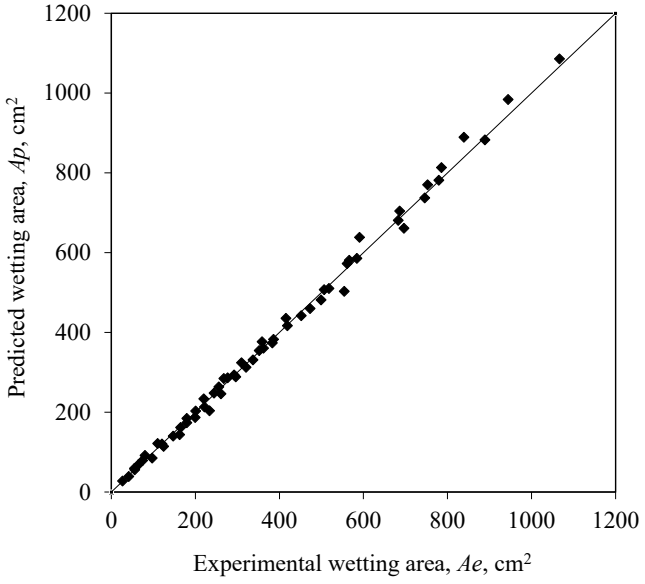

Figure 5. Comparison between the experimental and predicted wetting area.

Şekil 5. *Deneysel ve tahmin edilen ıslak kesit alanı büyüklüklerinin karşılaştırılması.*

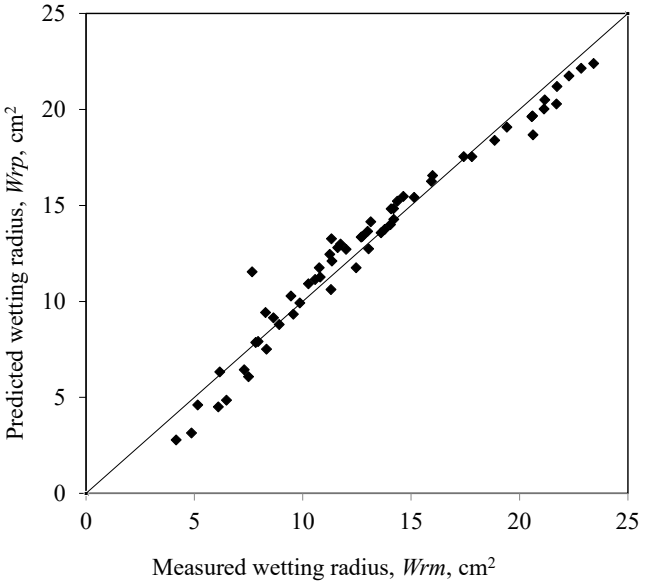

Figure 6. Comparison between the measured and predicted wetting radius.

Şekil 6. *Ölçülen ve tahmin edilen ıslatma yarıçaplarının karşılaştırılması.*

The measured and predicted values of maximum wetting depth were found to be compatible with each other with a coefficient of determination of 0.947 for each time t of the water application period between 5 and 60 minutes. This agreement is valid for the whole emitter discharges which were used in the experiments (Figure 7). These results indicate that the model proposed in this study can be used to estimate the maximum wetting depth for each time t of the water application time under a surface emitter. This method can be used for optimum irrigation timing for drip irrigation systems.

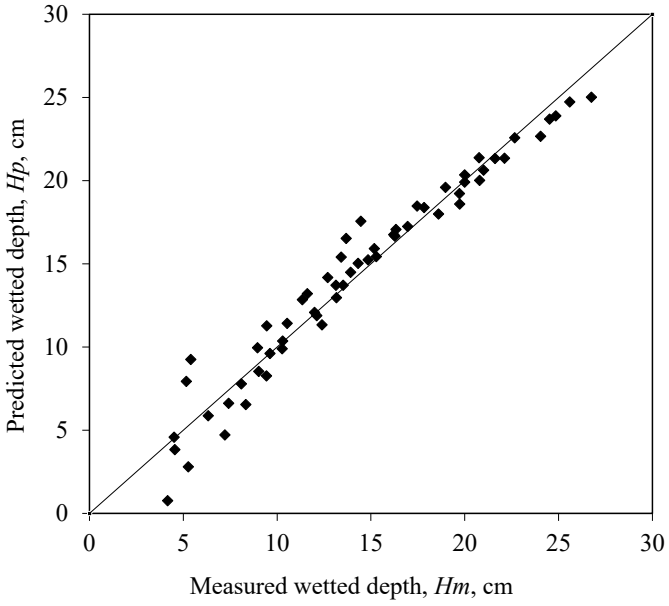

Figure 7. Comparison between the measured and predicted wetting depth.

Şekil 7. *Ölçülen ve tahmin edilen ıslatma derinliklerinin karşılaştırılması.*

A study was conducted by Bhatnagar & Chauhan (2008) to predict the components of the wetting pattern under a surface emitter. A numerical modeling approach was used. A time-dependent varying wetting radius was considered. The model was verified by the results of the investigation conducted by Bresler (1978) and Taghavi et al. (1984) . When the numerical model developed by Bhatnagar & Chauhan (2008) was run for q_1=2100 cm^3 h^{-1} and q_2=3300 cm^3 h^{-1} discharges, the advance of the water front up to the radial distance (r) was estimated well. However, higher values were estimated by the model for the higher values of r than those observed. The reason for this situation was explained that it could be the edge effects in the experiments. In the present study, the cross-sectional areas of the wetting patterns that occurred under the 1.7, 2.6, 3.0 and 4.0 L s^{-1} emitter discharges showed increases as a function of the increase in discharge and water application time (Figure 4). In addition, by conducting the experiments for a larger number of emitter discharges, the changes in the magnitudes of the wetting pattern parameters could be observed in more detail (Figure 3). The areas of the wetting patterns as a function of time, the wetting radius on the soil surface and the wetting depth for each emitter discharge for each time t of the water application period can be estimated by the numerical models developed in this study (Figures 5, 6 and 7). High coefficients of determination for these parameters (0.995, 0.961 and 0.947) were obtained by the proposed model in this investigation. These findings show that the models developed in the study can be used to predict the values of the components of the pattern for each time t of the water application time for different emitter discharges. In this way, the most appropriate time for water application can be determined that provides the closest match between the pattern and the plant root zone. This is of great benefit for the optimal design and operation of drip irrigation systems and for planning the timing of irrigation.

Al-Ogaidi et al. (2016) conducted a study to estimate the wetting pattern that occurs under a surface drip irrigation system using an empirical model. When the emitter discharge was increased from 3 L h^{-1} to 4.5 L h^{-1}, the wetting radius and wetted depth also increased by 9.81% and 19.09%, respectively. The extent of the wetting pattern in the profiles with sandy soils were higher than that in the profiles with clayey soils, as the fine-textured soils can store more water than the coarse-textured soils. This delays the horizontal and vertical advance of water in fine-textured soils. These results are in general agreement with the results of Li et al. (2007). Moncef et al. (2002) used three different emitter discharges in the laboratory experiments conducted on silty soils. Li et al. (2003) conducted laboratory experiments on loamy soils for a range of emitter discharges. It was found that the model proposed by Al-Ogaidi et al. (2016) gave good results in the studies presented above. The proposed model underestimated the wetting diameter. In addition, a different value for the wetting depth was determined than in the previous studies. The reason given for these results was that the previous experiments had been carried out under completely different conditions. In the present study, the area of the whole wetting pattern is determined by a mathematical model. This solution technique is important because it ensures compatibility between the cross-section of the root zone and the wetting pattern in the soil profile under a surface emitter. In this way, a wetting pattern can be determined that is suitable for the development of the crop's root zone.

The previous empirical models developed by Schwartzman & Zur (1986), Malek & Peters (2011), Amin & Ekhmaj (2006), Al-Ogaidi et al. (2015) and Naglič et al. (2014) estimated only two points of the wetting pattern: the wetting diameter at the soil surface and the wetted depth. In contrast, the model proposed by Al-Ogaidi et al. (2016) also estimated the maximum wetting width that occurred below the soil surface in addition to these two points, but no model was developed. In the present study, the model in equation (5) was developed, which estimates the area of the total wetting pattern that occurs at each time t of the irrigation application time (Figure 5). Since the – previously mentioned parameters defining the overall wetting pattern are considered in this process, more accurate results are obtained. Thus, both the main shape representing the 2D wetting patterns that occur under different irrigation conditions (Figure 1, Figure 2) and the area of the overall wetting pattern are estimated. In addition, the wetting radius and maximum wetting depth are estimated by the numerical models developed in this study (equations 6 and 7). The results show that the area of the wetting pattern, the wetting radius and the maximum wetting depth can be estimated by the models proposed in this study. High coefficients of determination confirm these results for these parameters.

Consequently, it is possible to obtain a pattern that is suitable in shape and size with the root zone of the crop, which shows temporal variations depending on the growth stage of the plants. The results of this study show that the models proposed in this investigation can be used to estimate the cross-sectional area of the 2D pattern, the wetting radius and the maximum wetting depth that occur under a surface emitter with different discharges for each time t of the water application period.

CONCLUSION

In this study, the principal shape representing the 2D wetting patterns occurring under the 1.2, 1.7, 2.6, 3.0, and 4.0 L h^{-1} discharges of the surface emitter under uniform soil profile conditions was defined (Figure 1, Figure 2), and the area of this pattern was determined by an analytical solution method (equations 3 and 4). The parameters of the wetting radius, the maximum wetting depth and the maximum wetting width in the soil profile, and the depth of this maximum wetting width from the soil surface allow the overall wetting pattern to be defined. The cross-sectional areas of the wetting patterns showed an increase as a function of the increases in emitter discharges (Figure 4). These results are consistent with the movement characteristics of the water under the surface emitter. In addition, the wetting radius, wetting depth and cross-sectional area of the wetting pattern were estimated for each time t of the water application period for all emitter discharges used in the experiments by the numerical models developed in this study. High coefficients of determination (0.961, 0.947 and 0.995) were obtained for the above parameters.

The results of this study show that the proposed models can be used to estimate the cross-sectional area of 2D pattern, wetting radius and wetting depth that occur under a surface emitter with different discharges for each time t of the water application period. In this way, a contribution is made to improving the optimal design and management of drip irrigation systems.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: VD, MK, HY, MN, RCA; sample collection: VD, MK, HY, MN, RCA; analysis and interpretation of data: VD, MK, HY, MN, RCA; statistical analysis: VD, MK, HY, MN, RCA; visualization: VD, MK, HY, MN, RCA; writing manuscript: VD, MK, HY, MN, RCA.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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Research Article
(Araştırma Makalesi)

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Comparison of the amount of CO_2 released during plant maintenance processes in traditional and xeriscape projects

Klasik ve kurakçıl peyzaj yaklaşımlarına göre tasarlanan parkların bitkisel bakım işlemleri sırasında salınan CO_2 miktarının karşılaştırılması

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ABSTRACT

Objective: It is aimed to calculate and compare the amount of CO_2 released during the plant maintenance processes of parks designed according to traditional and xeriscaping approaches.

Materials and Methods: The study area's dry periods were documented using the De Martonne Drought Index and Walter hydrometric diagrams. Proposed projects were designed, and the amounts of CO_2 released during annual plant maintenance operations implemented in existing and proposed projects were calculated and compared using the carbon footprint approach. Carbon footprints from personnel and equipment were calculated separately.

Results: The results have shown that parks designed according to the traditional landscaping approach result in approximately 649.300% more CO_2 emissions from personnel and % 200.1 more CO_2 emissions from equipment during annual plant maintenance operations when compared to xeriscapes. In existing projects, the largest carbon emissions were determined to be due to electricity consumption from drilling during irrigation. Lawn mowers were found to be the most frequently used piece of garden equipment in existing parks, contributing to the highest carbon emissions.

Conclusion: Since the plant maintenance operations applied to xeriscape design reduce the water and carbon footprint, it will make great contributions to ecology and economy, especially in the fight against and adaptation to climate change.

ÖZ

Amaç: Klasik ve kurakçıl peyzaja göre tasarlanan parkların bitkisel bakım işlemleri sırasında salınan CO_2 miktarının hesaplanması ve karşılaştırılması amaçlanmıştır.

Materyal ve Yöntem: Araştırma alanının kurak dönemleri De Martonne Kuraklık İndeksi ve Walter hidrometrik diyagramlarıyla ortaya konulmuştur. Öneri projeler tasarlanmış, mevcut ve öneri projelere uygulanacak yıllık bitkisel bakım işlemleri sırasında salınan CO_2 miktarları karbon ayak izi yaklaşımıyla hesaplanmış ve karşılaştırılmıştır. Personelden ve ekipmandan salınan karbon ayak izi ayrı ayrı hesaplanmıştır.

Araştırma Bulguları: Yıllık bitkisel bakım işlemleri sırasında klasik peyzaj yaklaşımına göre tasarlanan parkların, kurakçıl peyzaja göre personelden kaynaklı yaklaşık %649.300, ekipmandan kaynaklı ise % 200.1 daha fazla CO_2 salınımına yol açtığı tespit edilmiştir. Mevcut projelerde en fazla karbon salınımının sulama sırasında sondajdan kaynaklı elektrik tüketimine bağlı olduğu belirlenmiştir. Çim biçme makinesinin mevcut parklarda en sık kullanılan ve en fazla karbon salınımına neden olan bahçe ekipmanı olduğu belirlenmiştir.

Sonuç: Kurakçıl peyzaj tasarımına uygulanacak bitkisel bakım işlemlerinin az olmasından dolayı su ve karbon ayak izini küçülttüğü için iklim değişikliğiyle mücadele ve adaptasyonda özellikle ekolojiye ve ekonomiye büyük katkılar sunacaktır.

INTRODUCTION

Climate change is the world's foremost problem. It is known that it results from global warming, leading to extreme weather events, reduced biodiversity, and adverse effects on food, water, ecosystems, etc. (Wandana et al., 2021). The initial noticeable impact of climate change is that the rise in temperature has led green areas, created with traditional landscape principles that prioritize aesthetics, to require more frequent watering, resulting in significant water use.

Due to severe drought conditions, water use in Denver, USA were restricted, and irrigation in lawn areas and gardens were banned. Consequently, the plants in the gardens withered, causing landscape architects in Denver to promote what they called "Xeriscaping", which emerged in the early 1980s, allowing the maintenance of conventional aesthetics with low water consumption (Welsh, 2000). For the purpose of adaptation to climate change, the xeriscape approach can provide substantial savings in irrigation for green areas. The main factor accelerating climate change is the rise in CO_2 emissions in the atmosphere, which has the highest rate among greenhouse gases (Nunes et al., 2020; Malhi et al., 2021). Carbon footprint is the measure of the damage caused to the environment by human activities (e.g., transportation, heating, electricity consumption, and purchased products, etc.) considering the amount of greenhouse gas produced, measured in units of carbon dioxide (Anonymous, 2024a). It is believed that all professional disciplines need to develop strategies to reduce carbon footprints in order to slow down climate change. Ingram (2012) and Ingram et al. (2016) measured the carbon footprint of a plant species in their studies, while Park et al. (2021) measured the carbon footprint in landscape tree production. The review of national and international literature indicates that no research has previously calculated and compared the amount of CO_2 emitted during the annual plant maintenance of traditional and xeriscape projects.

Urban open and green spaces, especially those containing large trees, have significant potential to capture carbon in the atmosphere and reduce the effects of climate change in cities (Vasagadekar et al., 2023). Park et al. (2021) stated that trees not only capture carbon during their development process, but also cause carbon emissions due to their production, transportation, planting, management, removal, disposal, and recycling throughout their life cycle. Despite the fact that increasing the quantity of green areas is beneficial due to their carbon storage properties in order to mitigate the effects of climate change, utmost attention must be paid to their quality. Green areas designed with a traditional landscape approach require regular maintenance operations, during which landscape equipment that usually requires fossil fuel are used, leading to carbon emissions. Rather than focusing solely on aesthetic factors when selecting plants, design choices should account for their appropriateness in relation to the local ecology and ongoing maintenance needs throughout the plants' lifespan. Xeriscape designs, noted for their water saving, will offer great ecological and economic benefits in combating and adapting to climate change, as they will have lower carbon emissions due to less need for plant maintenance and garden equipment to be used in the process.

This study aims to redesign two parks in Konyaaltı and Döşemealtı districts of Antalya province, originally designed using a traditional landscape approach, by employing the xeriscaping approach, as a proposal, and to create annual plant maintenance programmes as well as estimating and comparing the amount of CO_2 emitted to the atmosphere from the personnel and equipment used in the maintenance stages, with the formulas created.

MATERIALS and METHODS

The main materials of the study consist of two parks, each selected in accordance with the purpose of the study, from Döşemealtı and Konyaaltı central districts of Antalya province. One of the parks is in Gürsu region of Konyaaltı district and the other one in Düzlerçamı region of Döşemealtı district. The study was conducted between 2020 and 2024 (Figure 1) by using AutoCAD in the design of the projects and Microsoft Excel to create various graphics and tables and make calculations.

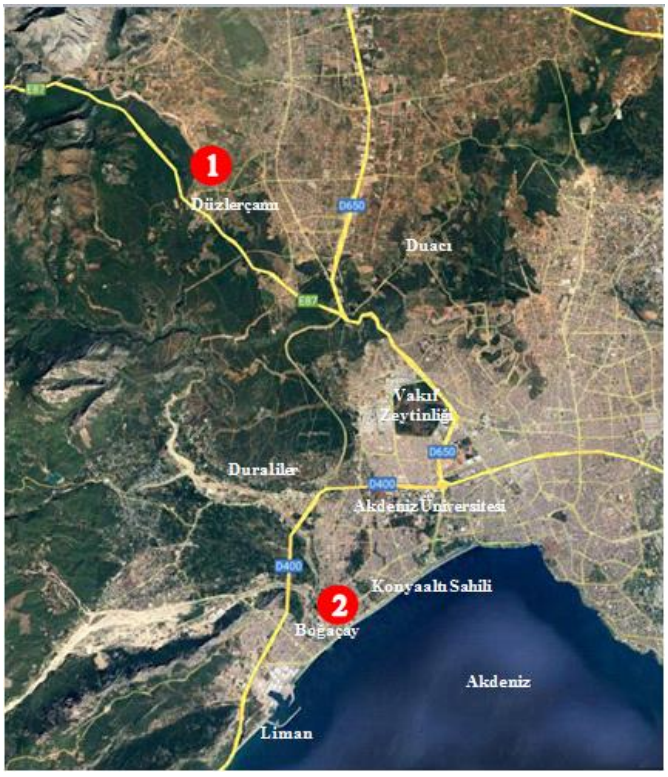

Figure 1. Location of sample parks (using Anonymous, 2024b) **1: Sample park area in Döşemealtı district, 2: Sample park area in Konyaaltı district*.

Şekil 1. *Örnek parkların konumu (Anonymous, 2024b'den yararlanılarak) *1: Döşemealtı ilçesindeki örnek park alanı, 2: Konyaaltı ilçesindeki örnek park alanı.*

The research was conducted in two formats- field and office-, involving five stages. In the initial stage of the study, data was gathered regarding the climate features of Antalya, as well as climate change, xeriscaping and carbon footprints. At this stage, data on parks obtained from Döşemealtı and Konyaaltı Municipalities and climate data sourced from MGM were utilised. In addition, precipitation and temperature data were used to determine the dry periods of the research zones with the De Martonne drought index and Walter (1970) hydrometric diagrams.

According to the Anonymous (2016), the parameters included in the formula of the De Martonne drought determination method are the annual average temperature and annual total precipitation values. The annual drought index (I_{DM}) value is obtained with the calculation made according to Formula 1.

$$I\mathrm{DM} = \frac{P}{T+10} \quad (1)$$

I_{DM}: Annual drought index, P: Annual total precipitation (mm), T: Annual mean temperature (°C)

De Martonne monthly drought index values are calculated according to the following formula 2.

$$IM = \frac{12.P\prime}{T\prime+10} \quad (2)$$

I_M: Monthly drought index, P': Monthly total precipitation (mm), T': Monthly average temperature (°C)

In these formulas, the +10 value added to the T and T' values is a coefficient used to make the negative temperature value in some places positive. Table 1 shows the climate characteristics for the I_{DM} and I_M values calculated according to the De Martonne formula.

Table 1. De Martonne index values and climate characteristics (Anonymous, 2016)

Çizelge 1. *De Martonne indeks değerleri ve iklim özelliği (Anonymous, 2016)*

I_{DM}	Climatic features
Less than 5	Arid
5 – 10	Semi-arid
10 – 20	Semi-arid to Humid
20 – 30	Semi-humid
30 – 60	Humid
More than 60	Very humid

The arid periods of the research area were revealed by drawing Walter (1970) hydrometric diagrams according to the annual average temperature (°C) and average precipitation (mm) values.

In the second stage, two sample parks suitable for the study purpose were selected from among the parks located in Döşemealtı and Konyaaltı districts, where field analyses were conducted. In the light of the field analyses and the data obtained, the selected parks were redesigned regarding vegetation and structural elements, aligning with the xeriscaping method, ecology of the region, and sustainable design principles while integrating a climate-friendly approach into the study. The park in Konyaaltı was built in 2015, while the park in Döşemealtı was built in 2016, and the fact that their construction years were close to each other made comparison possible. The park in Konyaaltı is 1,126 m^2, while the park in Döşemealtı is 1,056 m^2, being quite similar in size. Both parks are morphologically close to flat. The plants used in the suggested plant designs were determined by using the plant list created by Çetin (2016) and the information on the care requirements of plant species found in some nurseries within the borders of the Antalya district.

In the third stage of the research, the annual general maintenance processes for the existing and proposed plant design projects were determined. The annual maintenance program applied to the park according to the existing project was created according to the data obtained from the annual routine maintenance and work programs prepared by the Agricultural Engineers and Landscape Architect Chiefs responsible for maintenance operations in Konyaaltı Municipality. Due to the similar size of the existing parks in both districts, along with their design with a traditional landscape approach and the use of similar plant species, an annual plant maintenance program was created for the existing projects and another one for the proposed projects designed with the xeriscaping approach. The annual maintenance programs were divided into two periods as November-March and April-October.

In the fourth stage, the CO_2 amounts released during the annual plant maintenance of the parks, according to the existing and proposed plant projects were calculated and compared using the carbon footprint approach. The carbon footprints caused by plant maintenance was calculated separately as emitted from personnel (labour) and equipment. The CO_2 released due to personnel activities was calculated as liters and CO_2 released due to equipment use as kilograms. According to Doğan (2002), the CO_2 emissions from maintenance personnel were calculated according to the formulas developed within the scope of the study, while those from equipment were calculated according to the formulas developed within the scope of the study. According to Doğan (2002), the amount of CO_2 released into the air by people varies according to their occupation status, and these values are presented in Table 2. Accordingly, the occupation degree of the operator and those responsible for irrigation with drilling was taken as II, and the occupation degree of those using plant maintenance equipment and working in irrigation with water trucks as III.Fuel consumption in automobiles is basically proportional to the engine power/cylinder volume of the vehicle. By examining the fuel consumption of vehicles of different brands and models with the same engine/cylinder volume, average carbon footprint calculations per engine power were made. In general, 2.33 kg of carbon dioxide gas is released by burning 1 liter of gasoline (Bahçeci 2023). In the scope of this study, this value was taken as the basis for the amount of carbon dioxide released by burning gasoline.

Table 2. The amount of CO_2 people emits into the air according to their occupation (Doğan, 2002)

***Çizelge 2**. İnsanların meşguliyet durumlarına göre havaya verdikleri CO_2 miktarı (Doğan, 2002)*

Occupation	Occupation Degree	CO_2 emission amount (lt/h)
Sitting	I	15
Light manual work	II	23
Manual work or slow walking	III	30
Heavy work or fast walking	IV	30

In the existing parks, while automatic irrigation systems are used for watering, electricity is consumed due to drilling activities. The amount of electricity consumed due to drilling varies depending on factors such as the size, power, and depth of the drilling, and since this value can be measured in the existing park in Konyaaltı district, calculations were made accordingly. In this park, the value on the drilling panel was reset before activating the irrigation system and was measured after ½ hour and multiplied by 2 to determine that the hourly consumption was 106,400 kW. According to Ener Rüşen & Koç (2019), calculations are made based on the data, revealing that approximately 0.55 kg of CO_2 is released from 1 kWh of electricity consumption. The amount of CO_2 released due to drilling is shown in Formula 3.

$$DI = t.e.0{,}55\ kg/kWh \quad (3)$$

DI: Amount of CO_2 released from irrigation by drilling, t: Working time (hour), e: one hour of electricity consumption (kWh), 0.55 kg/kWh: CO_2 released from 1 kWh electricity consumption

Based on Engin (2015)'s acknowledgement that 1 liter of fuel emits 2.4 kg CO_2 (eq) in the equation for transportation-related CO_2 emissions in the ready-mix concrete industry, the figure was likewise used as a reference for the water truck. The indicator of this vehicle was examined for the fuel consumption of the water truck and it was found to consume approximately 50 liters of fuel in approximately 100 km. According to the known speed formula (x=v.t), it travels 100 km in 2 hours at 50 km/h, which is the speed limit according to Anonymous (2024c), so the 1-hour fuel consumption was calculated as 25 liters for this study and the CO_2 emissions from irrigation with the water truck operating was formulated. It has been determined that gasoline-powered garden equipment, including a push lawn mower, a pruning saw, a hedge trimmer and a bicycle-type scythe, are generally used in annual plant maintenance. When calculating CO_2 emissions from landscape equipment, firstly the catalogues of such equipment were examined and interviews were made with various companies that sell them, however, no data could be obtained regarding fuel consumption. Consequently, the landscape equipment used by Konyaaltı Municipality was examined in the field, and a method was devised by adding 150 ml of gasoline into the fuel tanks of this machinery to measure with a chronometer in order to find out the duration of gasoline consumption while actively operating in the park, and relevant formulas were created. In summary, when the hourly fuel consumption of such landscape machinery was calculated in the same way, it was found to be 0.53 l/h for a push lawn mower, 0.36 l/h for a pruning saw, 0.56 l/h for a hedge trimmer, and 1.29 l/h for a bicycle scythe. The amount of CO_2 released during landscape equipment and water truck on can be calculated by substituting the values in Formula 4.

$$LW = t.f.c \quad (4)$$

LW: the amount of CO_2 released from landscape equipment and water trucks, t: working time (hour), f: hourly fuel consumption (lt), c: CO_2 emission released from 1 lt or 1 kWh consumption. If the machinery runs on diesel, c=2.33 lt/kg; if it runs on gasoline, then c=2.4 lt/kg.

In the final stage of the study, the CO_2 emissions during the maintenance processes in the parks related to the planting design projects designed with xeriscaping approach were compared with those of the traditional landscaping, and some recommendations were proposed for promoting xeriscaping nationwide, particularly in Antalya, for the purposes of combating against and adapting to climate change.

RESULTS and DISCUSSION

Evaluation of climatic characteristics

This study used the climatic data for the years 1933-2021 obtained from the Antalya Airport's climate station numbered 17300, which is located at 36 latitude, 30 longitude, and 51 m above sea level and belongs to the Anonymous (2022a). Monthly drought index values for different periods were calculated according to the De Martonne formula. The notable values were the arid periods between June and September in the years of 1940-1949, 1950-1959, 1970-1979, 1980-1989, 1990-1999, 2000-2004, and 2020-2021. In addition, it was determined that 5 months out of 12 months were arid and 2 months were semi-arid between 2020 and 2021 (Table 3).

Table 3. Monthly seasonal drought index values of Antalya Airport Station (1933-2021) according to the De Martonne method

Çizelge 3. *De Martonne yöntemine göre Antalya Havalimanı İstasyonu (1933-2021) aylık dönemsel kuraklık indeksi değerleri*

Months	1933-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2004	2005-2009	2012-2014	2015-2019	2020-2021
I	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid
II	Very humid	Very humid	Humid	Very humid	Very humid	Very humid	Very humid	Humid	Very humid	Humid	Humid	Semi-humid
III	Humid	Humid	Humid	Very humid	Humid	Very humid	Humid	Humid	Humid	Semi-humid	Humid	Semi-humid
IV	Semi-arid-Humid	Semi-humid	Semi-arid-Humid	Semi-humid	Semi-arid-Humid	Semi-humid	Semi-humid	Very humid	Humid	Very humid	Semi-arid-Humid	Arid
V	Semi-arid-Humid	Semi-arid	Semi-arid	Semi-arid-Humid	Semi-arid-Humid	Semi-arid	Semi-arid-Humid	Semi-humid	Semi-humid	Semi-arid-Humid	Semi-arid-Humid	Semi-arid
VI	Semi-arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Semi-arid	Arid
VII	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Semi-arid	Arid	Arid	Arid
VIII	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid	Arid
IX	Semi-arid	Arid	Arid	Semi-arid	Arid	Arid	Arid	Arid	Semi-humid	Semi-arid	Semi-arid	Arid
X	Semi-arid-Humid	Semi-humid	Semi-humid	Semi-humid	Humid	Semi-humid	Humid	Semi-arid	Very humid	Humid	Semi-arid-Humid	Semi-arid
XI	Very humid	Humid	Humid	Humid	Humid	Very humid	Very humid	Very humid	Very humid	Humid	Humid	Semi-humid
XII	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid	Very humid

When the arid periods of the research area were calculated by drawing Walter (1970) hydrometric diagrams according to the annual average temperature (°C) and average precipitation (mm) values, it was determined that there was an arid period of approximately 1 month for the years 2005-2009, 3 months for 1933-1939 and 2015-2019, 3.5 months for 1960-1969 and 2012-2014, 4 months for 1970-1979, 1980-1989, 1990-1999, 4.5 months for 1940-1949, 1950-1959 and 2000-2004, and 6.5 months for 2020-2021.

Comparison of existing and proposed plant design projects

Redesign of parks with xeriscaping approach as a proposal

A comprehensive analysis was first conducted in the park and its surroundings. In plant selection, attention was paid to the fact that the species were of Mediterranean origin and/or well adapted to Mediterranean ecological conditions, resistant to diseases and pests with low maintenance requirements, especially irrigation, but with more functional usage areas, and high landscape values in terms of aesthetic features. Vasagadekar et al. (2023) emphasized that natural tree species in parks are a natural solution to increase their ability to absorb atmospheric CO_2 in terms of storing more carbon compared to exotic species. Another advantage of natural plants is that they do not create a waste load on the environment by reducing chemical use. Taking these advantages of the proposed parks into account, emphasis is placed on choosing native plants and grouping those with similar maintenance requirements. Çetin & Mansuroğlu (2018) emphasized that native plants are crucial for reflecting a region's identity and culture and ensuring the continuity of species. Grass species, which are the plant group that consumes the most water in the landscape, require regular maintenance for a pleasant and aesthetic appearance, and some of these processes increase the use of fossil fuels and cause environmental pollution. For all these reasons, grass species are not preferred in either project. In the design, natural rocks are included to imitate the natural appearance of the species used in their natural environment and to provide a natural-like appearance. In addition, various mulch materials are preferred because they offer many benefits such as saving water and providing insulation, preventing weed growth and plants from competing. An aesthetic appearance can be achieved by creating patterns with these mulch materials in different colors and textures. The preferred mulch materials include wood chips, crushed stones, yellow sand, and pumice. In both proposed projects, sand is to be laid widely around the pergolas both for families to rest and for children to have fun playing. Sand also assumes a functional role and increases permeable grounds. Thus, it will also contribute to the nutrition of underground water. It has been planned to lay the packaging wastes of these materials under these mulch materials in order to prevent weed growth. Since mulch materials are sometimes sold in bulk and unpackaged, it could be suggested to lay newspapers under them. Since species with low water consumption and high drought tolerance are preferred in the projects, an irrigation system is not recommended. In extreme cases, additional irrigation with a water truck will be planned, and since this process will rarely be needed, it is believed that it will not have a major impact on carbon emissions. Thus, the use of plastic materials and excavation and filling caused by the irrigation system in the park can be prevented.

Evaluation of existing and proposed plant design projects in Döşemealtı district

In the existing project of the park, 27 different plant taxa were preferred, 25.9% of which (*Laurus nobilis* L.*, Liquidambar orientalis, Pinus pinea, Nerium oleander* 'Nana', *Platycladus orientalis, Cynodon dactylon* and *Aloe vera* are of Mediterranean origin. Although *P. orientalis* is a species compatible with the Mediterranean ecology, it seems to be planted very frequently as a hedge plant, a total of 1200. Considering the future diameter of this plant, it is believed that the number of plants should be kept lower. The reason is that adding more plants than necessary in a given area heightens the competition among plants for water and nutrient needs, as well as pruning and other maintenance tasks. In addition, when used as a hedge, they would need regular pruning, and therefore irrigation. A total of 65 kg of grass, approximately 80 gr/m^2, is used in the park. When the plant species in the existing park were evaluated, it was determined that there were plants with low, medium, and relatively high water requirements and that the plant groups with all the maintenance needs, especially irrigation, in the plant design of the park were grasses and shrubs used as hedges. Figure 2 illustrates the existing plant design project of this park.

Figure 2. Current planting design project of the park in Döşemealtı district.

Şekil 2. *Döşemealtı ilçesindeki parkın mevcut bitkisel tasarım projesi.*

In the proposed plant design project of the park, on the other hand, 18 different plant taxa are preferred and 77.8% of them are of Mediterranean origin. These taxa include *Ceratonia siliqua*, *Cupressus sempervirens, Olea europaea, P. orientalis, Vitex agnus-castus*, *Erica carnea, Lavandula officinalis*, *Myrtus communis, Rosmarinus officinalis*, *Santolina chamaecyparissus, Hedera helix, Sedum rupestre* 'Angelina', *Thymus serpyllum* and *Opuntia ficus-indica* (Çetin, 2016; Anonymous, 2022b). The proposed project involves the use of *Lantana montevidensis*, a non-Mediterranean species that adapts well to the area's ecological conditions, features a sprawling growth habit, produces abundant and vibrant flowers, and has minimal water needs. Due to their succulent structure, drought tolerance, different colour, form and texture, *Aptenia cordifolia, Sedum reflexum* 'Blue Spruce' and *Agave americana* taxa are used to provide diversity in the area. Since these succulent ground covers (*Aptenia cordifolia, Sedum reflexum* 'Blue Spruce') do not require maintenance operations, such as mowing, pruning, and spraying, they also save labour, while their use prevents carbon emissions from personnel and pruning equipment. In the proposed project, *C. siliqua*, which is evergreen and requires little water and maintenance, is deemed appropriate for providing shade on walkways, and *H. helix*, one of the climbing species, is likewise deemed suitable for increasing shading on pergolas and providing a natural and aesthetic appearance with its decorative leaves and evergreen feature. In areas technically allocated as transformer

areas, grass and ground cover species that do not form deep roots and do not pose a safety hazard are used or left empty. Since this section was designed as a green area in the current project, *Sedum rupestre* 'Angelina' is preferred as an alternative in the proposed project in order to make the transformer area comparable. Mediterranean origin *C. sempervirens* and *V. agnus-castus* are to be used right across from the transformer to screen the transformer area. As stated in Kösa's (2023) study, the low-medium water requirements of *C. sempervirens* and *V. agnus-castus* species are additional considerations in the selection process. The proposed plant design project of this park is presented in Figure 3.

Figure 3. Proposed plant design project of the park in Döşemealtı district.
Şekil 3. *Döşemealtı ilçesindeki parkın öneri bitkisel tasarım projesi.*

Evaluation of existing and proposed plant design projects in Konyaaltı district

In the existing project of the park, 14 different plant taxa were preferred, 14.3% of which are of Mediterranean origin. These species include *P. orientalis* and *C. dactylon* (Çetin, 2016; Anonymous, 2022b). *Ruellia brittoniana*, which is prominent with its flowers, requires frequent and regular watering, especially in summer. In addition, since it is preferred as a hedge plant in the park, it is regularly pruned, which increases the need for irrigation. A total of approximately 80 gr/m^2, 66.72 kg of grass seed was used in the park. The examination of the species generally preferred in the park showed that it was designed with a medium water demand, high attractiveness in the landscape, and an understanding that prioritized aesthetics. The current planting design project of this park is presented in Figure 4.

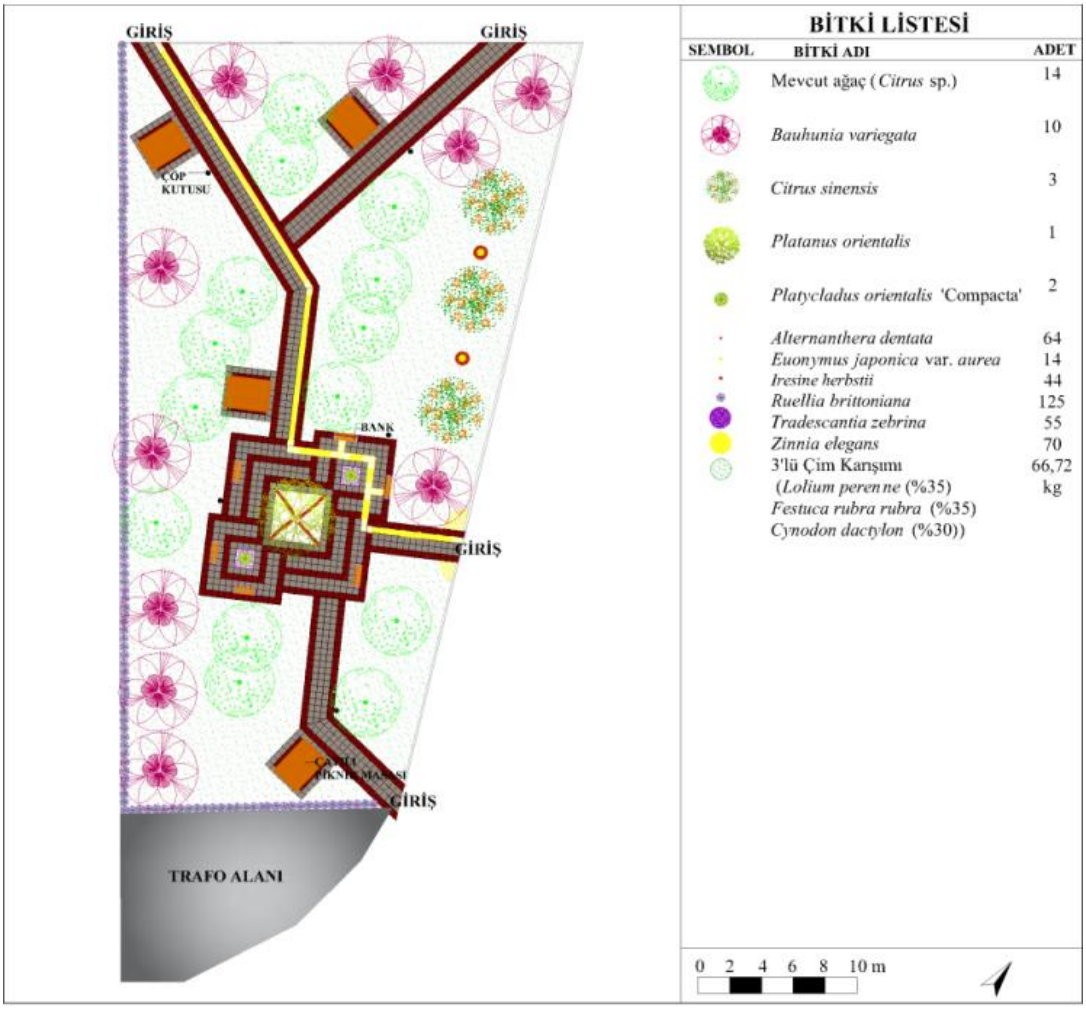

Figure 4. Current plant design project of the park in Konyaaltı district.

Şekil 4*. Konyaaltı ilçesindeki parkın mevcut bitkisel tasarım projesi.*

In the proposed project, 20 different plant taxa are preferred to increase the diversity of species, 70% of which are of Mediterranean origin. *Cercis siliquastrum*, *C. sempervirens, L. nobilis, Pistacia terebinthus*, *Tamarix tetrandra*, *V. agnus-castus, M. communis, R. officinalis, S. chamaecyparissus, Spartium junceum, Jasminum fruticans*, *T. serpyllum, Sedum rupestre* 'Angelina' and *A. vera* are the taxa of Mediterranean origin (Çetin, 2016; Anonymous, 2022b). In addition to these, the proposed project involved the use of *Lantana montevidensis*, that has a sprawling growth habit, abundant and showy flowers with a very low water requirement, though it is of foreign origin, and also *Carpobrotus acinaciformis, Sedum reflexum* 'Blue Spruce', *Agave americana*, *Aloe variegate,* and *Euphorbia tirucalli* taxa, which have low irrigation requirements because they store water in their bodies. In addition, it is thought that these succulent species will create diversity in the landscape with their interesting forms and leaves. *C. sempervirens* and *P. terebinthus* are planted in rows on the side of the park closest to the school due to their shielding from the noise coming from the school and their visual appeal. *C. siliquastrum* is preferred to provide shade for the walkways and to add color to the park with its pink flowers. *Jasminum fruticans*, which has attractive features in plant design with its pleasant scent and yellow decorative flowers as well as providing a lively and pleasant appearance as an alternative to the wooden roofed canopies in the existing project, is to be used to shade the pergolas. The proposed planting design project of this park is presented in Figure 5.

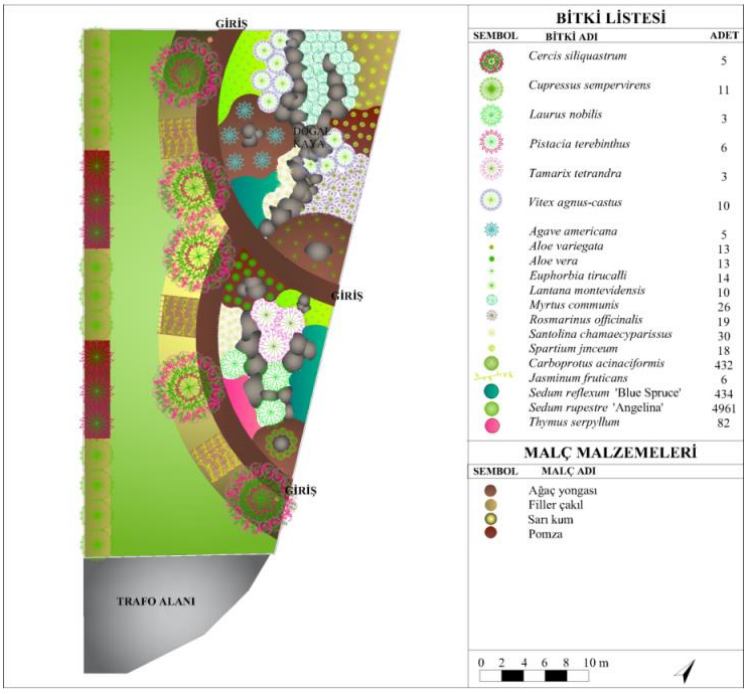

Figure 5. Proposed plant design project of the park in Konyaaltı district.

Şekil 5. *Konyaaltı ilçesindeki parkın öneri bitkisel tasarım projesi.*

Calculation and comparison of CO_2 amounts released during annual plant maintenance of parks according to existing and proposed plant design projects

Calculation of plant maintenance processes applied to existing parks between November and March and the amount of CO_2 released

General maintenance operations applied during this period include irrigation, lawn mowing, weeding, pruning, and scything. A total of 1150 lt CO_2 was released from personnel and 331.068 kg CO_2 from equipment in the November-March period due to the plant maintenance of the existing projects in Döşemealtı and Konyaaltı districts (Table 4).

Table 4. Plant maintenance program of existing parks and amount of CO_2 released between November and March

Çizelge 4. *Mevcut parkların Kasım-Mart dönemi bitkisel bakım programı ve salınan CO_2 miktarı*

Plant maintenance procedures (November and March)	Equipment used	Amount of CO_2 released by personnel (lt)	Amount of CO_2 released from equipment (kg)
Irrigation	Drilling	10 times (1 time in 15 days for 1/2 hour) 115 lt	292.6
Mowing the lawn	Push Lawn Mower	10 times (1 time in 15 days for 2 hours) 600 lt	24.698
Weed cleaning	Manual	5 times (1 time per month for 1.5 hours) 225 lt	None
Pruning	On Trees (High Branch Pruning Saw), On Shrubs (Hedge Cutting and Trimming Machine)	3 times (Hard pruning of trees once a season for 1 hour, 2 times a season, shape pruning of shrubs once every 2 months for 1.5 hours) 120 lt	Trees 0.839 Shrubs 3.914
Scything	Bicycle Type Scythe	3 times (1 hour to walking paths) 90 lt	9.017
	TOTAL	1150 lt	331.068

Calculation of plant maintenance operations to be executed in the proposed parks between November and March and the amount of CO_2 estimated to be released

Maintenance processes to be applied during this period includes irrigation, weeding, pruning, and trimming. It is estimated that 255 lt of CO_2 will be released from the personnel and 63,425 kg of CO_2 from the equipment in the November-March period due to the plant maintenance of the proposed projects in Döşemealtı and Konyaaltı districts (Table 5).

Table 5. Plant maintenance program of the proposed park projects and the amount of CO_2 estimated to be released between November and March

Çizelge 5. *Öneri Projelerin Kasım-Mart dönemi bitkisel bakım programı ve salınan CO_2 miktarı*

Plant maintenance procedures (November-March)	Equipment used	Amount of CO_2 released by personnel (lt)	Amount of CO_2 released from equipment (kg)
Irrigation	Water truck	2 times (2 times in season for 1/2 hour) 30 lt	60
Weed cleaning	Manual	3 times (once every 2 months for 2 hours) 180 lt	None
Pruning	On Trees (High Branch Pruning Saw)	1 time (Hard pruning of trees once a season for 1/2 hour) 15 lt	0.419
Scything	Bicycle Type Scythe	1 time (1 time per season, 1 hour on walking paths) 30 lt	3.006
	TOTAL	255 lt	63.425

Calculation of plant maintenance processes applied to the existing parks between April and October and the amount of CO_2 released

Maintenance processes applied during this period include irrigation, lawn mowing, weed cleaning, pruning, trimming, and spraying. It has been determined that 4791 liters of CO_2 from personnel and 234,635 kg of CO_2 from equipment were released during the April-October period due to the plant maintenance of existing projects in Döşemealtı and Konyaaltı districts (Table 6).

Calculation of plant maintenance operations to be executed in the proposed parks between April and October and the amount of CO_2 estimated to be released

Maintenance processes to be applied during this period include irrigation, weeding, pruning and trimming. It has been estimated that during the plant maintenance of the proposed projects in Döşemealtı and Konyaaltı districts, 660 lt of CO_2 will be released from the personnel and 219,273 kg of CO_2 from the equipment in the April-October period (Table 7).

Table 6. Plant maintenance program of existing parks for the period April-October and the amount of CO_2 released

Çizelge 6. *Mevcut parkların Nisan-Ekim dönemi bitkisel bakım programı ve salınan CO_2 miktarı*

Plant maintenance procedures (April-October)	Equipment used	Amount of CO_2 released by personnel (lt)	Amount of CO_2 released from equipment (kg)
Irrigation	Drilling	84 times (3 times a week for 1/2 hour) 966 lt	117.04
Mowing the lawn	Push Lawn Mower	28 times (Once a week for 2 hours) 1680 lt	69.154
Weed cleaning	Manuel	28 times (1 time per week for 1.5 hours) 1260 lt	None
Pruning	Hedge Cutting and Trimming Machine	14 times (1 time in 15 days, 1.5 hours of pruning of bushes) 630 lt	27.401
Scything	Bicycle Type Scythe	14 times (once in 15 days, 1/2 hour walking paths) 210 lt	21.04
Spraying	Manually operated backpack sprayer	3 times (herbiside application to walkways 3 times a season, 1/2 hour) 45 lt	None
	TOTAL	4791 lt	234.635 kg

Table 7. Plant maintenance program in the proposed park projects for the April-October period and the amount of CO_2 estimated to be released

Çizelge 7. *Öneri parkların Nisan-Ekim dönemi bitkisel bakım programı ve salınan CO_2 miktarı*

Plant maintenance procedures (April-October)	Equipment used	Amount of CO_2 released by personnel (lt)	Amount of CO_2 Released from Equipment (kg)
Irrigation	Water truck	7 times (1 time per month for 1/2 hour) 105 lt	210
Weed cleaning	Manual	7 times (Once a month for 2 hours) 420 lt	None
Pruning	Hedge Cutting and Trimming Machine	5 times (1 time in 45 days, 1/2 hour for shaping the bushes) 75 lt	3.262
Scything	Bicycle Type Scythe	2 times (2 times a season, 1 hour to walking paths) 60 lt	6.011
	TOTAL	660 lt	219.273

Comparison of CO_2 emissions during annual plant maintenance of parks according to existing and proposed plant design projects

When comparing the current traditional landscape projects in Antalya Döşemealtı and Konyaaltı districts with the proposed xeriscaping-designed projects regarding carbon emissions from annual plant maintenance processes, it was found that the current projects (5941 lt) produced approximately 649.300% more carbon emissions than the proposed projects (915 lt) due to personnel, while the current projects (565,703 kg) resulted % 200.1 more carbon emissions than the proposed projects (282.698 kg) attributed to equipment use. It was determined that the highest amount of CO_2 released from equipment during annual plant maintenance processes occurred during irrigation operations in both existing traditional landscape projects (409.64 kg) and proposed xeriscape projects (270 kg) (Table 8). Similarly, Park et al. (2021) determined that the two largest sources of carbon emissions in landscape tree cultivation are irrigation and fertilization operations, and that 33-55% of all emissions are produced in irrigation in particular. In existing parks designed according to the traditional landscape design approach, 47 hours of irrigation is needed annually, while 4.5 hours are believed to be sufficient in proposed parks designed according to xeriscaping. In addition, it has been determined that the labour spent for the irrigation process of existing projects is 10,444 times that of proposed projects (Table 8). We have been informed that when existing parks are to be irrigated, the personnel need to go to there every time to manually open the conditioner and operate the drilling. Since vehicles are required to go to the drilling, fossil fuel consumption occurs again, thereby increasing the carbon footprint. In addition, since electricity is consumed while drilling is running, carbon emissions increase. In existing parks designed with a traditional landscape approach in Döşemealtı and Konyaaltı districts, the duration of annual maintenance processes is 6,852 times more than that of proposed parks designed with xeriscaping (Table 9). In another study conducted in Antalya, the current state of the park was contrasted with the proposed project designed with xeriscaping, revealing that the proposed project would save 43.31% in annual maintenance costs, with the observation that 51.38% of the current state of the park was covered with grass being the main factor causing the increase in maintenance costs (Çetin 2016; Çetin et al., 2018). Moreover, the highest amount of CO_2 was released from the push lawn mower among the landscape equipment used in the current projects. In Döşemealtı and Konyaaltı districts, existing parks designed using a traditional landscape approach require 76 hours of lawn mowing each year, but opting against grass in the proposed parks using a xeriscape design is likely to significantly help in lowering carbon emissions from personnel and equipment during maintenance.

Table 8. The amount of CO_2 released during annual vegetative maintenance of parks according to existing and proposed projects

Çizelge 8. *Mevcut ve öneri projelere göre parkların yıllık bitkisel bakımı sırasında salınan CO_2 miktarı*

Annual plant maintenance processes	Existing Projects		Proposed Projects	
	Amount of CO_2 to be released by personnel (lt)	Amount of CO_2 to be released from equipment (kg)	Amount of CO_2 to be released by personnel (lt)	Amount of CO_2 to be released from equipment (kg)
Irrigation	1081	409.64	135	270
Mowing the lawn	2280	93.852	0	0
Weed cleaning	1485	0	600	0
Pruning	750	32.154	90	3.681
Scything	300	30.057	90	9.017
Spraying	45	0	0	0
TOTAL	5941	565.703	915	282.698

Table 9. Duration of annual plant maintenance operations of parks according to existing and proposed projects (hours)

Çizelge 9. *Mevcut ve öneri projelere göre parkların yıllık bitkisel bakım işlemlerinin süresi (saat)*

Annual Plant Maintenance Processes	Existing Projects			Proposed Projects		
	November-March (hours)	April-October (hours)	Total Annual (hours)	November-March (hours)	April-October (hours)	Total Annual (hours)
Irrigation	5	42	47	1	3.5	4.5
Mowing the lawn	20	56	76	0	0	0
Weed cleaning	7.5	42	49.5	6	14	20
Pruning	4	21	25	0.5	2.5	3
Scything	3	7	10	1	2	3
Spraying	0	1.5	1.5	0	0	0
		TOTAL	209		TOTAL	30.5

CONCLUSION AND RECOMMENDATIONS

As a consequence, the climate analyses conducted in this study reveals that in Antalya, where approximately 7 months of the year are arid and semi-arid, xeriscape practices are no longer just a subject of discussion but should be implemented in landscape architecture projects. Xeriscapes allow for sustainable, functional, and aesthetic landscapes that require less maintenance and cause less damage to the environment during maintenance operations. In planting design projects, in addition to aesthetics and functionality, analyzing carbon emissions during the life cycles of plants is of great importance in terms of minimizing the damage to nature caused by their use. As emphasized by researchers such as Ingram (2012), Ingram et al. (2016) and Park et al. (2021), plant production should be conducted by analyzing the life cycle of plants and considering their effects on carbon emissions. There is no doubt that the choice of materials in landscape design will be beneficial in mitigating the effects of climate change. This study, on the other hand, examines the plant landscape projects designed with different approaches (traditional and xeriscape) as a whole, measures the carbon footprint within the scope of annual plant maintenance, and provides practical results directly for implementation. For this reason, the findings of this study hold significant value. If correct landscape designs are not implemented, carbon is to be released continuously due to plant maintenance. When the current traditional landscape projects in Döşemealtı and Konyaaltı districts and the proposed xeriscape projects are compared in terms of annual CO_2 emissions, it has been determined that the current projects cause approximately 649.300% more CO_2 emissions due to personnel and % 200.1 more CO_2 emissions due to equipment than the proposed projects due to annual plant maintenance operations. These differences are especially due to grass and hedge plants that require regular maintenance. It has been determined that the highest carbon emission

in plant maintenance operations in the current projects is due to electricity consumption while drilling during irrigation operations. It could be suggested that if plants that require regular irrigation are to be preferred in the parks, the use of an automatic smart irrigation system that saves water thanks to the remotely controlled weather monitoring systems will also be a rational choice. It has also been determined that the push mower is the most frequently used garden equipment in existing parks (76 hours per year) and the one that causes the most carbon emissions. Considering the large water requirement and carbon footprint of grass, along with the natural resources it depletes and contaminates, as well as for the sake of our future, it is believed that it should not be preferred beyond athletic fields. R&D studies should be carried out on alternatives that can be used instead of grass in sports areas. The use of predominantly natural plant species in proposed xeriscape designs has also reduced maintenance requirements and CO_2 emissions resulting from maintenance. As stated by Çetin & Mansuroğlu (2018), nursery owners should focus on natural plant production and produce these plants at low costs, rather than importing plants from abroad at high costs.

In this study, it has been quantitatively demonstrated that the carbon footprint and annual maintenance period due to annual plant maintenance operations in existing parks designed according to the traditional landscape approach are higher than that in the proposed parks designed according to the xeriscape.

As a result, the traditional landscape design approach, which prioritizes aesthetics in plant selection, should be abandoned in favour of the xeriscaping approach. In xeriscapes, since there is less need for plant maintenance, the damage to the environment and natural resources is also less, which is believed to benefit both ecology and economy, especially by decreasing water usage and carbon emissions in the battle against and adaptation to global climate change.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: NÇ, SM; analysis and interpretation of data: NÇ, SM, SK; statistical analysis: NÇ, SM; visualization: NÇ, SM; writing manuscript: NÇ, SM, SK.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that an ethics committee is not required for this study.

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Research Article
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Effect of wind corridors on thermal comfort in urban and rural settlement areas*

Kentsel ve kırsal yerleşim alanlarında rüzgar koridorlarının termal konfora etkisi

* This article is summarized from Nursevil YUCA's doctoral thesis.

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ABSTRACT

Objective: This study aims to investigate the impact of pedestrian-level wind speed on thermal comfort in urban and rural areas with high elevation and distinct climatic and topographic characteristics.

Materials and Methods: Hourly meteorological data from the districts of Çaldıran, Muradiye, and Erciş in Van Province were used for the period 2018–2023. Physiological Equivalent Temperature (PET) values were calculated using RayMan Pro 2.1 software. Relationships between PET and meteorological variables were evaluated using Multiple Linear Regression and Pearson Correlation analyses, and the results were visualized using maps.

Results: While the average maximum temperature is experienced in Muradiye in July with 37.8ºC, the lowest temperature is experienced in Çaldıran with -9.5ºC, and the monthly average wind values are found to be the highest in Çaldıran with a long-term average of 0.3-0.8 m/s, in Muradiye it is between 0.3-0.6 m/s, and in Erciş it is 0.1 m/s every month.

Conclusion: Thermal comfort dynamics differ between urban and rural areas. Therefore, microclimatic design and wind corridor planning should be adapted to the settlement type.

ÖZ

Amaç: Bu çalışma, rakımı yüksek, farklı iklim ve topoğrafya özelliklerine sahip kentsel ve kırsal alanlarda, yaya seviyesindeki rüzgâr hızının termal konfor üzerindeki etkilerini incelemeyi amaçlamaktadır.

Materyal ve Yöntem: Van ilinin Çaldıran, Muradiye ve Erciş ilçelerine ait 2018-2023 dönemi saatlik meteorolojik verileri kullanılarak, RayMan Pro 2.1 programı ile fizyolojik eşdeğer sıcaklık (FES) hesaplanmıştır. FES ile meteorolojik değişkenler arasındaki ilişkiler, Çoklu Doğrusal Regresyon ve Pearson Korelasyon analizleriyle değerlendirilmiş; bulgular haritalar ile görselleştirilmiştir.

Araştırma Bulguları: Ortalama maksimum sıcaklık 37.8ºC ile Temmuz ayında Muradiye'de yaşanırken, en düşük sıcaklığın ise -9.5ºC ile Çaldıran'da yaşandığı, aylık ortalama rüzgar değerlerinde ise Çaldıranın uzun yıllar ortalamasında 0.3-0.8 m/s en yüksek seviyede seyrederken, Muradiye 0.3-0.6 m/s aralığında, Erciş ise her ay 0.1 m/s olduğu ortaya konmuştur.

Sonuç: Kentsel ve kırsal alanlarda farklı termal konfor dinamikleri söz konusudur. Bu nedenle, mikroklimatik tasarım ve rüzgâr koridorlarının planlanması, yerleşim tipine göre şekillendirilmelidir.

INTRODUCTION

With rapid urbanization, urban settlements have expanded significantly (Kurt Konakoğlu & Büyükgüner, 2021), while rural areas have gradually been pushed into the background. In this process, urban living environments have been improved through the development of green and open spaces, increased building density, and enhanced educational opportunities. Indeed, when thermal comfort studies in outdoor environments are reviewed, it is evident that most research focuses on urban areas (Yılmaz et al., 2018). Conversely, rural settlements and their thermal comfort characteristics have been relatively overlooked.

Since the economic, sociological, environmental, and climatic conditions of urban and rural settlements differ considerably, their thermal comfort levels also vary significantly. One significant difference is the impact of wind, which is often reduced in urban settings due to the density of buildings (Özlü et al., 2019). Therefore, findings from urban thermal comfort studies cannot be directly applied to rural areas. Thermal comfort is defined as the climatic range that allows individuals to feel at ease and healthy, based on the average of meteorological parameters such as air temperature (ºC), relative humidity (%), wind speed, and cloudiness (Yılmaz et al., 2021).

There are two primary types of thermal stress: extreme heat and extreme cold, both of which affect human well-being, comfort, and health. Studies have shown that cardiovascular-related mortality rates increase significantly during periods of thermal stress, particularly during the summer months when people spend more time outdoors (Laschewski & Jendritzky, 2002; Urban et al., 2017). Although cold-related mortality is also significant (Hajat et al., 2007), its causes are less understood and underemphasized (Urban et al., 2017). In recent years, global warming has increased the frequency and severity of heatwaves, prompting numerous studies focusing on the impacts of high temperatures (Rahmstorf & Coumou, 2011; Tomczyk et al., 2023). However, despite their influence, cold stress periods have received relatively little attention in the thermal comfort literature.

To better assess outdoor thermal comfort, several bioclimatic indices have been developed. The most widely used of these indices, the PET (Physiological Equivalent Temperature) index, considers both meteorological variables and human thermoregulatory factors, such as clothing and activity level. Most thermal comfort studies are conducted in temperate or hot climates, often focusing on urban heat islands (UHI), thermal zoning, or monthly temperature averages. However, rural areas, which differ significantly in structure and vegetation, present distinct wind environments. These include natural open-air flows, which vary considerably from urban wind dynamics shaped by dense construction (Takebayashi & Moriyama, 2009). In rural settlements, pedestrian-level wind speeds have a direct impact on daily life, especially in winter, when cold stress increases due to wind chill. This makes maintaining thermal comfort more difficult.

Van Province, located in eastern Türkiye, contains significant wind corridors due to its high elevation and mountainous terrain. One of the most prominent is the Gönderme Wind Corridor, which originates in Çaldıran, passes through Muradiye, and continues toward Erciş (Figure 1). Wind speed plays a crucial role in thermal perception, significantly influencing the comfort levels of residents.

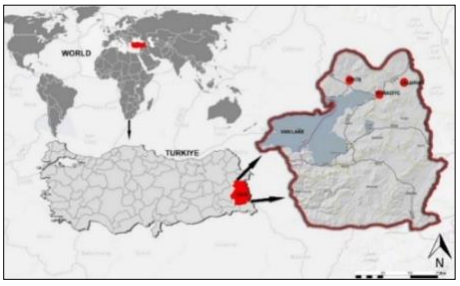

Figure 1. Study area.
Şekil 1. *Çalışma alanı.*

This study aims to assess the thermal comfort levels in Çaldıran and Muradiye, two districts characterized by rural settlement patterns and exposure to wind corridors, and to understand how building density, proximity to Lake Van, and wind dynamics affect thermal comfort. Erciş, a district with urban characteristics and also influenced by the wind corridor, was chosen for comparison. Urban wind environments impact both human comfort and urban ecosystems; yet very few studies have examined the mechanical or thermal effects of pedestrian wind in such contexts (Blocken et al., 2013; Wang et al., 2022).

This study provides novel insights into the interaction between wind corridors, large water bodies, and thermal comfort, particularly in the unique context of Van Province's urban and rural settlements. It is intended to serve as a foundation for future research, especially for studies focusing on thermal planning and comfort strategies around Lake Van, the largest lake in Türkiye.

MATERIALS and METHOD

Materials

The material of this study comprises Van Province and its immediate surroundings, located in the eastern part of Türkiye. Van is situated in the Eastern Anatolia Region and is known for its harsh continental climate, rugged topography, and significant elevation differences. The city has historically served as a settlement area for various civilizations, offering fertile soils and access to freshwater resources such as Lake Van (Kılıç, 2021). The province presents a unique microclimatic structure, shaped by the interaction between Lake Van, a large inland body of water, and the surrounding mountainous terrain. These geographic features contribute to spatial variations in thermal conditions and wind dynamics across the region. Within the scope of this study, three districts were selected as representative sampling areas based on their differing land use, elevation, and settlement typologies:

- Çaldıran, with an average elevation of 2050 meters, represents a rural, high-altitude settlement located in the northern part of the province and is directly influenced by the Gönderme wind corridor.
- Muradiye, with an elevation of approximately 1705 meters, also reflects rural characteristics, featuring a combination of agricultural lands and open plains.
- Erciş, situated at 1750 meters, represents a more urbanized settlement closer to Lake Van, where structural density and built-up areas are higher than in the other two districts.

These elevation differences are not only relevant for characterizing the topographic variation across the study area but also play a critical role in determining local microclimatic conditions, particularly air temperature, wind flow patterns, and thermal comfort levels.

Study area: Çaldıran District

Çaldıran District, located in the northern part of Van Province, is characterized by its high altitude (2050 meters above sea level) and severe continental climate, making it one of the coldest districts in Türkiye during the winter months. The region is directly influenced by the Gönderme Wind Corridor, which channels strong and persistent north-south winds throughout the year. Seasonally, Çaldıran experiences dry and clear summers, whereas winters are extremely cold, snowy, and partially cloudy. Annual temperatures typically range from –11ºC to 26ºC, with occasional extremes ranging from –18ºC to 29ºC. Hydrologically, the Bendimahi Stream, which originates within the district boundaries, traverses the central plain and flows into Lake Van, approximately 35 km to the south (Ministry of National Education, 2024). The district's open topography, minimal built-up areas, and exposure to high winds contribute significantly to its distinct microclimatic conditions, particularly in terms of thermal stress and wind-induced cooling.

Study area: Erciş District

Erciş District is situated approximately 100 kilometers north of Van city center, positioned 5 kilometers inland from Lake Van, at an elevation of 1750 meters above sea level. It encompasses the Erciş Plain, one of the largest and most agriculturally active lowland areas bordering the lake, with a surface area of approximately 2115 km². Climatically, Erciş experiences warm, dry summers and cold, snowy winters. Average annual temperatures range from –10ºC to 28ºC, with rare fluctuations below –17ºC or above 30ºC. July typically marks the warmest period, with sky clarity reaching up to 99%. The southern extension of the Gönderme Wind Corridor also affects the district, albeit to a lesser extent, due to the urban density and modified land surface characteristics. These urban features are thought to moderate wind exposure and contribute to the formation of UHI effects during warmer seasons (Weather Spark, 2024).

Study area: Muradiye District

Muradiye District lies 86 kilometers northeast of Van city center and covers a geographical area of approximately 1100 km². The district exhibits a transitional topography, comprising both mountainous terrain and partial plains, with an average elevation of 1705 meters. Its climatic regime is defined by hot and dry summers and long, cold, and wet winters. Annual air temperatures generally fluctuate between 2ºC and 35ºC, with extremes rarely falling below –3ºC or exceeding 38ºC. Similar to Çaldıran, Muradiye is also traversed by the Gönderme Wind Corridor, which exerts a notable influence on the district's climatic dynamics, particularly through the north-to-south movement of strong cold winds. Despite its proximity to mountainous regions, Muradiye maintains a rural settlement structure, characterized by relatively low building density and extensive open landscapes, which increase its vulnerability to wind-induced thermal stress during the winter months (Weather Spark, 2024).

Method

Analysis of meteorological data

Observation data from meteorological stations located in the districts of Çaldıran, Muradiye, and Erciş were used in this study. To ensure comparability among all stations, the analysis focused on the period between 2018 and 2023, during which consistent and robust data were available. The characteristics of the stations are presented in Table 1.

Table 1. Features of meteorology stations

Çizelge 1. *Meteoroloji istasyonlarının özellikleri*

Stations	Location	Altitude	Land Usage Features
Çaldıran Station	39° 08' 16"N 43° 55' 28"E	2050 m	Rural settlement area: Generally, there are agricultural lands with little construction (2-4 floors) and abundant planting. It is 35 km away from Lake Van.
Erciş Station	38° 55' 45"N 43° 23' 44"E	1750 m	Urban settlement area: It is a settlement area where the construction and planting are generally at a medium level (5-7 storeys). It is located around Lake Van.
Muradiye Station	38° 59' 45"N 43°45' 39" E	1700 m	Rural settlement area: Generally, there are agricultural lands with little construction (4-5 floors) and abundant planting. It is 12 km away from Lake Van.

A comprehensive literature review was conducted to identify appropriate indices for evaluating outdoor thermal comfort. Based on this review, the Physiological Equivalent Temperature (PET) index was selected, as it is the most widely used indicator for assessing outdoor thermal comfort. The PET index estimates human thermal comfort based on the human energy balance model, accounting for the combined effects of meteorological parameters, including shortwave and longwave solar radiation, air temperature, relative humidity, and wind speed, as well as thermo-physiological factors, such as clothing insulation and activity level (Höppe, 1999). PET was chosen because it transforms the assessment of a complex outdoor climate environment into a simple indoor scenario on a readily understandable, physiologically equivalent basis. Its results are expressed in degrees Celsius, making it easily comprehensible to everyone (Matzarakis et al., 2007; Norouziasas et al., 2022).

In this study, PET values were calculated using the RayMan Pro 2.1 model, which integrates all relevant variables for thermal comfort analysis and provides the most accurate results (Koss, 2006). This program was chosen because it is frequently used to determine outdoor thermal comfort conditions (Krzyżewska et al., 2019; Yılmaz et al., 2021). A standard profile representing a healthy adult male aged 35 years, 175 cm tall, weighing 75 kg, with a clothing insulation value of 0.9 clo, and a metabolic workload of 80 W was used for the calculations. The PET values obtained from Rayman Pro 2.1 were interpreted according to the thermal stress classification ranges proposed by Matzarakis and Mayer in (1999), which are still used as the basis for outdoor thermal comfort ranges in many studies, including international studies (Table 2).

Table 2. Thermal sensation and stress levels of the PET index

***Çizelge 2**. PET indeksinin termal hissi ve stres seviyeleri*

PET° C	Human Temperature Sense	Thermal Stress Level
< 4,0	Extreme Cold	Extreme Cold Stress
4,1–8,0	Cold	Strong Cold Stress
8,1–13,0	Cool	Medium Cold Stress
13,1–18,0	Slightly Cool	Mild Cold Stress
18,1–23,0	**Comfortable**	**No Thermal Stress**
23,1–29,0	Light Warm	Mild Heat Stress
29,1–35,0	Hot	Medium Heat Stress
35,1–41,0	Very hot	Strong Heat Stress
>41,0	Extreme Heat	Extreme Heat Stress

In calculating the Physiological Equivalent Temperature (PET) index, hourly data for air temperature, relative humidity, wind speed, cloudiness, and solar radiation are utilized. The index is based on the human energy balance equation, which considers both environmental and physiological variables.

The PET model uses the following general heat balance equation:

M + W + Q* (Tmrt, v) + QH (Ta, v) + QL (e, v) + QSW (e, v) + QRe (Ta, e) + S=0

Where: - M: Metabolic rate (activity level), W: Mechanical work, Q*: Radiation budget, QH: Sensible heat exchange, QL: Latent heat exchange (evaporation), QSW: Latent heat from sweating, QRe: Respiratory heat exchange (sensible and latent), S: Heat storage in the body, Ta: Air temperature, e: Vapor pressure, v: Wind speed, Tmrt: Mean radiant temperature

Wind speed data obtained from meteorological stations are typically measured at a height of 10 meters. However, to reflect pedestrian-level conditions, wind speeds must be adjusted to a reference height of 1.1 meters, which corresponds to the approximate center of gravity of a standing human body (Nastos & Matzarakis, 2019).

This adjustment is made using the following logarithmic wind profile equation:

WS_1.1=WS_h * (1.1 / h)^a

Where: - WS_1.1: Wind speed at 1.1 meters (m/s), WS_h: Wind speed at height h (usually 10 meters) - h: Measurement height (10 m), a: Empirical coefficient based on surface roughness, z0: Surface roughness length (obtained from the European Wind Atlas). The empirical coefficient a is calculated using the equation: a=0.12 * z0 + 0.18 as proposed by Irmak et al. (2020).

Multiple linear regression analysis of PET values

Regression analysis is a statistical tool used to estimate the relationship between the dependent variable and the independent variable. In other words, it focuses on how the dependent variable changes in response to changes in the independent variables (Yilmaz et al., 2018). More than one variable can come together and affect another variable. On the other hand, these variables can also influence one another. In such cases, when more than one variable needs to be used, it is referred to as "multiple regression analysis" (Kılıç, 2013).

In the study, multiple regression analysis was performed to determine how the PET values obtained from numerous variables and other variables affect the meteorological climate data. At this stage, the data were standardized, as the values of the meteorological climate data (temperature (Ta, ºC), humidity (RH—%), wind (m/s), and cloudiness (Octas)) were not in the same category.

Conducting Pearson correlation analysis of PET values

Correlation analysis is a statistical method used to examine the direction and strength of the relationship between two variables (Höppe, 1999). The correlation coefficient (r) ranges from –1 to +1. A negative value indicates an inverse relationship, while a positive value indicates a direct linear relationship. The closer the coefficient is to ±1, the stronger the relationship (Çağlak & Matzarakis, 2024).

In this study, Pearson Correlation analysis was conducted to assess the direction and magnitude of the relationship between the meteorological variables and the PET values derived from them. The interpretation of the Pearson correlation coefficients was based on the classification intervals presented in Table 3 (Çağlak & Matzarakis, 2024).

Table 3. Pearson correlation coefficient ranges

Çizelge 3. *Pearson korelasyon katsayısı aralıkları*

Correlation Coefficient (R2)	Comment
R<0.2	No Relationship
0.2-0.4	Low Relationship
0.4-0.6	Moderate Relationship
0.6-0.8	High Relationship
R >0.8	Very High Relationship

RESEARCH FINDINGS AND DISCUSSION

This study evaluated monthly changes in meteorological parameters and PET values between 2018 and 2023 in the Çaldıran, Muradiye, and Erciş districts. Analysis of monthly average temperatures obtained from hourly climate data between 2018 and 2023 revealed that the highest value was recorded at Muradiye station in August, with 24.2ºC, and the lowest value was recorded at Çaldıran station in January, with 9.5ºC (Table 4). The fact that monthly average temperatures in Erciş were generally higher than those in Çaldıran is consistent with previous findings on temperature differences between urban and rural areas (Özlü et al., 2019; Shi et al., 2015). Interestingly, despite being a rural district, Muradiye recorded higher average temperatures than Erciş in some months. This anomaly is primarily attributed to Muradiye's proximity to large water bodies, which act as thermal buffers, thereby reducing extreme temperatures in surrounding areas (Nakayama & Fujita, 2010).

Table 4. Monthly average temperature data (2018-2023)
Çizelge 4. *Aylık ortalama sıcaklık verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-9,5	-8,3	-0,2	5,9	11,3	17	20,6	21	16,1	9,2	2,5	-3,4	6,8
Muradiye Station (Rural)	-3,3	-2,1	3,6	9,1	14,1	20,3	24,1	24,2	19,2	13,5	5,6	1,1	10,7
Erciş Station (Urban)	-3,2	-2,1	3,4	8,7	13,5	19,5	23,1	23	18,1	11,3	5,3	1	10,1

An examination of the monthly average maximum temperatures between 2018 and 2023 shows that January values were identical across all three stations. In the remaining months, however, Muradiye and Erciş stations consistently recorded higher maximum temperatures than Çaldıran. Moreover, Muradiye and Erciş displayed similar values throughout the year, except in October, where a noticeable divergence was observed. The most significant temperature difference between Muradiye and Çaldıran was 7.5 ºC in October, followed by 5.1 ºC in December. The smallest difference occurred in September (2.5 ºC) and November (2.7ºC). The greatest urban–rural temperature contrast between Erciş and Çaldıran was noted in December, with Erciş being 5ºC warmer, highlighting the effect of urban warming (Table 5).

Table 5. Monthly average maximum temperature data (2018-2023)
Çizelge 5. *Aylık ortalama maksimum sıcaklık verileri (2018-2023*)

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	8,4	6,8	15,8	20,6	25,8	31	34,4	33,2	31,2	24,3	16,4	8,8	21,3
Muradiye Station (Rural)	8,4	9,9	19,7	23,6	28,7	34,4	37,8	36,9	33,7	31,8	19,1	13,9	24,8
Erciş Station (Urban)	8,4	10,6	19	23,6	28,4	33,7	37	37,2	32,3	26,8	19	13,8	24,1

Analysis of monthly average minimum temperatures indicates that Erciş station recorded higher values than the other stations in September, reflecting the urban heat retention effect during night hours. In contrast, Çaldıran station consistently exhibited the lowest minimum temperatures throughout the year, a result of its high elevation, continental climate characteristics, and exposure to open wind corridors (Table 6).

Table 6. Monthly average minimum temperature data (2018-2023)
Çizelge 6. *Aylık ortalama minimum sıcaklık verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-33,8	-32,6	-22,1	-8,9	-2,4	3,2	6,7	5,9	1,8	-7,5	-9,9	-27,2	-10,5
Muradiye Station (Rural)	-20,3	-17,6	-11,1	-3,7	1	6	11,4	10,2	0	0	-6	-16,5	-3,7
Erciş Station (Urban)	-20,6	-19,5	-12,9	-4	-0,2	6,5	10,3	7,8	3,9	-2,5	-6,5	-15,6	-4,4

An evaluation of monthly average relative humidity data reveals that Çaldıran station consistently recorded higher humidity levels compared to the other stations (Table 7). This can be attributed to the district's distinct hydrological and ecological features, including the Bendimahi Stream, which extends approximately 35 km toward Lake Van, the Çaldıran Plain, Kaz Lake, and surrounding reed beds located about 7 km from the district center. Additionally, wetland areas covering 223 km², along with extensive meadow and pasturelands, significantly contribute to the region's elevated atmospheric moisture levels. These natural elements enhance evapotranspiration, which in turn increases local humidity.

Table 7. Monthly average relative humidity data (2018-2023)
Çizelge 7. *Aylık ortalama bağıl nem verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	83	83	78	68	60	48	49	43	42	56	71	80	56,7
Muradiye Station (Rural)	70	73	71	62	59	44	35	33	40	58	72	76	55
Erciş Station (Urban)	67	69	65	57	55	42	35	35	42	59	64	70	55

Wind speed data obtained from The Meteorological Service were adjusted to reflect pedestrian-level conditions by reducing the measurement height from 10 meters to 1.1 meters, which corresponds to the center of gravity of a standing human body. As a result of this adjustment, the wind speed values presented in Table 8 are lower than the original measurements taken at 10 meters.

Table 8. Monthly average wind speed data (2018-2023)

Çizelge 8. *Aylık ortalama rüzgar hızı verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	0,4	0,4	0,7	0,8	0,8	0,7	0,8	0,7	0,7	0,5	0,4	0,3	0,6
Muradiye Station (Rural)	0,4	0,4	0,5	0,5	0,5	0,6	0,6	0,6	0,5	0,4	0,3	0,3	0,4
Erciş Station (Urban)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

An examination of the monthly wind speed averages shows that Çaldıran station consistently recorded higher wind speeds than Muradiye and Erciş stations between March and November. In contrast, Erciş station exhibited the lowest wind speeds across all months. This difference can be attributed to urban morphology, as narrow streets and densely built structures in urban areas hinder airflow and reduce wind speed (Shui et al., 2018). Additionally, unlike the other districts, Erciş is not positioned between mountain ranges and Lake Van, which limits the formation of a natural wind corridor. These findings are consistent with previous studies comparing urban and rural wind dynamics, which indicate that urban centers with dense building stock tend to have significantly lower wind speeds than high-altitude, open rural areas (Shi et al., 2015; Özlü et al., 2019).

The analysis of monthly average maximum wind speed values indicates that Çaldıran station consistently recorded higher values than both Erciş and Muradiye stations throughout the year (Table 9). The highest monthly average maximum wind speed was observed in May (4.3 m/s), followed by December (4.1 m/s). In contrast, Erciş station exhibited the lowest maximum wind speeds in all months except January, which further supports the finding that urban morphology restricts wind flow, reducing both average and peak wind conditions.

Table 9. Monthly average maximum wind speed data (2018-2023)

Çizelge 9. *Aylık ortalama maksimum rüzgar hızı verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	3,4	3,1	3,8	4	4,3	3,1	2,9	3,2	3,4	3,3	2,8	4,1	3,4
Muradiye Station (Rural)	1,9	1,8	3,7	2,3	3	2,2	1,9	1,7	2,2	1,7	1,7	2,2	2,1
Erciş Station (Urban)	2,5	0,6	0,9	0,7	0,9	0,6	0,7	0,6	0,7	0,7	0,5	0,8	0,8

To better understand the impact of pedestrian-level wind and its relationship with PET values, data on the monthly number of stormy and strong wind days between 2018 and 2023 were obtained from the Turkish State Meteorological Service. Among the stations, Çaldıran recorded the highest number of stormy days, totaling 57 days, with May identified as the stormiest month. Erciş followed with 14 days, while Muradiye experienced the lowest number of stormy days with only 5. In terms of strong wind days, Çaldıran again ranked first, with a total of 629 days over the six years. The peak months were May (88 days), June (101 days), and July (92 days). Erciş station reported 310 strong wind days, with a concentration particularly in April (50 days), May (46 days), and July (41 days). Muradiye had the lowest total, with 221 strong wind days, including April (38 days), May (30 days), and July (36 days).

These findings highlight the climatic intensity and variability of wind conditions in the study area, particularly in Çaldıran, and underscore the importance of integrating wind data into thermal comfort assessments and urban-rural planning strategies.

Interpretation of PET values

Monthly average pet distribution maps

In the PET distribution maps generated for the study areas, red tones indicate heat stress, blue tones represent cold stress, and green areas signify thermal comfort zones with no significant stress. Since the focus of this research is to examine the impact of wind corridors on thermal comfort in residential areas, PET values were interpreted in conjunction with average wind speeds, the number of stormy days per month, and the frequency of strong wind days. Wind data analyses revealed that Çaldıran station had the highest wind speeds from March to November (Table 8). When corresponding PET values were examined, Çaldıran consistently experienced extreme cold stress during these months, while the thermal conditions in Muradiye and Erciş varied more moderately. Notably, in May, Çaldıran exhibited moderate cold stress, whereas the other stations experienced only mild cold stress (Table 10). This can be attributed to the fact that May had both the highest wind speed and the most significant number of stormy days in Çaldıran during the six-year study period.

Furthermore, during July, when Çaldıran recorded its highest number of strong wind days, no thermal stress was observed there, while mild heat stress was detected in Muradiye and Erciş (Table 10, Figure 2). These observations align with previous studies, which have reported that increased wind speed in cold seasons reduces thermal comfort due to the amplified cooling effect of wind, and that open rural settlements are generally cooler than urban areas, particularly due to pedestrian-level wind exposure (Yılmaz et al., 2021). Consistent with the literature, this study confirms that Çaldıran, due to its high wind speeds, frequent stormy days, and strong wind conditions, experiences more pronounced cold stress, highlighting the crucial role of wind in shaping local thermal comfort dynamics.

Table 10. Monthly average PET data (2018-2023)

Çizelge 10. *Aylık ortalama PET verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-13,2	-11,2	-2,3	4,3	10,8	17	20,5	20,2	14,4	7,1	-0,2	-6,6	5,5
Muradiye Station (Rural)	-4,2	-4,3	2,7	9	15	21,5	25,4	24,9	18,8	12,5	3,7	-1,3	10,3
Erciş Station (Urban)	-5,4	-3	4,1	10,7	16,9	23	26,8	25,8	19,5	11,6	4,3	-0,7	11,1

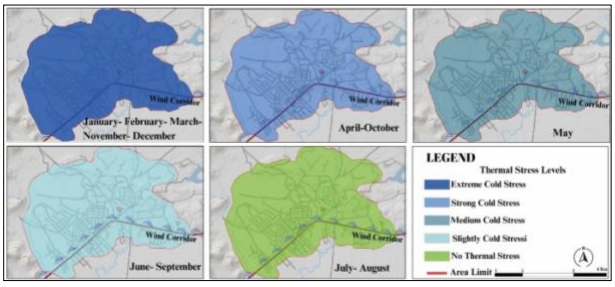

Figure 2. Monthly average PET distribution map of Çaldıran station (2018-2023).

Şekil 2. *Çaldıran istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

An analysis of Figure 3 reveals that the overall PET averages in Erciş, representing an urban settlement, are generally more favorable in terms of thermal comfort. However, this trend reverses during the summer months, particularly in July and August, where PET values increase significantly, leading to heat stress conditions. This finding is consistent with the results of Irmak et al. (2020), who reported that urban areas exhibited the highest PET values, and Yılmaz et al. (2021), who emphasized that regions with lower elevation and reduced wind exposure tend to experience elevated PET levels. These observations align with the broader literature on UHI, where densely built urban environments are significantly warmer than adjacent rural areas due to factors such as impervious surfaces, reduced vegetation, and limited ventilation (Rizwan et al., 2008; Connors et al., 2013).

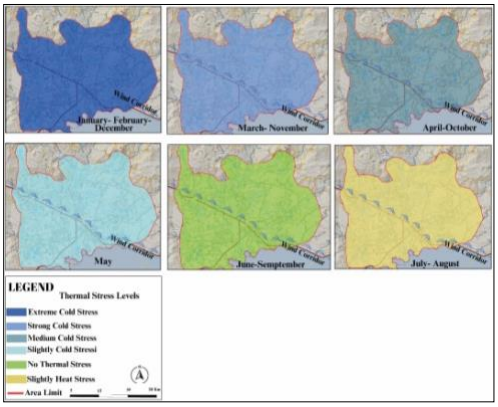

Figure 3. Monthly average PET distribution map of Erciş station (2018-2023).

Şekil 3. *Erciş istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

Although Muradiye and Erciş stations display similar climatic characteristics, the most notable difference lies in their settlement typologies Muradiye represents a rural environment, while Erciş reflects urban characteristics. Despite this contrast, PET distribution maps indicate comparable patterns between the two, with Muradiye experiencing extreme cold stress for five months and Erciş for only three months (Figures 3, Figures 4). The modifying effects of tree density and land use types may explain this similarity in PET distributions. According to Maniatis et al. (2020), while urban centers in cold climates and areas with dense tree cover may benefit from improved thermal comfort due to wind shielding and radiative trapping, open rural settlements with high proportions of unshaded green areas may exhibit lower PET values in winter due to the cooling and shading effects of vegetation.

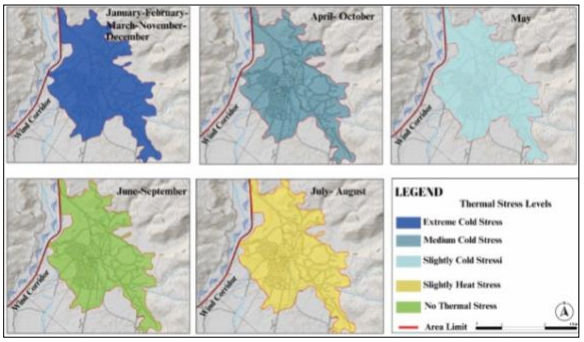

Figure 4. Monthly average PET distribution map of Muradiye station (2018-2023).

Şekil 4. *Muradiye istasyonunun aylık ortalama PET dağılım haritası (2018-2023).*

The monthly average PET values for Çaldıran station are lower than those of Muradiye and Erciş throughout the year. This outcome is expected given that Çaldıran consistently records lower air temperatures, while maintaining higher average humidity and wind speed values. Additionally, Çaldıran's elevation (2050 m) and its location within an active wind corridor contribute to further reductions in PET values by intensifying cold stress conditions. When comparing Erciş and Muradiye, although both stations exhibit similar temperature profiles, the slightly higher wind speeds in Muradiye result in lower PET values relative to Erciş (Table 10). However, in October, Muradiye station records the highest air temperature among all three locations (Table 4), which directly influences its PET value, making it the station with the highest thermal comfort level for that particular month.

Monthly average maximum pet distribution maps

An examination of the monthly maximum PET values reveals that the Erciş station consistently exhibits the highest PET values throughout the year, when compared to the other two stations. The difference between Erciş and Muradiye in terms of maximum PET is relatively small, suggesting similar peak thermal comfort conditions in these two districts. In contrast, Çaldıran station consistently records the lowest maximum PET values, reinforcing the impact of its high altitude, strong wind exposure, and cooler climatic conditions (Table 11).

Table 11. Monthly average maximum PET Data (2018-2023)

Çizelge 11. *Aylık ortalama maksimum PET Verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	14,6	15,5	25,5	28,8	32,7	39	44,8	41,9	39,7	31,7	21,6	13,6	29,1
Muradiye Station (Rural)	10,3	17,3	28	32,4	38,3	44,1	49,2	47,8	41,9	38,5	26,4	18,4	32,7
Erciş Station (Urban)	16,6	21,3	28,2	36,1	42,2	47,8	52	51	47,1	38	30,3	20,7	35,9

As previously emphasized, several topographic and locational factors contribute to Çaldıran station being the site with the lowest heat stress among the three study areas (Figure 5). These include its significantly higher elevation compared to Muradiye and Erciş, its mountain-encircled rural setting, its greater distance from Lake Van, and the fact that a substantial portion of the Gönderme wind corridor traverses this district. These elements collectively enhance wind-driven cooling effects and limit heat accumulation, thereby reducing PET values and associated thermal stress levels.

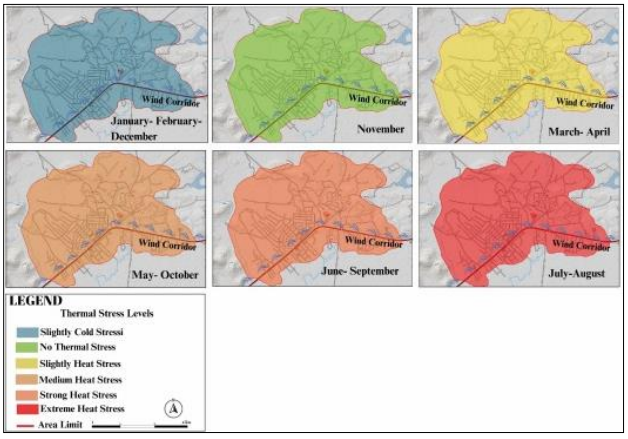

Figure 5. Monthly average maximum PET distribution map of Çaldıran station (2018-2023).

Şekil 5*. Çaldıran istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023).*

The occurrence of extreme heat stress in Erciş station during certain months is primarily influenced by its proximity to Lake Van, its relatively low altitude, and its urban settlement character (Figure 6). These factors contribute to reduced ventilation and increased heat retention, particularly during the summer season. Although Muradiye station shares similar geographic conditions, being close to Lake Van and located at a low elevation, it experiences less heat stress than Erciş. This difference can be attributed to Muradiye's rural setting and its position within the Gönderme wind corridor, which enhances natural air circulation and mitigates thermal accumulation (Figure 7).

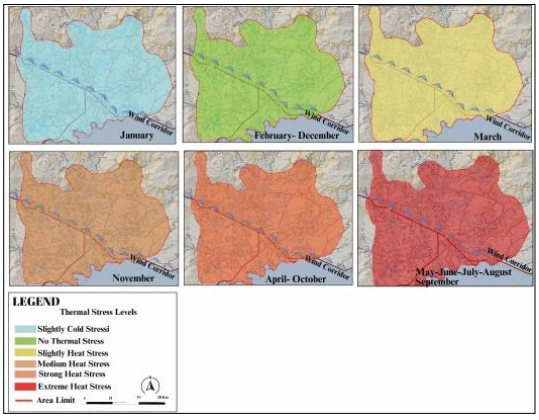

Figure 6. Monthly average maximum PET distribution map of Erciş station (2018-2023).

Şekil 6. *Erciş istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023).*

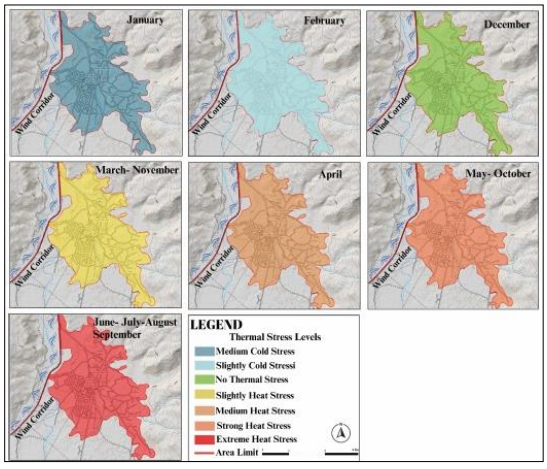

Figure 7. Monthly average maximum PET distribution map of Muradiye station (2018-2023)

Şekil 7. Muradiye istasyonunun aylık ortalama maksimum PET dağılım haritası (2018-2023)

Monthly average minimum pet distribution maps

An analysis of the monthly average minimum PET values at Çaldıran station reveals that the area is subject to extreme cold stress throughout the entire year (Table 12). In Erciş, intense cold stress is observed in July, while extreme cold stress dominates the remaining months. Similarly, Muradiye station experiences strong cold stress in July and August, and extreme cold stress during all other months. These findings reflect the pronounced influence of high elevation, low night-time temperatures, and seasonal wind activity on nocturnal thermal discomfort, particularly in open rural environments such as Çaldıran and Muradiye.

Table 12. Monthly average minimum PET data (2018-2023)

Çizelge 12. *Aylık ortalama minimum PET verileri (2018-2023)*

Months	1	2	3	4	5	6	7	8	9	10	11	12	Avg.
Çaldıran Station (Rural)	-40,1	-39,2	-28	-14,9	-8,2	-1,9	0,3	0,3	-4	-14	-16,4	-33,2	-16,6
Muradiye Station (Rural)	-17,5	-24,6	-17,6	-8	-4,1	0,6	4,6	4,2	-1,7	-6,7	-12,6	-22,4	-8,8
Erciş Station (Urban)	-26,6	-26,3	-19,6	-9,6	-5,4	1,5	5	3,1	-1,2	-8,8	-13,1	-21,5	-10,2

Investigation of the relationship between pet values and climate data with statistical analysis

According to the results of the Pearson correlation analysis conducted to assess the relationship between PET values and meteorological parameters at Çaldıran station, a robust positive correlation was found between PET and air temperature (r=0.978), indicating that temperature is the most influential factor affecting thermal perception. A strong negative correlation was observed between PET and relative humidity (r=–0.725), suggesting that increased humidity levels are associated with lower PET values.

In addition, a moderate positive correlation was found between PET and wind speed (r=0.401), while cloudiness showed a weak negative correlation with PET (r=–0.253). All relationships were statistically significant (*p*=0.000) (Table 13). These findings highlight the dominant role of temperature and humidity, followed by wind, in determining PET values in high-altitude rural environments like Çaldıran.

Table 13. Çaldıran Pearson correlation table

Çizelge 13. *Çaldıran Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (*p*)
Humidity	-0,716	1			0.000
Wind	0,425	-0,358	1		0.000
Cloud	-0,296	0,435	0,014	1	0.000
PET	0,978	-0,725	0,401	-0,253	0.000

The Pearson correlation analysis performed for Erciş station revealed a very strong positive correlation between PET values and air temperature (r=0.908), confirming temperature as the dominant determinant of thermal comfort in this urban area. A weak negative correlation was found between PET and relative humidity (r=–0.220), indicating a limited inverse relationship.

In contrast to rural stations, wind speed showed no significant correlation with PET (r=–0.041), highlighting the diminished effect of wind due to urban morphological features that reduce air circulation. Cloudiness, on the other hand, exhibited a weak positive correlation with PET (r=0.276). All correlation values were statistically significant (*p*=0.000) (Table 14). These findings suggest that in urban contexts like Erciş, thermal comfort is primarily driven by temperature, while wind has little to no influence on PET levels.

The Pearson correlation analysis for Muradiye station revealed a robust positive correlation between PET values and air temperature (r=0.942), indicating that temperature is the primary factor influencing thermal comfort. A strong negative correlation was also found between PET and relative humidity (r=–0.738), indicating that increased humidity significantly reduces perceived thermal comfort.

Table 14. Erciş Pearson correlation table

Çizelge 14. *Erciş Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (P)
Humidity	-0,182	1			0.000
Wind	0,052	-0,130	1		0.000
Cloud	0,223	0,328	0,124	1	0.000
PET	0,908	-0,220	-0,041	0,276	0.000

In addition, wind speed and cloudiness both exhibited low positive correlations with PET (r=0.364 for each), suggesting that while their effects are more modest compared to temperature and humidity, they still contribute to thermal perception in this rural district. All correlations were statistically significant (*p*=0.000) (Table 15). These results indicate that Muradiye's PET values are shaped by a combination of temperature, humidity, and moderate wind activity, consistent with its position along a wind corridor and rural landscape features.

Table 15. Muradiye Pearson correlation table

Çizelge 15. *Muradiye Pearson korelasyon tablosu*

Variable	Heat	Humidity	Wind	Cloud	Importance Level (*p*)
Humidity	-0,748	1			0.000
Wind	0,403	-0,465	1		0.000
Cloud	-0,348	0,444	-0,113	1	0.000
PET	0,942	-0,738	0,364	0,364	0.000

According to the Pearson correlation analysis, a powerful positive relationship was identified between air temperature and PET values across all three stations, confirming temperature as the primary determinant of thermal comfort. At Çaldıran and Muradiye, a positive correlation was also found between wind speed and PET values, indicating that wind contributes positively to thermal perception in these open rural environments. In contrast, Erciş station exhibited a weak negative correlation with wind speed, suggesting that wind has a negligible influence on PET in urban settings.

When examining relative humidity, Çaldıran and Muradiye both displayed a strong negative correlation with PET values, whereas Erciş showed a weak positive correlation. These findings imply that high humidity levels in rural areas are associated with decreased PET, while in urban areas, the relationship is minimal and inconsistent. Overall, the monthly average PET values in Çaldıran and Muradiye were found to be primarily influenced by temperature, with wind speed being the secondary factor. In Erciş, temperature remained the dominant factor, while wind had no meaningful effect, and humidity had only a minor negative impact. This comparative evaluation underscores the importance of local climatic and morphological contexts in shaping thermal comfort dynamics.

CONCLUSION and RECOMMENDATIONS

This study investigated the impact of meteorological variables on pedestrian-level thermal comfort in three climatically and topographically distinct settlements: Çaldıran, Muradiye, and Erciş. The findings reveal that air temperature, wind speed, relative humidity, and cloudiness significantly influence PET values; however, the nature and strength of these influences vary depending on elevation, topographic structure, proximity to water bodies, and urban-rural settlement characteristics. Çaldıran, with its high elevation, open rural environment, and exposure to a strong wind corridor, consistently exhibited the lowest PET values throughout the year, mainly due to enhanced cold stress. Muradiye, although similarly rural and topographically complex, presented more moderate PET values. In contrast, Erciş, as an urban settlement at a lower elevation, demonstrated higher PET values during summer due to reduced wind movement and UHI effects, while maintaining relatively comfortable conditions in winter.

These results underscore the need for climate-responsive spatial planning that extends beyond temperature-centric approaches, incorporating seasonal wind behavior, landform context, and settlement morphology to ensure thermally livable environments.

Recommendations

Integrated climate-based spatial planning should be adopted. Thermal comfort analyses must guide decisions regarding building orientation, street geometry, vegetation layout, and public space design.

In high-altitude rural areas (e.g., Çaldıran):

Figure 2 shows that Çaldıran's monthly average PET values are cooler than those of other settlements. In this regard: The settlement layout should maximize solar gain in winter through south-facing streets and facades.

- Structural design must minimize wind exposure without entirely blocking natural air circulation.
- Vegetation and building forms should be arranged to reduce wind intensity at the pedestrian level while maintaining visual openness.
- Materials with high thermal mass (e.g., stone, brick) should be prioritized for insulation.

In low-altitude urban settlements near large water bodies (e.g., Erciş):

Figures 3 and 6 show that Erciş station exhibits warmer ranges in terms of thermal stress. Therefore:

- Summer heat stress should be mitigated through shade-providing vegetation, permeable surfaces, and reflective materials.
- Urban morphologies should enable cross-ventilation via strategic street alignment and building gaps.
- Tree canopies, green walls, and water features should be integrated to alleviate the UHI effect.

General principles applicable to all settlements:

- Seasonal variation in thermal comfort should be addressed with distinct summer and winter strategies.
- Wind should be viewed not only as a cooling agent but also as an ecological and health-related factor influencing air quality and ventilation.
- Wind corridors must be preserved and integrated into planning frameworks to balance thermal comfort and environmental ventilation.
- PET and other biometeorological indices should be institutionalized as key indicators in urban and landscape policy-making, especially in areas experiencing climatic extremes.

In conclusion, this study demonstrates that thermal comfort in outdoor environments is not solely governed by air temperature but is also deeply influenced by a combination of topographic features, elevation, wind corridors, settlement morphology, and proximity to large bodies of water. While urban areas like Erciş benefit from higher PET values in colder seasons due to heat retention, they face increased heat stress during summer months due to restricted wind flow and dense structural texture. Conversely, rural areas such as Çaldıran and Muradiye are more vulnerable to cold stress, particularly in winter, due to higher altitudes and exposure to strong winds. These findings underscore the need to develop climate-responsive design strategies tailored to the unique spatial and environmental characteristics of both rural and urban settlements. Integrating PET-based assessments into planning processes can significantly enhance public health, spatial quality, and seasonal livability in climatically diverse regions.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: NY, ŞA., and MAI; sample collection: NY, ŞA., and MAI; analysis and interpretation of data: NY, ŞA., and MAI; statistical analysis: NY; visualization: NY; writing manuscript: NY, ŞA., and MAI.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that ethical approval was not required for this study.

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Research Article
(Araştırma Makalesi)

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Analysis of the relationship between agricultural credit utilization and agricultural input price index

Tarımsal kredi kullanımı ile tarımsal girdi fiyat endeksi arasındaki ilişkinin analizi

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ABSTRACT

Objective: This study aims to investigate the relationship between agricultural credit (vital for the continuity of agricultural activities) and the Agricultural Input Price Index, which shapes the cost environment in which these activities take place.

Material and Methods: The analysis employs monthly data spanning January 2015 to March 2024. Methodologically, it applies the Fractional-Frequency Fourier ADF unit root test, the Fractional-Frequency Fourier ADL cointegration test, and the Fractional-Frequency Fourier TY causality test.

Results: The empirical findings indicate that a 1% rise in the Agricultural Input Price Index is associated with increases in agricultural credit utilization of 0.95% in the long-run and 0.18% in the short-run. The results of the cointegration test are further supported by the results of the causality test.

Conclusion: The findings suggest that sustaining agricultural production nationwide requires targeted financial support for all producers engaged in farming—particularly small-scale farmers—through low- or zero-interest credit facilities channelled via publicly capitalized commercial banks. Such support would mitigate the adverse effects of rising input prices, reduce underutilization of essential inputs, and help avert productivity losses.

ÖZ

Amaç: Bu çalışma, tarımsal faaliyetlerin devam etmesi için gereken tarımsal kredi ile bu faaliyetleri etkileyen Tarımsal Girdi Fiyat Endeksi arasındaki ilişkiyi incelemeyi amaçlamaktadır.

Materyal ve Yöntem: 2015 Ocak-2024 Mart dönemini kapsayan aylık verilerin kullanıldığı çalışmada yöntem olarak Kesirli-Frekanslı Fourier ADF birim kök testi, Kesirli-Frekanslı Fourier ADL eş bütünleşme testi ve Kesirli-Frekanslı Fourier TY nedensellik testi uygulanmaktadır.

Araştırma Bulguları: Analiz bulgularına göre Tarımsal Girdi Fiyat Endeksi değerinde yaşanan %1'lik yükseliş, tarımsal kredi kullanımını uzun ve kısa dönemde %0,95 ve %0,18 oranında yükseltmektedir. Nedensellik testinin sonuçları, eş bütünleşme testinin sonuçlarını desteklemektedir.

Sonuç: Bulgular, ülke genelinde tarımsal üretimin sürdürülebilmesi için, özellikle küçük ölçekli çiftçiler başta olmak üzere, tarımla uğraşan tüm üreticilere yönelik, kamu sermayeli ticari bankalar aracılığıyla düşük veya sıfır faizli kredi imkanları şeklinde hedeflenmiş finansal desteğin gerekli olduğunu göstermektedir. Bu tür bir destek, artan girdi fiyatlarının olumsuz etkilerini hafifletecek, temel girdilerin yetersiz kullanımını azaltacak ve verim kayıplarını önlemeye yardım edecektir.

INTRODUCTION

Agriculture—commonly recognized as the earliest productive activity in human history—remains vital both for domestic food security and for participation in international markets. Deemed indispensable given its role in producing basic foodstuffs, the sector has been reshaped by technological advances and now encompasses a range of production techniques (Topal, 2010). The sector's share of Gross Domestic Product (GDP) declined from 25.8% in the 1980s to 4.8% in 2022. Its growth rate stood at 0.6% in 2022, while data for the second quarter of 2023 indicate a 1.2% increase. In 2022, agriculture accounted for 15.8% of total employment. Despite its diminished weight in the economy—driven by industrial expansion, technological breakthroughs, and growth in services—agriculture retains its strategic importance, particularly through its contributions to employment and external trade (Ministry of Trade of the Republic of Türkiye, 2024). As a sector of central importance in both Türkiye and the global economy, agriculture shapes socio-ecological as well as economic systems. Although Türkiye benefits from fertile soils, established infrastructure, and ongoing technological progress, the sector also faces significant constraints. Chief among these, for agricultural enterprises, is access to finance, which constitutes a major obstacle to investment and sustained productivity (Taşkıran & Özüdoğru, 2010; Keskin, 2024).

Disruptions in supply and demand driven by global warming, climate change, pandemics, and armed conflicts have once again underscored the strategic significance of agriculture and livestock. The COVID-19 pandemic, in particular, revealed the central role these sectors play in national resilience. Ensuring the uninterrupted continuation of agricultural activities is therefore essential. Given its contributions to intergenerational continuity, the satisfaction of food demand, food security, and the provision of industrial raw materials, the sector also necessitates the establishment of a self-sufficient structure (Kutluay et al., 2021; Yaman et al., 2021). The adoption of technology in agriculture supports the development of an environmentally conscious, innovative, sustainable, and digitally enabled production paradigm. This transformation—captured by the term "Agriculture 4.0"—entails the integration of digital systems and smart farming applications, which are expected to enhance productivity and strengthen sustainability (Ertaş, 2020). Policy frameworks concerning food and sustainability will decisively shape the sector's trajectory. Indeed, food stands alongside energy and defense among the most critical and strategic domains (Sertyeşilışık, 2022).

Multiple determinants shape production costs in agriculture, including fluctuations in petroleum prices, climate change, price indices, the dollar exchange rate, fuel and electricity costs, and irrigation and drying expenses. Cost dynamics are further influenced by price movements in primary factors of production—labor, land, and capital (Köftecioğlu & Paksoy, 2024). Cost inflation transmits to output prices, constraining demand. In turn, cost-driven price increases compress production possibilities and contribute to a shrinking sectoral share within the broader economy. Accordingly, targeted support measures, coherent policy design, and sustainable initiatives are critical. Access to finance during the production phase is also widely recognized as a binding constraint on sectoral development. To mitigate this constraint, public and private actors deploy instruments such as subsidized credit, incentives, and exemptions. Sectoral credit utilization for June, July, and August 2024 is reported in Table 1.

A review of Table 1 indicates broad-based increases across all categories from June through August. Utilization of short- and medium-run credit, as well as cash and non-cash facilities, expanded; however, non-performing credits also rose. Credit uptake within agricultural enterprises is thus being leveraged as a primary instrument to alleviate financing constraints. Another key sectoral indicator capturing price dynamics is the Agricultural Input Price Index (AIPI). Table 2 reports the June 2024 changes in this index, as published by the Turkish Statistical Institute (TurkStat).

Table 1. Distribution of sectoral credit utilization (thousand TL)

Çizelge 1. *Sektörel kredi dağılımı (bin TL)*

Periods	Short-run cash credits	Medium- and long-run cash credits	Cash credits	Non-performing credits	Total cash credits	Non-cash credits
2024/06	246,274,871	442,873,767	689,148,638	2,540,078	691,688,716	33,244,458
2024/07	252,046,464	452,057,009	704,103,473	2,754,025	706,857,498	33,788,436
2024/08	258,801,886	476,372,993	735,174,879	2,868,391	738,043,270	35,206,510

Source: Banking Regulation and Supervision Agency (BRSA), 2024.

Table 2. Change in the agricultural input price index (June 2024)

Çizelge 2. *Tarımsal girdi fiyat endeksi değişimi (Haziran 2024)*

Variable	Index	Month-over-month change (%)	Year-over-year change (%)
AIPI	564.93	0.93	47.56

Source: Turkish Statistical Institute, 2024.

An examination of the index indicates a 0.93% increase in June 2024 relative to the previous month and a 47.56% increase relative to the same month of the previous year. These increases are assessed to have influenced price dynamics.

This study aims to identify the relationship between agricultural credit and AIPI. Following the introduction, the literature is reviewed, the methodology is detailed, and the findings are reported. The conclusion presents assessments and policy recommendations.

Agriculture is recognized as a strategic sector that enables countries to meet essential needs and contributes to the economy through foreign trade. Numerous academic studies have examined issues such as financing, credit utilization, and price dynamics in agricultural enterprises. This section reviews research specifically focused on the agricultural sector and directly related to the topic of this study. Studies on agricultural credit and indices are summarized in terms of their objectives, methods, and findings in Table 3.

A review of the literature shows that agricultural credit is frequently examined in relation to production, productivity, and performance. Although the methods employed vary across studies, they typically include sector-specific recommendations and assessments. A notable gap in the literature, however, is the identification of the relationship between agricultural credit and AIPI. This gap constitutes the key motivation for the present study. The study's originality and contribution to the literature lie in establishing this relationship using up-to-date data.

Numerous theories in the literature, such as agricultural finance theory, risk and uncertainty theory, and contract farming theory, have discussed the relationship between agricultural production and financing. The model developed in this study adopts the Theory of Change, which posits that increased access to finance, technical knowledge transfer, and agricultural product markets will enhance productivity levels in the agricultural sector. The Theory of Change was introduced in 2014 by the Council on Smallholder Agricultural Finance. Its practical application is being implemented through case studies in various countries, and the results of these studies are regularly and transparently reported and shared with the public (Council on Smallholder Agricultural Finance, 2022).

Table 3. Summary of prior literature

Çizelge 3. *Literatür özeti*

Author(s)	Objectives	Methodology	Results
Çevik and Zeren (2014)	Determination of the relationship between agricultural credits and financial development for the period from December 2005 to October 2013 in Türkiye	Hatemi-J Asymmetric Causality Test	No significant relationship was found for negative shocks. Positive shocks in agricultural credit were found to Granger-cause financial development, leading to the conclusion that the agricultural sector holds a significant position within the financial system.
Ekwere & Edem (2014)	To examine the impact of agricultural credit on agricultural production among a sample of 136 small-scale farmers	Regression Analysis and Cobb–Douglas Production Function Analysis (CDPFA)	Access to agricultural credit positively affects agricultural production. The study recommended that the government and private-sector institutions provide farmers with regular credit.
Ogbuabor & Nwosu (2017)	To determine the effect of deposit money banks' agricultural credit on agricultural productivity in Nigeria over the period 1981-2014	Johansen Cointegration and Granger Causality Tests	It is stated that the availability of bank credit with favorable interest rates in the agricultural sector would positively affect agricultural production, and corresponding policy recommendations are provided.
Adanacıoğlu et al. (2017)	Identifying similarities and differences among Türkiye's 81 provinces by examining various agricultural indicators	Multidimensional Scaling (MDS) Method	The results indicate that provinces differ in their performance regarding agricultural credit. Credit should be utilized more efficiently; provinces with relatively weaker performance require further assessment. Moreover, the efficiency of functions such as production and marketing needs to be improved.
Yalçınkaya (2018)	Determining the impact of agricultural loans and non-performing agricultural loans on GDP	Granger Causality Analysis	The results show that agricultural credit Granger-causes GDP; there is bidirectional causality between agricultural GDP and total GDP; and no significant relationship is found with non-performing agricultural loans.
Amanullah et al. (2020)	Identifying the impact of credit constraints on the welfare of wheat-producing farmers operating in Pakistan	Ordinary Least Squares (OLS) and Logistic Regression	The result indicates that constraints on access to commercial bank credit adversely affect farmers' welfare and income.
Aytekin & Hatırlı (2021)	Identifying the determinants of unprocessed food inflation in Türkiye using data from 2016 to 2020	Vector Autoregressive Model (VAR) and Autoregressive Distributed Lag Model (ARDL)	Findings demonstrate that the variables have an inflationary effect on unprocessed food inflation, with the effect driven primarily by the import unit variable of food products manufacturing, followed by the agricultural input price index and the agricultural products producer price variable.
Semerci (2021)	Identifying the agricultural credit status of various farming enterprises operating in Türkiye using firm-level data	Neyman's Method and Various Statistical Analyses	The findings indicate that Ziraat Bank is the primary choice for agricultural credit; as farm size increases, credit demand also rises; and maintaining zero- or low-interest credit schemes is necessary for a sustainable structure.
Akçaöz et al. (2022)	Using an Antalya province sample to identify producers' socio-economic characteristics, credit usage, credit sources and terms, and their main problems	A Survey Study Conducted with 80 Producers	Ziraat Bank is preferred for credit use due to subsidized loans and favorable interest rates offered to enterprises, and that producers primarily borrow to finance agricultural inputs and to address working capital shortages.
Oğul (2022)	Testing the relationship between agricultural credit and agricultural production using data for the 1990-2020 period	Johansen Cointegration Test, FMOLS, DOLS and CCR Methods	The analysis confirms the presence of cointegration and indicates that increases in agricultural credit lead to higher agricultural production.

Table 3. Continued

Çizelge 3. *Devamı*

Author(s)	Objectives	Methodology	Results
Uygur & Öner Kaya (2022)	Exploring the relationship between agricultural credit and agricultural growth for the period 2005:Q1-2021:Q4	ARDL	The results indicate the presence of cointegration between the series and show that increases in agricultural credit have a positive effect on agricultural GDP.
Özyücel et al. (2022)	Discovering the causality relationships among food inflation, the agricultural producer price index, and agricultural input price indices in Türkiye for the period 2016M01-2022M08	The Hacker and Hatemi-J Bootstrap-Enhanced Toda-Yamamoto Causality Test, Based on Efron's Bootstrap Method	In conclusion, causality relationships are identified, and price dynamics are found to operate bidirectionally, suggesting the potential emergence of structural problems due to mutual feedback between prices. As a policy recommendation, the study proposes developing and implementing productivity-oriented policies in agriculture.
Manoharan & Varkey (2022)	Testing selected agricultural credit and productivity variables in India using data from fiscal years 1990-1991 to 2017-2018	Panel Data Analysis	The findings show that both direct agricultural credit and doubling the agricultural credit policy have positive effects on productivity, whereas indirect credits exert a negative effect. Accordingly, the study recommends implementing large-scale, productivity-oriented policies through direct credit channels to enhance agricultural productivity.
Önder (2023)	Testing agricultural and economic variables for Türkiye's seven geographical regions over 2004-2021	Dynamic Panel Data Analysis	The study finds a long-run relationship between agricultural credit and economic growth; however, agricultural credit is not a Granger cause of growth. Regional assessments further indicate that credits should be utilized efficiently and in a targeted manner to enhance outcomes.
Özden (2023)	Identifying the best model for forecasting the changes in the agricultural input price index	ARIMA, SARIMA, CNN and LSTM	It was concluded that ARIMA and CNN models performed the best prediction, and the two models were followed by the LSTM model.
Keskin & Çalışır (2024)	Testing the relationship between economic and agricultural variables in Türkiye using data from 1976 to 2021	ARDL, VAR and Granger Tests	In terms of cointegration, a negative effect between the two variables was identified both in the short- and long-run. Additionally, it was found that there is a unidirectional causality running from the interest rate to crop production.

MATERIALS and METHODS

In line with the objective of the study, monthly data on agricultural credits (AGCR) and AIPI were collected. The data on AGCR were obtained from the monthly bulletins published by the Banking Regulation and Supervision Agency (2024), while AIPI data were sourced from the relevant statistical tables of the Turkish Statistical Institute (2024). The dataset covers the period from January 2015 to March 2024, consisting of 111 observations for each variable. The starting point of January 2015 was chosen because the publication of AIPI commenced at that time. Considering the purpose of the study and the characteristics of the data, the analyses were carried out using EViews 13 and Gauss 24 programs.

The study employs contemporary time-series methods. Specifically, it applies, in order, the Fractionally-Frequency Fourier Augmented Dickey-Fuller (FFFADF) unit root test developed by Bozoklu et al. (2020), the Fractionally-Frequency Fourier Autoregressive Distributive Lag (FFFADL) cointegration test proposed by İlkay et al. (2021), and the Fractionally-Frequency Fourier Toda-Yamamoto (FFFTY) causality test introduced by Pata & Yılancı (2020). As all three tests are augmented with Fourier functions, they account for all structural changes present in the series.

$$\Delta AGCR_t = \alpha_0 + \alpha_1 \, sin(\frac{2\pi kt}{T}) + \alpha_1 \, cos(\frac{2\pi kt}{T}) + \alpha_2 AGCR_{t-1} + \sum_{i=1}^{P} \varphi_i \, \Delta AGCR_{t-1} + \varepsilon_t \quad (1)$$

$$\Delta AIPI_t = \beta_0 + \beta_1 \, sin(\frac{2\pi kt}{T}) + \beta_1 \, cos(\frac{2\pi kt}{T}) + \beta_2 AIPI_{t-1} + \sum_{i=1}^{P} \phi_i \, \Delta AIPI_{t-1} + \mu_t \quad (2)$$

In the FFFADF test, the models specified in Equations (1) and (2) are estimated. In these specifications, *AGCR* denotes agricultural credits, *AIPI* denotes the Agricultural Input Price Index, *Δ* is the first-difference operator, *π* is the constant 3.1416, *k* is the frequency parameter, *t* represents the time trend, *T* is the sample size, ε_t and μ_t are the error terms (Bozoklu et al., 2020).

$$\Delta AGCR_t = \alpha_0 + \beta_1 \, sin(\frac{2\pi kt}{T}) + \beta_1 \, cos(\frac{2\pi kt}{T}) + \delta_1 AGCR_{t-1} + \delta_2 AIPI_{t-1} + \delta_3 \Delta AGCR_{t-1} + \delta_4 \Delta AIPI_{t-1} + \nu_t \quad (3)$$

In the FFFADL test, the model specified in Equation (3) is estimated. In this specification, *AGCR* denotes the dependent variable, agricultural credits, while *AIPI* represents the independent variable, the Agricultural Input Price Index. Implementation of the test requires both variables to be integrated of order one, I(1) (İlkay et al., 2021).

$$AGCR_t = \alpha_0 + \alpha_1 \, sin\left(\frac{2\pi kt}{T}\right) + \alpha_1 \, cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{l+dmax} \gamma_i AGCR_{t-i} + \sum_{i=1}^{l+dmax} \lambda_i AIPI_{t-i} + \xi_t \quad (4)$$

$$AIPI_t = \beta_0 + \beta_1 \, sin\left(\frac{2\pi kt}{T}\right) + \beta_1 \, cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{l+dmax} \phi_i AGCR_{t-i} + \sum_{i=1}^{l+dmax} \delta_i AIPI_{t-i} + \zeta_t \quad (5)$$

In the FFFTY test, the models specified in Equations (4) and (5) are estimated. Within these models, *l* is the optimal lag length and *d max* represents the maximum order of integration among the variables (Pata & Yılancı, 2020). In this study, agricultural credits and the Agricultural Input Price Index are alternately assigned as the dependent variable to determine whether the causality between them is bidirectional or unidirectional.

The hypotheses of this study are as follows:

H_1: There is a statistically significant cointegration relationship between the Agricultural Input Price Index and agricultural credits.

H_2: There is unidirectional causality running from the Agricultural Input Price Index to agricultural credits.

RESEARCH FINDINGS

As depicted in Figure 1, the variables appear to follow a similar trajectory over time. However, this visual correspondence does not serve as conclusive evidence of a comovement. A definitive determination requires a more detailed and formal empirical analysis.

The course of the variables over time is as follows:

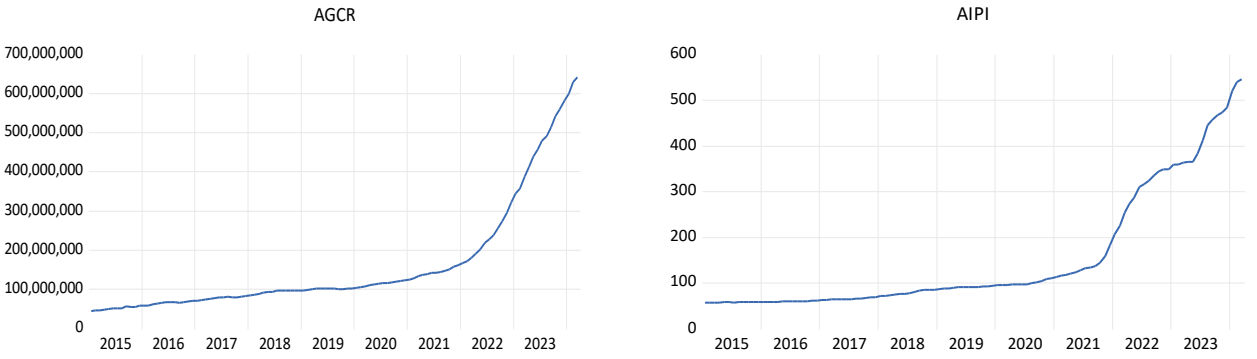

Figure 1. Course of series.

Şekil 1. *Değişkenlerin seyri.*

To mitigate potential issues related to scale and to stabilize variance, a natural logarithmic transformation was applied to both variables. Consequently, all subsequent analyses were conducted using these transformed series.

The analytical procedure began with unit root tests to assess the stationarity properties of each variable. Following this, the long-run relationship and causal linkages between the variables were investigated using cointegration and causality tests, respectively. The results of these empirical tests are presented sequentially below.

As shown in Table 4, the Fourier functions were found to be statistically insignificant for both variables. In such cases, the appropriate methodology, as outlined by Bozoklu et al. (2020), requires deferring to the results of the conventional Augmented Dickey-Fuller (ADF) test rather than the FFFADF test.

Table 4. Unit root test results

Çizelge 4. *Birim kök test sonuçları*

Variable	FFFADF unit root test		ADF unit root test	
	F test statistic	FADF test statistic	Test statistic	p-value
logAGCR	6.122[#]	-3.813	-1.024	0.935
logAIPI	1.532[#]	-0.650	-1.469	0.834
logAGCR(1)	-	-	-4.799	0.000[*]
logAIPI(1)	-	-	-4.012	0.011[**]

[#] This indicates that the Fourier terms are insignificant at the 10% significance level; the critical value used for comparison is 7.78.

[*] and [**] indicate that the corresponding variable is stationary at the 1% and 5% significance levels, respectively.

The conventional ADF test results indicate that both variables become stationary after taking their first differences, meaning they are integrated of order one, I (1). This finding satisfies the necessary precondition for applying the FFFADL cointegration test.

As shown in Table 5, the absolute value of the test statistic, |-6.217|, is greater than the absolute value of the critical value at the 1% significance level, |-4.859|. This result leads to the rejection of the null hypothesis of "no cointegration between the variables" confirming that a long-run cointegrating relationship exists.

Table 5. Cointegration test result

Çizelge 5. *Eşbütünleşme test sonucu*

Estimated model	Lag length	Frequency value (k)	Test statistic	Critical value	Cointegration relationship
logAGCR = *f* (logAIPI)	10	2.7	-6.217*	-4.859	There exists a cointegration relationship.

* Indicates significance at the 1% level. Note: In accordance with the applied methodology, the absolute values of the test statistic and the critical value are used for comparison.

Furthermore, the fractional value of the frequency parameter (k) indicates that the structural breaks affecting this cointegrating relationship are gradual and smooth, rather than abrupt.

As seen in Table 6, the long-run coefficient for the logAIPI variable is positive and significant at the 1% level. This indicates that the Agricultural Input Price Index has a statistically significant positive effect on agricultural credits. A 1% increase in the index is associated with a 0.95% increase in the use of credit in the long-run.

Table 6. Long-run coefficient result

Çizelge 6. *Uzun dönem katsayı sonucu*

Dependent variable: logAGCR				
Independent variable	Coefficient	Standard error	T-statistic	p-value
logAIPI	0.948	0.031	30.460	0.000*
c	14.129	0.149	94.590	0.000*
sin	-0.123	0.031	-3.952	0.000*
cos	-0.073	0.030	-2.386	0.018**

* and ** indicate that the corresponding variable is stationary at the 1% and 5% significance levels, respectively.

As shown in Table 7, the short-run coefficient for the logAIPI variable is positive and statistically significant at the 5% level. This finding suggests that the Agricultural Input Price Index also has a positive effect on agricultural credits in the short-run. A 1% increase in the index value leads to a 0.18% increase in credit usage.

Table 7. Short-run coefficient result

Çizelge 7. *Kısa dönem katsayı sonucu*

Dependent variable: logAGCR				
Independent variable	Coefficient	Standard error	T-statistic	p-value
d(logAIPI)	0.185	0.077	2.395	0.018**
Error Correction Coefficient	-0.072	0.025	-2.885	0.004*
c	0.019	0.004	4.843	0.000*

* and ** indicate that the corresponding variable is stationary at the 1% and 5% significance levels, respectively.

As seen in Table 8, there is a unidirectional causal relationship running from the logAIPI variable to the logAGCR variable (p<0.01). This result supports the findings of the FFFADL cointegration test applied earlier. Furthermore, since the frequency value (k) is fractional, it implies that the structural changes affecting causality are permanent. Finally, the analysis confirms both of the study's hypotheses.

Table 8. FFFTY test result

Çizelge 8. *FFFTY test sonucu*

Dependent variable	Independent variable	Test statistic	Bootstrap p-value	Frequency value (k)	Result
logAGCR	logAIPI	25.581	0.005*	1.9	logAIPI → logAGCR
logAIPI	logAGCR	7.687	0.566	1.9	logAGCR ↛ logAIPI

* Indicates significance at the 1% level. The number of simulations used is 10,000.

The findings of this study are consistent with those reported by Oluwasola & Alimi (2008), Chandio et al. (2021), and Rizwan et al. (2019). No studies were found that reported contradictory findings.

CONCLUSION and DISCUSSION

Agriculture is an activity that is carried out to meet the fundamental needs of nutrition and food demand, maintaining its importance for countries through export opportunities as well. Although its share has been partially overtaken by industrial activities compared to past years, the sector continues to preserve its strategic significance today. Establishing a self-sufficient structure is particularly crucial during periods like pandemics, crises, and wars. The sector, which reduces foreign dependency and adds value through the impact of new technologies, holds an indispensable position for nations due to both domestic and international activities. Various resources are utilized for financing, which is one of the most critical needs for businesses operating in the agricultural sector. In this context, agricultural loans are used by farmers to carry out production activities. Many studies have expressed the necessity of creating policies for loans with favorable interest rates and terms. In addition, input prices are another crucial point for farmers. Rising costs also increase prices, leading to difficulties in terms of demand. In this study, a quantitative analysis was conducted on the agricultural sector with a focus on finance and costs using available data. Within this scope, the relationships were identified, and policies for the sector were proposed. For financing, data on agricultural loans were obtained, and for costs, the Agricultural Input Price Index was used. Thus, by determining the relationship between these two variables, commentary on the sector's operations was provided. The fact that limited research has previously been conducted on the Agricultural Input Price Index is one of the original aspects of this study. The aim of the study is to identify the relationship between the two variables and to make financial inferences to promote sectoral development.

This study analyzes the relationship between changes in the value of the Agricultural Input Price Index and the amount of agricultural loans used, from the perspectives of cointegration and causality. The analysis employs fractional-frequency Fourier methods, specifically the Fourier ADL and TY tests, which account for both permanent and temporary structural changes. The findings from the analysis reveal that a 1% increase in the Agricultural Input Price Index leads to a 0.95% and 0.18% rise in the amount of agricultural loans used in the long- and short-run, respectively. This result is supported by the findings from the causality test. In line with these findings, it is clear that both long-run and short-run changes in the prices of inputs used in agricultural production shape the need for agricultural financing from commercial banks. At this juncture, Agricultural Credit Cooperatives, which possess a large organizational network throughout Türkiye and a wealth of experience, should continue to play an active role. They must intervene through their subsidiary companies like Gübretaş, Tareks, and Tarkim to focus on input production and thereby help lower prices. Furthermore, to reduce external dependency on inputs, other private sector organizations that produce inputs should also be encouraged to take an active role in production. It can be argued that supportive and incentive-based government policies (such as support/incentives for energy, investment location, and tax exemptions) would be effective in this regard. This approach would not only provide farmers with access to inputs at lower prices but also minimize the credit risk arising from the continuous use of agricultural loans.

Considering the volatility in agricultural input prices, flexible credit limits indexed to input prices should be established. This will protect farmers from cost shocks. Regional cooperative support funds should be created in different agricultural zones to enable cooperatives to accumulate equity and purchase inputs collectively. To counteract the anticipated annual increases in input costs, predefined fixed-rate subsidies should be introduced to reduce dependency on credit. Another way to lower input costs is to increase efficiency. In this context, government-supported 'smart farming practices' should be promoted. An insurance-based risk-sharing model, integrated into the agricultural credit system, should be developed to protect both farmers and banks against default risks. To increase capacity in input production, investments based on public-private partnerships should be encouraged, such as the state allocating land for the establishment of fertilizer plants in the private sector.

Building on this study, it is recommended to valuable researchers for future work that they investigate the impact of changes in the Agricultural Input Price Index on variables such as the total input consumption in Türkiye.

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: BM; sample collection: ÖK; analysis and interpretation of data: ÖK; statistical analysis: ÖK; visualization: BM; writing manuscript: BM.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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Research Article
(Araştırma Makalesi)

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Determination of the effect of plant growth regulators on agronomic characteristics of sweet corn by multivariate analysis

Tatlı mısırda bitki büyüme düzenleyicilerin agronomik özelliklere etkisinin çok değişkenli analizler ile belirlenmesi

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ABSTRACT

Objective: This study was conducted to determine the effects of gibberellic acid (GA_3) and sodium nitrophenol applications on agronomic traits in sweet corn.

Material and Methods: In the study designed as a factorial arrangement in a randomized block design, foliar applications of GA_3 (T1), sodium nitrophenol (T2), and GA_3 + sodium nitrophenol (T3) were applied to the plants.

Results: Plant growth regulators significantly improved the overall performance of sweet corn compared to the control. T3 treatment provided the highest values by increasing plant height by 30%, leaf area by 17%, cob diameter by 27%, cob yield by 12% and fresh cob yield by 22%. However, the effects of the treatments on cob length and seed number were limited. PCA revealed the significant effect of T3 treatment on vegetative traits such as plant height and leaf area, while correlation analysis showed that these traits had a strong positive relationship with fresh cob yield.

Conclusion: In sweet corn, these findings confirm the main contribution of vegetative development in yield increase and the high performance potential of the combined treatment. In conclusion, the combined application of GA_3 and sodium nitrophenol offers a promising approach for sustainable yield increase in sweet corn.

ÖZ

Amaç: Bu çalışma, şeker mısırda gibberellik asit (GA_3) ve sodyum nitrofenol uygulamalarının agronomik özellikler üzerindeki etkilerini belirlemek amacıyla yürütülmüştür.

Materyal ve Yöntem: Tesadüf blokları deneme deseninde faktöriyel düzenlemeye göre tasarlanan çalışmada, bitkilere yapraktan GA_3 (T1), sodyum nitrofenol (T2) ve GA_3 + sodyum nitrofenol (T3) uygulamaları yapılmıştır.

Araştırma Bulguları: Bitki büyüme düzenleyicileri, kontrole kıyasla şeker mısırın genel performansını önemli ölçüde iyileştirmiştir. T3 uygulaması, bitki boyunu %30, yaprak alanını %17, koçan çapını %27, koçan randımanını %12 ve taze koçan verimini %22 oranında artırarak en yüksek değerleri sağlamıştır. Ancak koçan uzunluğu ve tane sayısı üzerinde uygulamaların etkisi sınırlı kalmıştır. PCA analizi, T3 uygulamasının bitki boyu ve yaprak alanı gibi vejetatif özellikler üzerindeki belirgin etkisini ortaya koyarken, korelasyon analizi bu özelliklerin taze koçan verimiyle güçlü bir pozitif ilişki içinde olduğunu göstermiştir.

Sonuç: Şeker mısırda, bu bulgular vejetatif gelişimin verim artışındaki temel katkısını ve kombine uygulamanın yüksek performans potansiyelini doğrulamaktadır. Sonuç olarak, GA_3 ve sodyum nitrofenolün kombine uygulaması şeker mısırda sürdürülebilir verim artışı için umut verici bir yaklaşım sunduğunu göstermektedir.

INTRODUCTION

Sweet corn (*Zea mays* var. *saccharata*) is an agricultural crop distinguished by its high sugar content among corn species and holds substantial economic value worldwide. It serves as an important raw material for fresh consumption, the canning industry, and the broader food sector (Revilla et al., 2021). The genetic makeup of sweet corn is characterized by elevated sugar accumulation and reduced starch content compared to other corn varieties (Okumura et al., 2013). These attributes make sweet corn a popular choice in terms of both nutritional quality and flavour.

Sweet corn production in the world is approximately 1 million ha, production is approximately 9.7 million tons and yield is 9 tons ha^{-1}. Sugar corn production is highest in the USA (2.8 million tons), Mexico (1.1 million tons), Nigeria (793 thousand tons) and Indonesia (558 thousand tons) (FAO, 2023). The highest production is observed in the USA (2.6 million tons), followed by Mexico (1.1 million tons), Nigeria (776 thousand tons), and Indonesia (654 thousand tons) (FAO, 2021). In Türkiye, sweet corn is gaining significance both in agricultural production and the food industry. The country's climate and soil conditions provide favorable regions for sweet corn cultivation, particularly in the Mediterranean, Aegean, and Marmara regions (Eşiyok et al., 2004; Öktem & Öktem, 2006). Despite global production efforts, the supply of sweet corn does not fully meet market demand, one of the main major reasons being fort his is its relatively low yield potential (Laksono et al., 2018). In Türkiye, sweet corn production is subject to abiotic and biotic stress factors, including drought, high temperatures, and pest infestations (Öktem & Öktem, 2018). Particularly, irregular rainfall patterns and temperature fluctuations, which are intensifying due to climate change, can cause yield losses during critical developmental stages (IPCC, 2021). Therefore, implementing strategies that enhance yield and improve quality are critical to boosting farmers' income and supporting food security.

Plant growth regulators (PGRs) are chemical or biological substances used in agriculture to promote plant growth and regulate various physiological processes (Kumlay & Eryiğit, 2011). They are widely recognised as effective tools for increasing yield by influencing growth rate, flowering, fruit development, and stress tolerance (Taiz & Zeiger, 2010). A wide range of PGRs, including natural hormones and synthetic chemicals, can produce diverse outcomes depending on the plant species and application methods (Shahniza et al., 2020; Çakır et al., 2021; Mubarok et al., 2022). In sweet corn, the appropriate timing and dosage of PGR applications are critical for ensuring both plant health and economic profitability (Rademacher, 2015).

Gibberellic acid (GA_3) is one of the most well-known and extensively studied natural plant hormones. Gibberellins promote cell division and elongation, supporting physiological processes such as stem elongation, seed germination, and fruit development (Gupta & Chakrabarty, 2013; Algül et al., 2016). The use of GA_3 in agricultural practices has been investigated extensively, particularly for its potential to enhance yield and improve stress resistance. Its positive effects on cob size and seed development in sweet corn are among the key findings supporting its practical application (Al-Shaheen & Soh, 2018; Shahniza et al., 2020; Sopacua et al., 2022). However, the effects of GA_3 can vary depending on the species of plant, the environmental conditions, and the concentrations at which it is applied (Hedden & Thomas, 2016). Nitrophenols constitute a group of synthetic plant growth regulators, with derivatives such as 4-nitrophenol reported to enhance photosynthetic rates by modulating plant metabolism (Batool et al., 2023). These compounds can support root and stem development and improve nutrient uptake through auxin-like effects (Amin, 2007; Fang et al., 2023). Although the precise mechanism of action of nitrophenol compounds has not been fully elucidated, there is growing evidence suggesting that they activate antioxidant defense systems, thereby increasing plant resilience to abiotic stress (Djanaguiraman et al., 2004; Iwaniuk et al., 2023). While the agricultural use of nitrophenols is not yet as widespread as that of GA_3, they show potential as alternative growth regulators. However, research into the effects of nitrophenols on sweet corn is limited (Chen et al., 2019).Research exploring

the combined effects of growth regulators such as GA_3 and nitrophenols, on sweet corn is still scarce. Although GA_3 has been shown to enhance growth and yield parameters in sweet corn, the impact of nitrophenols remains largely unexplored.. This study therefore aimed to determine the effects of foliar application GA_3 and nitrophenol on the yield and yield components of sweet corn.

MATERIALS and METHODS

Materials

The research was conducted on Isparta University of Applied Sciences land over two consecutive growing seasons, in 2020 and 2021. A Kompozit sweet corn cultivar obtained from a private company was used as the experimental material. In addition, GA_3 ($C_{22}H_{26}O_8$; CAS No: 1373154-68-7) and sodium nitrophenol (a mixture of 9 g/L sodium p-nitrophenolate, 6 g/L sodium o-nitrophenolates, and 3 g/L sodium 5-nitroguaiacolate) were used as synthetic plant growth regulators. Gibberellic acid and sodium nitrophenol chemicals were supplied by Doğal Kimyevi Maddeler ve Zirai İlaçlar San. ve Tic. AŞ.

Climate and soil characteristics of the research site

Significant differences were observed in climatic variables (precipitation, humidity, and temperature) during the sweet corn growing periods of 2020 and 2021. In 2020, total precipitation was high in May but decreased considerably from June to September, humidity levels declined from May to July, while temperature increased until June and remained stable in July-August. In 2021, total precipitation peaked in May but dropped significantly in June-July; humidity also decreased from May to July, whereas temperature reached its highest value in June and fluctuated during the subsequent months. Overall, more stable temperature and humidity conditions were recorded in 2020, while 2021 experienced intense rainfall events and greater temperature fluctuations (Figure 1).

The experiment was conducted on soils with similar characteristics in both years. Soil sampling was done at a depth of 0-30 cm and before planting. Soil samples, collected from the experimental area exhibited a clay-loam texture, low organic matter content (1.5%), high lime content (28.7%), a pH of 7.66, low phosphorus content (23.5 mg kg^{-1}), and high potassium content (176.2 mg kg^{-1}).

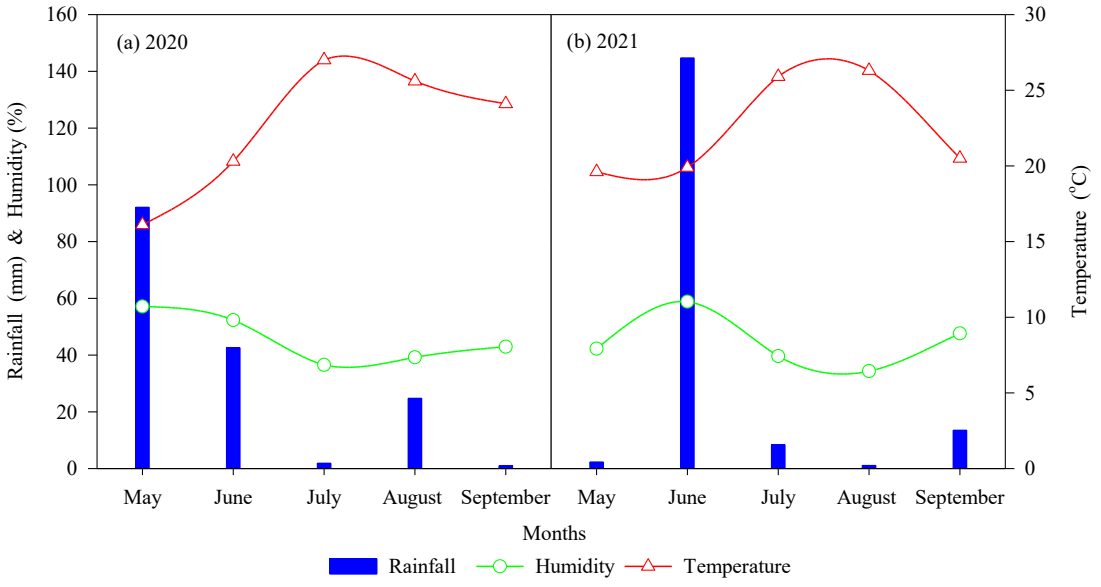


Figure 1. Climate data for the years in which the trial was conducted (2020-2021).

Şekil 1. Denemenin yürütüldüğü yıllara (2020-2021) ait iklim verileri.

Methods

The experiment was conducted in a randomized complete block design with a factorial arrangement and three replications. Foliar applications included control (pure water), GA_3 application, (100 mg L^{-1} ,T_1), sodium nitrophenolate application, (20 mg L^{-1}, T_2), and their combination (GA_3 + sodium nitrophenolate) (T_3). Each block contained four plots, totaling 12 plots overall. Sweet corn seeds were manually sown during the first week of May (3 May and 7 May, respectively) in both years, at a planting density of 70 × 20 cm, with four rows per plot (plot area: 14 m², 2.8 m × 5 m). Two seeds were sown per hill to optimize plant density, and following emergence, plants were thinned to one per hill at the 1-2 leaf stage (V1-V2). At sowing, 8 kg $da^{-1}$of P_2O_5 and 10 kg da^{-1} N were applied; an additional 10 kg da^{-1} of nitrogen was top-dressed when plants reached a height of 30-40 cm (Akgün et al., 2021). GA_3 (T1), sodium nitrophenol (T2), GA_3 + sodium nitrophenol (T3), and control (pure water) treatments were applied by spraying the aerial parts of the plants with a knapsack sprayer at a volume of 40 L ha^{-1} at the 6-leaf stage (BBCH 16). Drip irrigation was applied based on soil moisture status following planting, depending on climatic conditions. Weed control was performed manually when necessary.

At the end of the study, each plot was harvested separately during the milk maturity stage (BBCH 73-75), taking into account the physiological maturity of the plants. The effective harvest area was defined by excluding border rows and a 50 cm margin at the plot ends. From each harvest area, 10 plants were randomly selected for measurements. Plant height (cm), leaf area (cm²), cob length (cm), cob diameter (mm), seed number in cob, fresh cob yield (kg da^{-1}), and cob filling ratio (%) were determined.

Data analysis

The data obtained from the experiments were analysed usinganalysis of variance (ANOVA) based on a factorial arrangement within a randomized complete block design, withStatistix software package (version 8.1) being used for this analysis . Differences in means were determined using the least significant difference (LSD) test. To assess the relationships among the studied traits and the interactions between treatments and years, correlation matrices and principal component analysis (PCA) biplot graphs were generated using R software (version 4.3.2) andthe "PerformanceAnalytics", "psych", "ggplot2", "gridExtra", "ggbiplot", and "corrplot" packages.

RESEARCH RESULTS

In this study, the effects of gibberellic acid (GA_3) and sodium nitrophenolate applications on the yield and yield components of sweet corn were evaluated during the 2020 and 2021 growing seasons. The results revealed significant differences in plant height, leaf area, cob diameter, cob length, cob filling ratio, seed number in cob, and fresh cob yield depending on both the year and the applied treatments (Table 1;2). These findings indicate that plant growth regulators can play an effective role in the developmental processes of sweet corn, particularly in yield enhancement.

Plant height exhibited significant variation (p<0.01) between the years. The mean plant height was 213 cm in 2020, whereas it decreased to 159.43 cm in 2021. This reduction suggests that temperature fluctuations and irregular rainfall patterns observed in 2021 negatively affected plant development. In contrast, the more favorable climatic conditions in 2020 provided better support for sweet corn growth. Among the applications made in the study, it was found that the T3 group (GA_3 + sodium nitrophenolate) increased plant height by 30.6% compared to the control (Tables 1 & 2). A significant year × treatment interaction was detected for plant height (p<0.01) (Table 1).

In 2020, the highest plant height was achieved with T3 (237.87 cm), followed by T2 (213.87 cm) and T1 (201.87 cm), while the control group showed the lowest value (177.47 cm). In 2021, plant height

declined across all treatments. However, T3 again recorded the highest value (175.91 cm), followed by T2 (167.20 cm), T1 (162.70 cm), and the control (130.47 cm). In 2020, the differences between treatments were more pronounced, with T3 maintaining a clear superiority over the others (Figure 2). In 2021, plant height decreased, and the differences between treatments became narrower due to adverse environmental conditions. These results suggest that the effectiveness of plant growth regulators can vary according to environmental factors and they tend to be more pronounced under favorable climatic conditions, as observed in 2020. Similarly, leaf area was significantly affected by the year. While the mean leaf area was 563.75 cm² in 2020, it decreased to 457.67 cm² in 2021 (p<0.01). The lower leaf area in 2021 indicates that environmental stresses suppressed leaf development. Among the applications used in the study, the T3 group (GA_3 + sodium nitrophenolate) and the T2 group (sodium nitrophenol) increased the leaf area by 17.3% and 13.1%, respectively, compared to the control (Table 2). A significant year × treatment interaction was also observed for leaf area (Table 1). The interaction effect on leaf area is clearly illustrated in Figure 2. In 2020, T3 achieved the highest leaf area (600.13 cm²), followed closely by T2 (596.67 cm²). T1 exhibited an intermediate value (541.00 cm²), whereas the control group had the lowest leaf area (517.50 cm²). In 2021, leaf area decreased across all treatments. T3 recorded the highest value (466.33 cm²), followed by T2 (419.67 cm²), T1 (414.67 cm²), and the control (410.00 cm²). These findings suggest that in 2020, T3 and T2 treatments substantially promoted leaf development, leading to greater differences compared to the control. However, environmental stress factors in 2021 caused a general reduction in leaf area, minimisingthe differences between treatments (Figure 2).

When cob diameter was analyzed across years, it was found to be 5.04 cm in 2020 and 4.89 cm in 2021 (p<0.05). This slight decrease indicates that climatic conditions influenced cob development. Among the applications made in the study, the T3 group (GA_3 + sodium nitrophenolate) increased the cob diameter by 27% compared to the control. The T1 (4.72 cm) and T2 (4.88 cm) treatments produced better results than those of the control (p<0.01) (Table 1;2). The contribution of the combined treatment (T3) to cob development was notable. A significant year × treatment interaction was observed for cob diameter (Figure 2). In 2020, the highest cob diameter was obtained from the T3 treatment (6.07 cm), followed by T2 (4.73 cm) and T1 (4.53 cm), while the control group recorded the lowest diameter (4.32 cm). In 2021, cob diameters generally declined; however, the T3 treatment maintained the highest value (5.45 cm), followed by the T2 treatment (4.90 cm). The T1 treatment and the control group both had the same value (4.37 cm). These results suggest that the combined application was particularly effective in enhancing cob diameter under favourable environmental conditions in 2020. However, in 2021, cob diameter values decreased across all treatments, and the differences between them became less pronounced due to environmental stress factors.

Table 1.Analysis of variance table for agronomic traits of sweet corn according to year and treatments

Çizelge 1. *Tatlı mısırın agronomik özellikleri için yıllara ve uygulamalara göre varyans analizi tablosu*

Source	DF	Plant height [1]	Leaf area	Cob diameter	Cob length	Cob yield	Seed number in cob	Fresh cob yield
Block	2	15.6	966.3	0.01	1.28	17.04	3352	17940
Year (Y)	1	17216.3	67522.0	0.13	13.55	42.67	179363	137751
App. (A)	3	2477.8	8310.2	1.72	1.52	55.61	19228	99834
Y x A	3	178.6	224.4	0.12	1.54	1.44	3833	8937
Error	14	12.6	736.8	0.02	0.65	12.14	6172	19723
CV		1.91	5.31	2.76	4.10	5.45	13.06	7.89

1: Mean squared values of traits; DF: Degrees of freedom

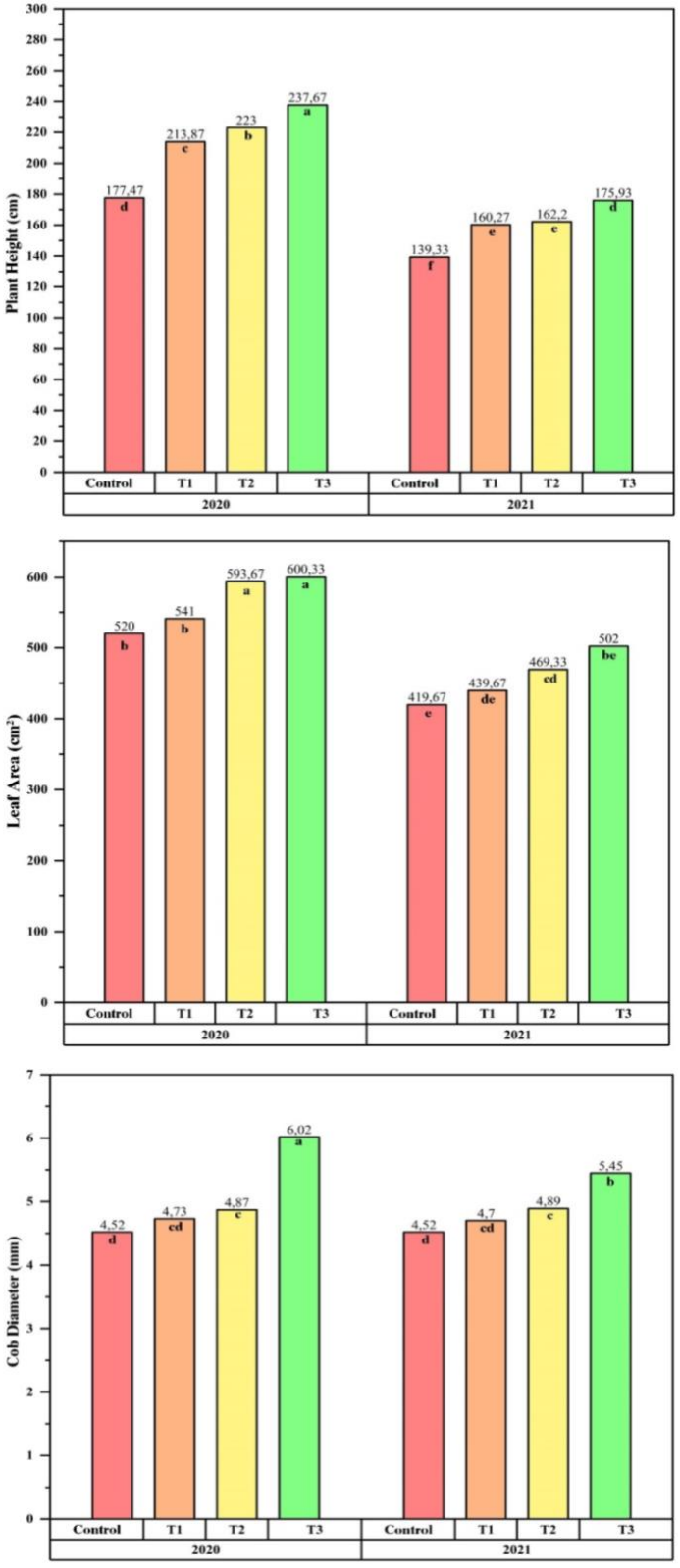


Figure 2. Year and treatment interaction for plant height, leaf area and cob diameter traits in sweet corn.

Şekil 2. *Tatlı mısırda bitki boyu, yaprak alanı ve koçan çapı özellikleri için yıl ve uygulama interaksiyonu.*

Table 2. Averages of agronomic traits of sweet corn according to year and treatments

Çizelge 2. *Tatlı mısırın yıllara ve uygulamalara göre agronomik özelliklerinin ortalamaları*

Source	Plant Height (cm)	Leaf Area (cm²)	Cob Diameter (cm)	Cob Length (cm)	Cob Performance (%)	Seed Number in Cob	Fresh Cob Yield (kg da⁻¹)
Years							
2020	213.00 a[1]	563.75 a	5.04 a	20.43 a	65.25	687.87 a	1845.2 a
2021	159.43 b	457.67 b	4.89 b	18.93 b	62.58	514.97 b	1716.2 b
LSD	3.11	23.76	0.12	0.7	3.05	68.78	122.97
F-value	1363.62**	91.65**	6.77*	20.75**	3.52 ns	29.06**	5.06*
Treatments							
Control	158.40 d	469.83 b	4.52 c	18.93	59.83 b	535.24	1595.2 c
T1	187.07 c	490.33 b	4.72 b	19.94	63.66 ab	580.89	1727.2 bc
T2	192.60 b	531.50 a	4.88 b	19.96	65.16 a	621.83	1861.1 ab
T3	206.80 a	551.17 a	5.74 a	19.90	67.00 a	667.72	1939.3 a
LSD	4.39	33.61	0.17	1.00	4.31	97.28	173.90
F-value	196.26**	11.28**	91.13**	2.33 ns	4.58*	3.12 ns	6.98**
Interaction (Year × Treatment)							
F-value	14.15**	7.01**	6.30**	2.37 ns	0.02 ns	0.62 ns	0.45 ns

**: $p \leq 0.01$; *: $p \leq 0.05$; ns: non-significant; [1]Different letters (a, b, c, d) next to means within the same column indicate significant differences according to LSD test.

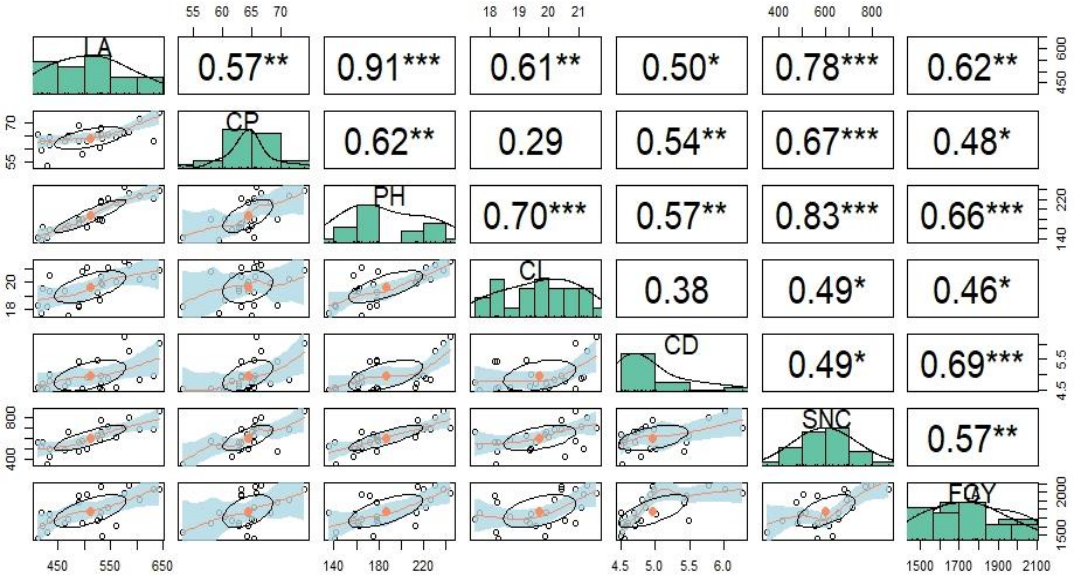
In terms of cob length, a decrease was observed from 20.43 cm in 2020 to 18.93 cm in 2021 ($p<0.01$), reflecting the influence of environmental factors over time. However, no statistically significant differences were found among treatments. The control (18.93 cm), T1 (19.94 cm), T2 (19.96 cm), and T3 (19.90 cm) treatments produced statistically similar results. Additionally, no significant year × treatment interaction was detected for cob length (Table 1). Cob performance showed no significant change over the years, with values calculated at 65.25% in 2020 and 62.58% in 2021. This suggests that climatic conditions had a limited effect on this parameter. Of the treatments used in the study, the T3 group (GA_3 + sodium nitrophenolate) and the T2 group (sodium nitrophenol) increased the cob performance values by 12% and 8.9%, respectively, compared to the control ($p<0.01$). No significant year × treatment interaction was observed for cob performance, indicating that the effects of the treatments were consistent across both years (Table 1).

The mean seed number in cob was 687.87 in 2020 and 514.97 in 2021 ($p<0.01$), suggesting that environmental stress negatively affected grain formation in 2021. Of the treatments, T3 (GA_3 + sodium nitrophenolate) produced the highest number of seeds per cob (667.72), howener, no statistically significant differences were observed among the control (535.24), T1 (580.89), and T2 (621.83) treatments (Table 1). These results suggest that the application of growth regulators had a limited effect on increasing the seed number per cob.

Fresh cob yield was determined as 1845.2 kg da⁻¹ in 2020 and 1716.2 kg da⁻¹ in 2021 ($p<0.05$), highlighting the influence of annual environmental variations on yield performance. Of the treatments applied in the study, the T3 group (GA_3 + sodium nitrophenolate) (1939.3 kg da⁻¹), increased the cob diameter by 21% compared to the control (1595.2 kg da⁻¹) ($p<0.01$). The T2 (1861.1 kg da⁻¹) and T1 (1727.2 kg da⁻¹) treatments also resulted in higher yields than the control. The positive impact of the combined treatment (T3) on fresh cob yield was clearly evident (Table 1).

The correlation analysis of agronomic traits revealed significant relationships (Figure 3). The strongest positive correlation was observed between leaf area and plant height (r=0.91, $p<0.01$),

indicating that an increase in leaf area directly supports taller plant growth. Similarly, strong positive correlations were found between plant height and both fresh cob yield (r=0.66, p<0.01), and between plant height and cob diameter (r=0.70, p<0.01). In contrast, cob length exhibited weak correlations with other traits, such as fresh cob yield (r=0.29), suggesting that cob length is influenced by genetic and environmental factors. A moderate positive correlation was also observed between cob performance and fresh cob yield (r=0.48, p<0.05), highlighting the contribution of cob filling to overall yield potential. Overall, leaf area and plant height appeared to play a key role in determining the fresh cob yield of sweet corn, while cob length and seed number per cob were less responsive to the treatments.



LA: Leaf area; CP: Cob Performance; PH: Plant height; CL:Cob Length; CD: Cob Diameter; SNC: Seed Number in Cob; FGY: Fresh Cob Yield

Figure 3. Correlation matrix of relationships between agronomic traits in sweet corn.

Şekil 3. Tatlı mısırda agronomik özellikleri arasındaki ilişkilerin korelasyon matrisi.

A principal component analysis (PCA) was conducted to further evaluate the effects of GA_3 and sodium nitrophenolate treatments on agronomic traits further (Figure 4). Two biplot graphs were generated: the first illustrating variation between years (Figure 4a) and the second showing variation between treatments (Figure 4b). In the PCA, the first principal component (PC1) explained 65.7% of the total variation, while the second principal component (PC2) explained 11.6%, together accounting for 77.3% of the cumulative variation.

In the year-based biplot (Figure 4a), the data points for 2020 (orange ellipse) clustered on the right side, while those for 2021 (yellow ellipse) clustered on the left. This separation suggests that year-specific environmental conditions caused significant variation in the agronomic traits of sweet corn. Parameters such as plant height (PH), leaf area (LA), cob length (CL), cob diameter (CD), seed number in cob (SNC), and fresh cob yield (FCY) were associated with the 2020 cluster, as indicated by the orientation of their vectors. In particular, the long vectors of plant height and leaf area indicate their dominant influence on the variation in 2020. Conversely, 2021 was associated with lower values in most traits, likely due to temperature fluctuations and irregular precipitation patterns. The cob performance (CP) vector was positioned close to both years, suggesting that this trait was less sensitive to annual environmental variations.

In the treatment-based biplot (Figure 4b), the T3 treatment (purple ellipse) was positioned on the right, while the control group (light pink ellipse) was positioned on the left. T1 (light green ellipse) and T2 (light blue ellipse) were distributed between these extremes. This distribution highlights the superior performance of T3 across multiple agronomic traits. The vectors for plant height, leaf area, cob diameter,

and fresh cob yield were oriented towards the T3 ellipse, confirming its dominant role in improving these parameters. In contrast, the vectors for cob length and seed number in cob were shorter and located closer to the control and T1 groups, indicating that these traits were less affectedby the treatments and more influenced bygenetic or the environment. factors. The cob performance vector was located between T2 and T3, emphasising the contribution of sodium nitrophenolate-containing treatments to cob filling. Overall, the synergistic effect of the T3 treatment enhanced the vegetative and generative development of sweet corn, resulting in superior agronomic performance.

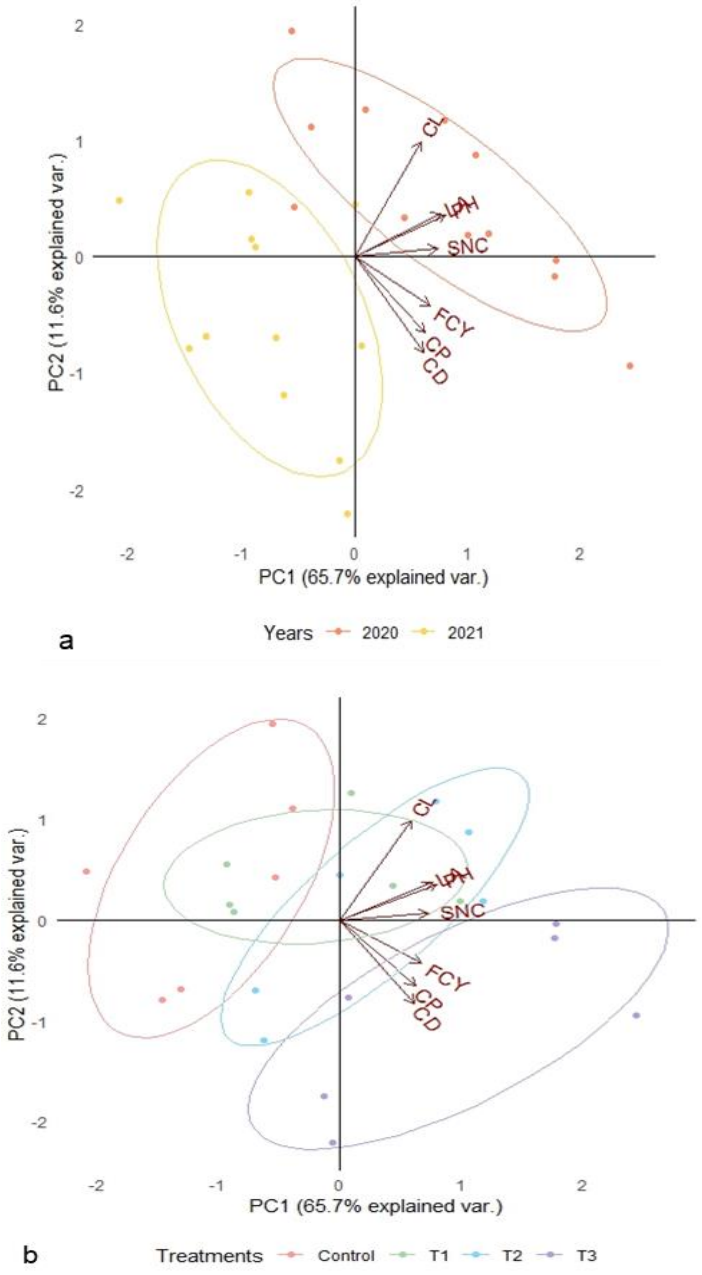


Figure 4. PCA-Biplot plot of agronomic traits for years (a) and treatments (b) in sweet corn.

Şekil 4. *Tatlı mısırda agronomik özelliklerin yıllar (a) ve uygulamalar (b) için PCA-Biplot grafiği.*

DISCUSSION

This study evaluated the effects of gibberellic acid and sodium nitrophenol applications on the yield and yield components of sweet corn in 2020 and 2021. The findings revealed that both environmental conditions and plant growth regulators both play a crucial role in the developmental processes of sugar maize development; significant differences were observed in parameters such as plant height, leaf area, cob diameter and fresh cob yield.

The parameters examined in this study, including plant height, leaf area, cob diameter, cob length, number of seeds per cob, and fresh cob yield of sweet corn exhibited higher mean values in 2020 compared to 2021. For instance, plant height decreased from 213 cm in 2020 to 159.43 cm in 2021 (p<0.01). Similarly, leaf area declined from 563.75 cm² to 457.67 cm², cob diameter from 5.04 cm to 4.89 cm, cob length from 20.43 cm to 18.93 cm, seed number in cob from 687.87 to 514.97, and fresh cob yield from 1845.2 kg da^{-1} to 1716.2 kg da^{-1}. These reductions are thought to be due to environmental factors encountered in 2021, particularly temperature fluctuations and irregular rainfall patterns (Figure 1). Öktem and Öktem (2018) reported that drought stress negatively affects the yield of sweet corn in the semi-arid regions of Türkiye. Furthermore, the IPCC (2021) report highlights that temperature increases and changes in precipitation regimes induced by climate change can lead to yield losses during crop development stages. In addition, Özata (2019) found that the average plant height of sweet corn genotypes ranged from 203.1 to 310.6 cm, cob diameter from 4.58 to 4.89 cm, cob length from 20.8 to 22.3 cm, and fresh cob yield from 1319.6 to 2423.8 kg da^{-1} across two different locations. The researcher emphasised the critical importance of genotype and environmental factors in sweet corn cultivation and noted that genotype × environment interactions have a significant impact on yield performance. Many researchers have reported that the yield and yield components of sweet corn vary depending on the genotype (Atakul, 2021; Ağaçkesen & Öktem, 2022; Temiz & Gökmen, 2023), environmental conditions where cultural practices (Eşiyok et al., 2004; Uçak et al., 2016), and where cultivation is practiced (Karaman et al., 2021; Akgün et al., 2023; Kılınç et al., 2023).

The effects of plant growth regulators on sweet corn revealed significant differences among the treatments, clearly demonstrating the potential of chemical agents used during plant development. The T3 treatment, produced the highest values for parameters such as plant height (206.80 cm), leaf area (551.17 cm²), cob diameter (5.74 cm), cob performance (67.00%), and fresh cob yield (1939.3 kg da^{-1}) were obtained compared to other treatments. In contrast, the control treatment exhibited the lowest values across all traits. These results indicate that plant growth regulators play an important role in supporting both vegetative and generative development in sweet corn. The positive effect of GA_3 on vegetative growth parameters such as plant height and cob diameter, is thought to result the physiological mechanisms of gibberellins that promote cell division and elongation. Gibberellins, lead to a marked increase in plant height by enhancing stem elongation and increasing cell wall flexibility (Hedden & Thomas, 2016). Additionally, the effect of GA_3 on cob diameter is associated with its promotion of cell growth in meristematic tissues, thereby supporting cob development (Srivastava, 2002). These findings support the potential of GA_3 in optimizing vegetative growth in sweet corn. For instance, Rademacher (2015) reported that GA_3 accelerates plant growth in agricultural applications, enhancing yield, and particularly improving cob development in crops such as maize. Similarly, Mishra et al. (2020) found that the application of GA_3 alongside standard fertilization strategies was effective in increasing cob diameter and the number of seeds per cob in sweet corn.

Sodium nitrophenolate improves the photosynthetic rate by enhancing carbon assimilation, thereby increasing the plant's energy production capacity (Chen et al., 2019). This promotes the expansion of leaf area, enabling the plant to capture more light energy. Application of sodium nitrophenolate application has been shown to increase plant height (Dobromilska et al., 2008), as well as leaf development and leaf number (Djanaguiraman et al., 2009). Furthermore, there is evidence that sodium nitrophenolate

enhances plant resistance of plants to abiotic stress conditions by activating antioxidant systems (Zhang et al., 2015). In the present study, the significant increases observed in traits such as plant height, leaf area, cob performance, and fresh cob yield in the T2 treatment compared to the control group support this mechanism. During the vegetative growth phase of maize, the application of sodium nitrophenolate enhances nitrogen uptake and metabolic processes (Amin, 2007), and its use has been found to promote maize growth (Michalski et al., 2008).

The superior performance of the T3 treatment across all parameters is attributed to the synergistic effects of GA_3 and sodium nitrophenolate. While GA_3 promoted vegetative growth, sodium nitrophenolate optimized photosynthesis and metabolic processes, supporting generative development. This combination improved both biomass production and reproductive organ development. For instance, the increase in fresh cob yield observed in T3 (1939.3 kg da^{-1}) compared to the control group (1595.2 kg da^{-1}) demonstrates the economic significance of this synergistic effect. Furthermore, the success of T3 in improving cob diameter (5.74 cm) and cob performance (67.00%) suggests that this application could be an effective strategy for enhancing sweet corn product quality. A similar synergistic effect was reported by Kumar et al. (2020), who found that the combined use of GA_3 and other growth regulators improved both yield and quality parameters in maize. Additionally, sodium nitrophenolate application has been shown to strongly inhibit IAA oxidase, which is responsible for regulating auxin activity, thereby promoting growth (Szparaga et al. 2018). Yao et al. (2023) is reported beneficial effect of combination of GA3 + sodium nitrophenolate who suggested that it has a promising application in improving plant growth. El-Fouly et al. (2014) found that low and medium concentrations of combination of GA3 + sodium nitrophenolate increased including chlorophylls, carotenoids, and leaves content of N, P and K on *Ficus deltoidea* seedlings with growth and chemical compositions.

Othman et al. (2024) compared different combination of GA3 + sodium nitrophenolate applications in jackfruit fruits and stated that it showed superior performance in terms of plant height, number of leaves per plant, stem diameter, fresh and dry weight of the plant, number of roots, and leaf area. In particular, combination of GA3 + sodium nitrophenolate was shown to have a positive effect on certain mechanisms that regulate plant growth and development. Additionally, GA3 was reported to promote apical dominance, increase growth, and play a beneficial role in physiological plant's functions. In this study, it is believed that the combination improved these characteristics, resulting in an increase in leaf area and, consequently, an increase in yield and yield components.

In conclusion, the combination of GA_3 and sodium nitrophenolate was found to be more effective as it targets different physiological processes in sweet corn. The vegetative growth-promoting effects of GA_3, combined with the enhancement of photosynthesis and stress tolerance by sodium nitrophenolate, optimised both plant development and yield under the T3 treatment. These findings emphasise the potential of plant growth regulators as strategic tools in sweet corn production, with combined applications offering significant promise for enhancing yield and quality.

CONCLUSION

This study examined the effects of GA_3 and sodium nitrophenolate applications on agronomic traits of sweet corn through multivariate analyses conducted over the 2020 and 2021 growing seasons. The T3 treatment (combination of GA_3 and sodium nitrophenolate) achieved the highest values for key parameters, including plant height (206.80 cm), leaf area (551.17 cm^2), cob diameter (5.74 mm), cob performance (67.00%), and fresh cob yield (1939.3 kg da^{-1}), thereby significantly improving both yield and its components. In contrast, cob length and seed number in cob remained unaffected by the treatments, suggesting the prevailing influence of genetic and environmental factors. Favorable climatic conditions in 2020 contributed to enhanced performance, whereas environmental stresses such as temperature

fluctuations and irregular precipitation in 2021 led to marked reductions. A significant year × treatment interaction was detected for plant height, leaf area, and cob diameter, with the superiority of T3 being more pronounced under the favorable conditions of 2020, whereas differences between treatments diminished in 2021. These findings underscore that the effectiveness of growth regulators is closely modulated by environmental factors, and highlight the potential of combined applications to enhance yield performance under variable conditions. In the study, the combined use of combination of GA3 + sodium nitrophenolate promotes plant yield and yield component development due to its synergistic effect on plants. Moreover, future longitudinal studies are warranted to better elucidate the impacts of climate change and to develop resilient and sustainable production strategies for sweet corn cultivation.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Concept and design of the study: RK; sample collection: RK, CT; data analysis and interpretation: RK, CT; statistical analysis: RK, CT; manuscript writing: RK, CT.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this study.

Ethical Statement

We declare that ethical approval was not required for this research.

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Conservation of natural heritage in the Bursa Hanlar District: An investigation into monumental plane trees*

Bursa Hanlar Bölgesi'nde doğal mirasın korunması: Anıt çınar ağaçları üzerine bir inceleme

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ABSTRACT

Objective: This study aims to identify the difficulties and challenges faced by monumental trees in a historically protected area, compare their current and desired living conditions and develop solutions to the issues they experience.

Material and Methods: The study assessed the current living conditions and physical state of the monumental plane trees. The differences were identified by comparing their current condition with their expected size and habitat to be protected. Monumental trees were examined in terms of trunk and crown health status, and solution proposals were developed for the identified problems.

Results: The data revealed that 85% of the monumental trees were below the required height and diameter. None of the monumental trees in the study area had sufficient living space. Furthermore, 95% of the trees exhibited inadequate root areas, and their forms had deteriorated due to deep pruning; 90% showed signs of branch dieback, 70% had galls and swellings, 55% insufficient crown area, and 50% had cavities and rot in their trunks.

Conclusion: To ensure the sustainability of the monumental trees in the study area, they must be protected according to the TS 13190 standard, with special care and rehabilitation measures implemented. Without these interventions, many of these monumental trees, which have already lost many characteristics, may disappear within a few decades.

Keywords: Maintenance, monumental trees, plant health, sustainability

ÖZ

Amaç: Bu çalışmada, UNESCO Dünya Miras Listesi'nde yer alan Bursa Hanlar Bölgesindeki anıt çınar ağaçlarının mevcut yaşam koşulları ile olması gereken yaşam koşullarının karşılaştırılması, bulundukları koşullarda maruz kaldıkları olumsuzlukların belirlenmesi ve çözüm önerilerinin geliştirilmesi amaçlanmıştır.

Materyal ve Yöntem: Çalışmada, anıt çınar ağaçlarının mevcut yaşam koşulları ve fiziki durumlarının tespiti yapılmıştır. Olması gereken boyutları ve korunması gereken yaşam alanı ile mevcuttaki durumları karşılaştırılarak farklar ortaya konulmuştur. Ağaçlar, gövde ve taç sağlık durumları açısından incelenmiş, tespit edilen problemler için çözüm önerileri geliştirilmiştir.

Araştırma Bulguları: Elde dilen verilere göre anıt ağaçların %85'nin olması gereken boy ve taç çapının altında kaldığı tespit edilmiştir. Çalışma alanındaki hiçbir anıt çınar ağacı için yeterli yaşam alanı bırakılmamıştır. Anıt ağaçların; yüzde 95'inin yetersiz kök alanına sahip olduğu ve derin budamalardan kaynaklı taç formunun bozulduğu, %90'ının dal kurumalarına, %70'inin ur ve şişkinliklere, %55'inin yetersiz taç alanına sahip olduğu, %50'sinin gövdesinde kovukların ve çürüklerin oluştuğu saptanmıştır.

Sonuç: Çalışma alanındaki anıt çınar ağaçlarının sürdürülebilirliği için TS 13190 Nolu standarda uygun olarak korunması, özel bakım ve rehabilitasyon uygulanması gerekmektedir. Kanunlarla belirlenen koruma alanı sınırlarına titizlikle uyulmalıdır. Aksi takdirde hâlihazırda birçok özelliğini kaybetmiş olan bu anıt çınar ağaçlarının birçoğu birkaç onyılda yok olup gidecektir.

Anahtar sözcükler: Bakım, anıt ağaçlar, bitki sağlığı, sürdürülebilirlik

INTRODUCTION

Monumental trees are the longest-living natural monuments and hold cultural and historical value. They symbolize immortality, power and peace. They are also the most important heritage of nature (Demir, 2019; Yener, 2022; Budău et al., 2025). Examples of these trees, which are tied to both sad and happy stories, can be found throughout our country (Asan, 2010). They also play a crucial role in sustaining traditions and maintaining ecological balance due to their historical significance (Cannizzaro & Corinto, 2014; Grigoriadis, 2021; Bulut, 2024).

Monumental trees are defined in the Regulation on the Procedures and Principles Regarding the Determination, Registration, and Approval of Protected Areas (RG, 28358) and Principle Decision No. 110 (2020) of the Ministry of Environment, Urbanization, and Climate Change (MEUCC). They are defined as “trees that exceed the typical dimensions of their species in age, diameter, and height, and/or hold a special place in local folklore, culture, and history, and/or possess a natural longevity that connects the past with the present and the future” (Şişman, 2014; Yener, 2022; Bulut, 2024). In our country, a cradle of many cultures and civilizations, numerous trees have survived the past that can be classified as monumental (Anonymous, 2016; Aslan, 2016; Bulut, 2024). In Evliya Çelebi's travel books, ten monumental trees in the region between Tavas and Muğla were described as "trees to be taken as an example" (Baytop, 2004).

Monumental trees are characterized by physical features that captivate the eye, including height, diameter, and crown shape. Their impressive structures and heights (Şişman, 2014; Budău et al., 2025), along with lifespans that can reach 15 to 20 times that of humans (Asan, 2010), draw significant attention. These trees symbolize cultural commitment, love of nature, and environmental awareness, making them important elements of both rural and urban landscapes (Atik et al., 2017; Polat, 2017; Demir, 2019; Genç & Güner, 2003; Grigoriadis, 2021). In Turkish societies, certain species of trees are regarded as sacred, linking them to holy sites. This belief has historically led to the planting of trees around places of worship and cemeteries (Arslan, 2014). Occasionally, these trees have also served as symbols of emotions and sources of inspiration for poems and songs (Şişman, 2014; Bulut, 2024). As a result, the relationship between Turks and trees is notably stronger than in many other cultures (Kuru, 2022). Additionally, some trees are valued for their unique trunk shapes and longevity, earning the designation of "monumental trees" (Uysal, 2014). Due to their symbolic significance and positive psychological effects, monumental trees are carefully protected worldwide (Efe et al., 2010; Bulut, 2024). They are respected for their associations with power, wealth and greatness. Also, they are respected for their roles in mythology and epics, their use as symbols in national flags and treaties, and their contributions to tourism and trade in their regions (Asan, 1987). Furthermore, they assist in estimating past climate events in dendroclimatological studies (Asan, 2010; Zencirkıran et al., 2016). This ecological heritage serves as a focal point and is a valuable resource for ecotourism. For instance, the İnkaya Plane Tree at the foothills of Uludağ in Bursa stands out as a significant monumental tree (Zencirkıran et al., 2016; Erken et al., 2019; Sen & Bahadir, 2022). Monumental trees are a part of natural or cultural landscapes and provide natural heritage features to the landscape in cities where natural elements are rapidly disappearing (Atik et al. 2017; Sen & Bahadir, 2022). Each monumental tree has a mystical or folkloric story in the local culture and witnesses national and historical events (Polat, 2017; Güneş & Önder, 2022; Petino et al., 2024). In historical and cultural heritage, monumental trees are the entities that leave the most traces in people's psychology and memory, whose appearance and size change according to years and seasons (Sarıbaş, 2015; Mejorado Velazco et al. 2020; Camarero et al., 2024). Therefore, the sustainability of monumental trees and their transfer to future generations are very important (Chen, 2015; Demirtaş & Özden, 2015; Grigoriadis, 2021).

The plane tree, a monumental species prevalent in Anatolia, particularly in Bursa, symbolizes majesty and permanence in Turkish culture (Özkaplan Yörüklü, 1997). For thousands of years, it has

represented power and authority in the region (Efe et al., 2010; Aslan et al., 2016). However, the monumental trees—historical elements of the Hanlar Region, one of Bursa's most significant historical sites—are diminishing in size, losing vitality, drying out, and collapsing due to wind. While the criteria for classifying a tree as monumental include dimensional, cultural, and visual features as outlined in Principle Decision No. 110 on the Determination of Monumental Trees, few monumental trees in Bursa have maintained their size characteristics. It is crucial to ensure the healthy transfer of these trees to future generations. Therefore, protecting their health, diagnosing issues, finding solutions, and taking necessary actions are priority concerns (Chen, 2015; Demirtaş & Özden, 2015; Grigoriadis, 2021).

According to Article 63 of the Constitution, the state is responsible for protecting natural assets. Provision 3/a-2 of KTVKK No. 2863 (1983) classifies monumental trees as immovable natural assets. Consequently, the state is obligated to take all necessary measures to safeguard these trees (Çevikçelik, 2021; Bulut, 2024). This responsibility is carried out by the Ministry of Environment, Urbanization, and Climate Change, specifically through the General Directorate of Protection of Natural Assets, a unit of ÇŞİDB (Güneş & Önder, 2022; Bulut, 2024).

Key regulations on monumental trees include several official documents. One is the Regulation on the Procedures and Principles for the Determination, Registration, and Approval of Protected Areas (2012). It was published in the Official Gazette on July 9, 2012 (No. 28358) and amended in 2013, 2017, 2020, and 2022. Another important document is Principle Decision No. 110, issued by the Ministry of Environment and Urbanization. It was approved during the 37th meeting on September 10, 2020. Clause (d) of this decision states that the crown diameter projection should define the protection area of monumental trees. The second paragraph of clause d prohibits ground covering, excavation, and construction activities that could harm the tree's root structure, nutrition or prevent water from reaching the roots within the protection area. It also prohibits any activities that may damage the crown, trunk, and roots or affect other plants in the vicinity. Furthermore, any activities within the protection area require permission from the Regional Commissions.

Despite this principle decision, there is lack of compliance in Bursa, many other areas in Türkiye and the world, where the habitats of monumental trees are frequently violated, threatening their survival (Gül, 2019; Çevikçelik, 2021; Yener, 2022; Jacobsen et al., 2023; Bulut, 2024).

This study aims to evaluate the current status and issues of the monumental plane trees in Bursa Hanlar Region Core Area, a UNESCO World Heritage Site. It will compare their existing condition to the desired status, identify the discrepancies, and propose solutions for sustainability.

The study fills a significant gap in the care and conservation of monumental plane trees in the Bursa Hanlar District. It emphasizes the need to evaluate the structural and vegetal heritage of our historical sites together. It highlights the fact that our living historical monuments, unlike structural monuments, require maintenance for their sustainability and the consequences of failure to do so. The detailed data obtained in the study and the proposed solutions developed in accordance with TSE 13137 (2005) and TSE 13190 (2006) standards make the study original and valuable for both scientific and practical purposes.

MATERIALS and METHODS

Materials

The study was conducted in Hanlar Region located in Bursa Province (40° 11′ 30″ N, 29° 3′ 40″ E), which has the highest concentration of historical artifacts and monuments in the city (URL-1, 2023). The historical region of Bursa was added to the UNESCO World Heritage temporary list in 2000. Figure 1 illustrates the core area and buffer zone of Hanlar Region.

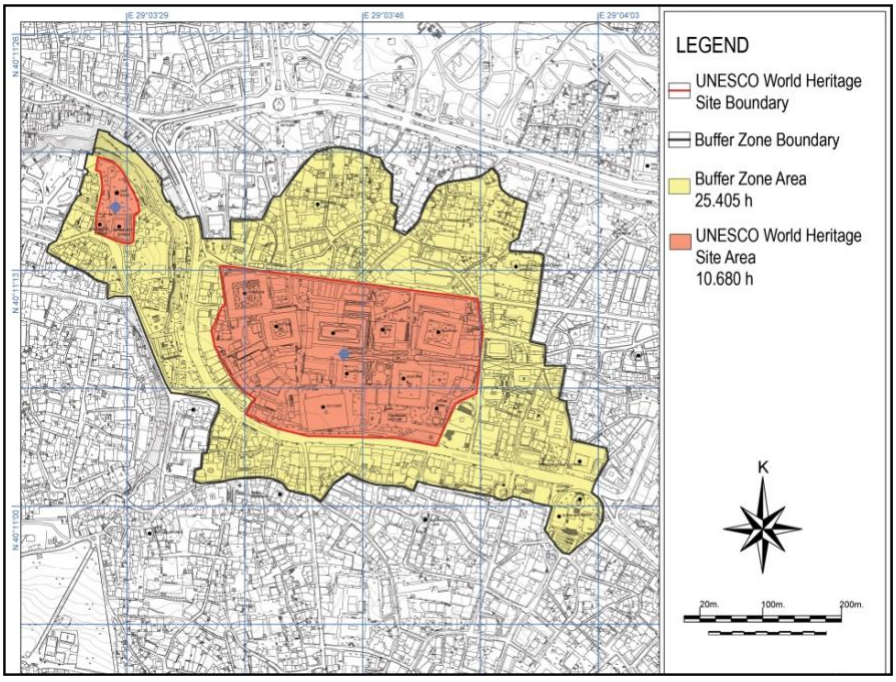

Figure 1. Hanlar Region core area and buffer zone (Bursa Site Management Unit, 2025).

Şekil 1. *Hanlar Bölgesi çekirdek alan ve tampon bölge (Bursa Alan Başkanlığı, 2025).*

This study examines 20 monumental plane trees located in the core area of Bursa Hanlar Region, and these trees are protected under Law No. 2863 on the Protection of Cultural and Natural Assets (1983) (Figure 2).

Figure 2. The monumental trees that are the material of the study and their locations in the Hanlar Region Core Area (Bursa Site Management Unit, 2025).

Şekil 2. *Çalışmanın materyali olan anıt ağaçlar ve Hanlar Bölgesi Çekirdek Alan'daki konumları (Bursa Alan Başkanlığı, 2025).*

Table 1 lists the locations of the monumental trees in the study, along with their inventory number codes and the qualities they currently protect.

Table 1. List of monumental plane trees examined in the study, their locations and characteristics

Çizelge 1. *Çalışmada incelenen anıt çınar ağaçlarının listesi, konumları ve özellikleri*

No	Trees	Inventory number	Tree code	Currently Protected Monument Tree Characteristic	Location	Coordinate
1	*Platanus orientalis*	16-2	OSM-525	Age-History	Pirinçhan Courtyard	X:419967.7103 Y:4450546.44619
2	*Platanus orientalis*	16-1	OSM-524	Age-History	Pirinçhan Courtyard	X:419964.63286 Y:4450564.73414
3	*Platanus occidentalis*	18-1	OSM-527	Age-History	in front of Hünkâr Turkish delight	X:420036.49948 Y:4450567.19733
4	*Platanus occidentalis*	70	OSM-528	Age-History	İvazpaşa Mosque Garden	X:420069.32413 Y:4450557.80916
5	*Platanus orientalis*	49	OSM-533	Age-History	in front of Çınar kebab	X:420062.52143 Y:4450326.41043
6	*Platanus occidentalis*	56	OSM-532	Age-History	in front of Yesevi Kebap	X:420043.63154 Y:4450328.84947
7	*Platanus orientalis*	51-6	OSM-534	Age-History	in front of Çınar Cafe	X:420180.64581 Y:4450333.07124
8	*Platanus orientalis*	37-1	OSM-535	Age-History	Behind Ulu Mosque Fountations	X:420155,33205 Y:4450352.36817
9	*Platanus orientalis*	38-1	OSM-536	Age-History	Behind Ulu Mosque Fountations	X:420155.56627 Y:4450355.7036
10	*Platanus orientalis*	39-1	OSM-537	Age-History	Behind Ulu Mosque Fountations	X:420155.85869 Y:4450358.15214
11	*Platanus orientalis*	51-5	OSM-539	Age-History	Across from Bursa Silk Shop	X:420193.22221 Y:4450358.01652
12	*Platanus orientalis*	51-4	OSM-540	Age-History	Kozahan Entrance right side	X:420258.86971 Y:4450354.66941
13	*Platanus occidentalis*	30-1	OSM-549	Age- crown diameter	Kozahan Courtyard	X:420254.39307 Y:4450411.35407
14	*Platanus occidentalis*	30-4	OSM-551	Age- crown diameter - History	Kozahan Courtyard	X:420232.86757 Y:4450386.90317
15	*Platanus occidentalis*	30-3	OSM-552	Age-History	Kozahan Courtyard	X:420232.97066 Y:4450395.84824
16	*Platanus orientalis*	30-2	OSM-553	Age-History	Kozahan Courtyard	X:420234.92759 Y:4450409.03989
17	*Platanus occidentalis*	30-6	OSM-548	Age-History	Kozahan Inner Courtyard	X:420285.79416 Y:4450408.74133
18	*Platanus orientalis*	31-3	OSM-546	Age-History	Orhan Mosque Garden	X:420308.64885 Y:4450373.37046
19	*Platanus orientalis*	31-2	OSM-547	Age-History - Folkloric	Orhan Mosque Garden	X:420285.93762 Y:4450379.33498
20	*Platanus orientalis*	51-1	OSM-543	Age-History	Behind Orhan Mosque	X:420300.7953 Y:4450335.58255

Methods

The method of this study consists of three stages.

First stage

The study commenced with a literature review that involved researching information about monumental trees, correlating relevant laws and regulations regarding their protection and examining previous studies on the subject.

Second stage

This stage involved fieldwork, in which measurements of the height, trunk diameter, trunk circumference, and crown diameter of the monumental trees in Bursa Hanlar Region—designated as the study area—were taken. The ages of the trees were determined using the monumental tree plates affixed to their trunks. Concurrently, measurements were made of the soft ground living area available for the roots. The presence of structures within the designated living space for the trees and the paving status in this area were assessed, and distance measurements were recorded. Observations were conducted regarding tip drying (top collapse), side branch drying, disease factors, trunk decay, and improper pruning practices, with observation reports prepared for each tree (Pan et al., 2025).

Height measurement: The distance from the soil level to the highest point of the branches of the tree was measured in meters using a laser meter (Pietraszko et al., 2022).

Trunk circumference and diameter measurement: The trunk circumference was measured in meters at a height of 130 cm from the soil surface using a tape measure. The trunk diameter was measured from the same height (Pietraszko et al., 2022) (Figure 3).

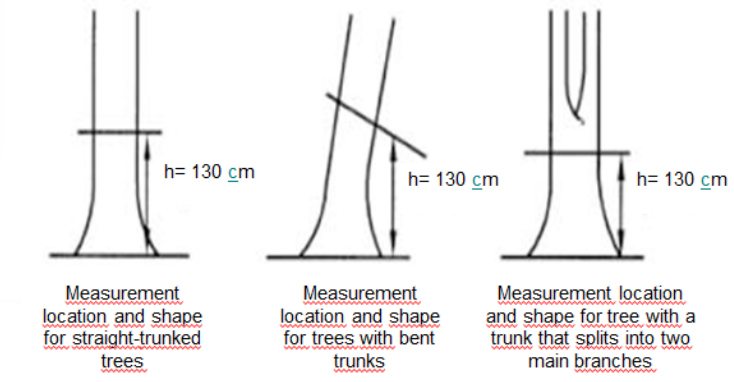

Figure 3. Measurement location of trunk diameter and trunk circumference (Uzun, 1997; Pietraszko et al., 2022).

Şekil 3. *Gövde çapı ve gövde çevresi ölçüm yeri (Uzun, 1997*; *Pietraszko et al., 2022).*

Crown diameter measurement: To measure the crown diameter, the crown projections of the tree were taken in the main directions (North-South and East-West), and the diameters were measured using a tape measure. The average of these two values was recorded as the crown diameter (Pietraszko et al., 2022; Yang et al., 2024) (Figure 4).

Monumental tree height, crown, and living space status ınformation: Situation charts were created for monumental trees, along with plan and section view drawings made using AutoCAD and Photoshop, to compare the current and required measurements of monumental trees in terms of height, crown diameter, and living space areas. Studies by Genç & Güner (2001), Gül (2019), Kuru (2022), and Camarero et al. (2024) informed the development of this status information. The measurement data collected from our field study were processed into status charts. In addition to current measurements,

information on age, height, crown diameter, trunk diameter, circumference, and both current and ideal living space were compiled into status lists. The monumental features section details which characteristics (age, height, diameter) qualify a tree as monumental (Polat, 2017; Çevikçelik, 2021; Yener, 2022; Yang et al., 2024) (Figure 4).

In the section on health information and problem identification, the conditions affecting the health and integrity of the tree are outlined. This includes the presence of fungal infection, Sap exudation from the trunk, crown top collapse, deep pruning damage, branch dieback, galls and swellings on the trunk, and cavities and rot. Regarding the living space of the tree (protection area), the available soft soil for roots and growth and the ground covering material were assessed (Wilkaniec et al., 2021; Pietraszko et al., 2022; Jacobsen et al., 2023).

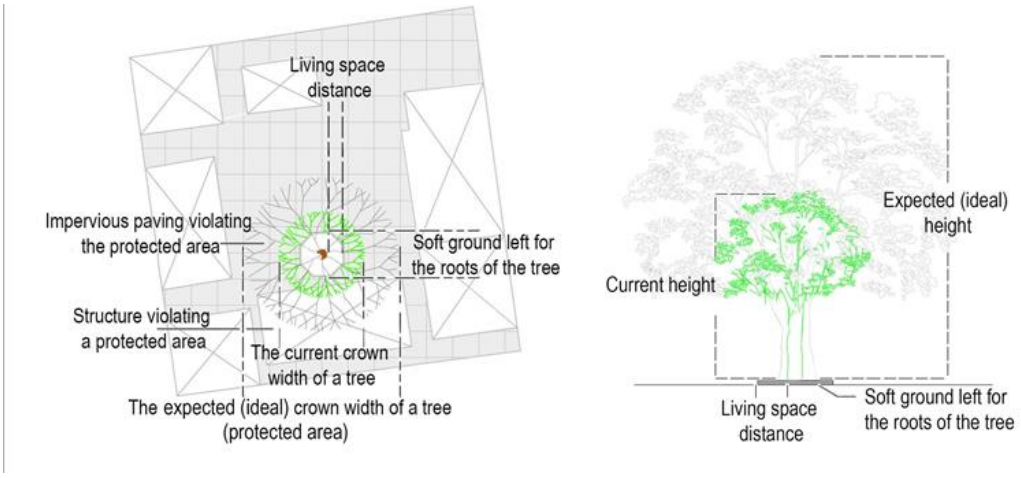

Figure 4. Measured dimensions of monumental trees, and comparison of current and ideal dimensions.

Şekil 4. *Anıt ağaçlarda ölçülen boyutlar ve mevcut ile olması gereken boyutların karşılaştırılması.*

Later, a table was created for the studied monumental trees, calculating their required height, crown diameter dimensions according to age, and necessary protection area. This table was developed based on Principle Decision No. 110 regarding the designation of monumental trees as natural entities, along with studies by Genç & Güner (2003), Gül (2019), and Kuru (2022). According to Principle Decision No. 110 and Standard No. TS 13137, the average height of first-class plane trees (*Platanus* spp.) should exceed 25 m. To qualify as a monumental tree, the Eastern Plane Tree must have a minimum height of 25 m and a minimum crown diameter of 20 m, as per Standard No. TS 13137, Genç & Güner (2003), and Yang et al. (2024).

To determine the required crown diameters of monumental plane trees, the trees in the study area were divided into age groups with 20- year intervals, resulting in nine groups: 120-140, 141-160, 161-180, 181-200, 201-220, 221-240, 241-260, 261-280, and 281- 460. Average crown diameter and height data for each age group were provided by Tatlı et al. (2000), Genç et al. (2002), Genç & Güner (2003), Şişman (2014), Aslan (2016), and Gül (2019). The data based on measurements taken from healthy monumental *Platanus orientalis* trees listed in Mejorado Velazco et al. (2020), Güneş & Önder (2022), Kuru (2022), and MEUCC (2025) as they were measured in the field. Subsequently, the height and crown diameter each monumental tree should have according to its age group were calculated based on the collected data.

The narrowest area between the trunk of the monumental tree and the hard ground was measured in centimeters to assess the available living space for the tree. In calculating the differences between the required (expected) and existing living space, the tree crown projection limit was considered the outer boundary of the living space (protected area) (Principle Decision No. 110, 2020; Yener, 2022; Pan et al., 2025).

Third stage

At this stage, deficiencies and solutions were proposed for the problems identified during the field studies.

RESULTS and DISCUSSION

The data obtained at the end of the study regarding the dimensions and living space of 20 monumental plane trees in Hanlar Region Core Area are presented in Table 2. The findings indicate that the tree height is significantly below the required 39 m specified for Eastern and Western plane trees in Annex 1 of Principle Decision No. 110. Only three monumental trees meet the minimum height standard of 25 m for first-class forest tree species, as specified by Genç & Güner (2003) and Aslan (2016) in Principle Decision No. 110. Seventeen trees fall below the minimum standards for monumental plane trees. Based on the average dimensions of monumental plane trees in Türkiye, only two trees meet the required height for their age group. These trees are located behind the fountains in the Ulucami Garden. They are notably distanced from surrounding structures, are close to a water source, and have larger living spaces than other species. Monumental plane tree number 4, which exceeds the expected height, is situated in the garden of İvaz Paşa Mosque. The growth of the tree is likely due to side branch pruning because of its proximity to the mosque wall. It should have averaged 25.85 m, but its actual average height is 19.00 m. In the study by Akgün et al. (2018), 4 out of 5 monumental plane trees surpassed the 25 m standard, while this rate was much lower in our study. The reduced height in these trees is attributed to the collapse of their tops due to a lack of maintenance.

When examining the crown diameter as one of the dimensional characteristics of monumental trees, it is important to note that the minimum crown diameter standard for such trees, as stipulated by Genç et al. (2002), Aslan (2016) and as outlined in Annex-4 of Principle Decision No 110 is 20 m. In the study area, three monumental trees meet this criterion. Specifically, trees numbered 7 (located in front of Çınar Cafe), 9 (behind Ulu Mosque Shelters), and 12 (at the entrance of Koza Han) qualify. Notably, trees numbered 7 and 12 are situated in Gazi Orhan Park, where they enjoy a more expansive living space and are distanced from surrounding structures. Conversely, tree number 9 is positioned on the boundary of Ulucami Garden and Gazi Orhan Park, also benefiting from a relatively spacious living area and protective zone. It is observed that 50% of the protection area for monumental tree number 7, 75% of the protection area for monumental tree number 9, and 40% of the protection area for monumental tree number 12 is designated as soft permeable ground (grass area). Among the monumental plane trees, only tree number 12, located in the square of Gazi Orhan Park across from the entrance of Koza Han, meets the expected crown width averages established for healthy monumental plane trees. With a crown diameter of 29.64 m, it singularly embodies the characteristics of a monumental tree within the study area. In terms of crown diameter, a significant majority of the trees (85%) fall short of the expected average dimensions of 25.65 m, with actual measurements averaging only 14.89 m (Table 2).

Asan (2010) posited that the most salient characteristic of monumental plane trees is their size, which significantly enhances their impact on human and social psychology. However, in the context of the present study, it was determined that there are only three monumental plane trees in the study area, representing a mere 15% of the total. In contrast, Akgün et al. (2018) reported more favorable findings in their research; specifically, two out of five measured plane trees fell below the 20 m diameter standard, while three were measured above this threshold.

Table 2. Differences between the dimention required to be of the studied monumental plane trees according to their ages and their current dimensions

Çizelge 2. *Çalışılan anıt çınar ağaçlarının yaşlarına göre olması gereken ortalama ideal boyutları ile mevcuttaki boyutları arasındaki farklılıklar*

Monumental tree species	Age (2025)	Height of the monumental tree (m)		crown diameter (m)		Trunk diameter (cm)	Trunk circumference (m)	Living space distance (m) (From trunk to crown edge border)		Floor covering material in the monumental tree canopy cover
		Current dimension	ideal dimension*	Current dimension	ideal dimension**			Current (m)	ideal distance according to the existing crowns (m)***	
1. *Platanus orientalis*	206	10	26	10.80	26	113	3.13	2.20	5.40	Concrete coating
2. *Platanus orientalis*	186	17	25	19.07	25	119	3.70	2.20	9.53	Concrete coating
3. *Platanus occidentalis*	131	18	25	13.41	25	72	2.25	0.20	6.70	Granite cube stone flooring + Concrete
4. *Platanus occidentalis*	156	28	25	18.43	25	88	1.71	0.60	9.22	Andesite slab stone flooring
5. *Platanus orientalis*	226	19	26	9.60	26	156	4.44	1.10	4.80	Granite cube stone flooring + Concrete
6. *Platanus occidentalis*	131	8	25	5.74	25	80	2.98	0.50	2.87	Andesite slab stone flooring
7. *Platanus orientalis*	208	24	26	23.21	26	170	5.10	0.50	11.61	Green area+Basalt slab stone flooring
8. *Platanus orientalis*	271	27	27	14.02	27	125	3.50	0.35	7.01	Cube stone flooring
9. *Platanus orientalis*	141	23	25	23.00	25	112	3.70	0.60	11.50	Green area + Natural stone flooring
10. *Platanus orientalis*	160	25	25	19.54	25	130	4.03	1.35	9.77	Green area + Paving stone flooring
11. *Platanus orientalis*	236	16	27	14.06	26	170	5.10	1.30	7.03	Green area + Paving stone flooring
12. *Platanus orientalis*	136	22	25	29.64	25	200	5.35	2.60	14.82	Green area + Paving stone flooring
13. *Platanus occidentalis*	247	15	27	8.88	26	146	4.88	1.00	4.44	Cube stone flooring
14. *Platanus occidentalis*	126	19	25	10.07	25	47	1.56	1.00	5.03	Cube stone flooring
15. *Platanus occidentalis*	146	15	25	14.34	25	77	2.55	1.00	7.17	Cube stone flooring
16. *Platanus orientalis*	187	21	25	14.50	25	117	2.64	1.20	7.25	Cube stone flooring
17. *Platanus occidentalis*	252	19	27	15.15	27	172	5.21	0.20	7.58	Cube stone flooring
18. *Platanus orientalis*	446	16	30	7.41	28	284	8.95	0.00	3.72	Slate stone flooring
19. *Platanus orientalis*	181	19	25	10.07	25	114	3.28	0.30	5.03	Slate stone flooring
20. *Platanus orientalis*	206	19	26	16.85	26	115	3.25	1.50	8.43	Green area + Paving stone flooring
Mean	198.95	19.00	25.85	14.89	25.65	130.3	3.87	0.99	7.45	

* According to the Annex-1 of the Principle Decision No. 110 and Genç & Güner (2003), the minimum tree height determined for the Eastern Plane Tree to be selected as a monumental tree is 25 meters.

** The minimum crown diameter standard required for a monumental tree to receive full points in the determination of the monumental tree given in the Annex-4 table of the Principle Decision No. 110 is 20 m.

*** According to the principle decision No. 110 taken at the meeting No. 37 of the Ministry of Environment and Urbanization dated 10.09.2020, the conservation area (Living space) that have to be between the trunk and the crown adge border has calculated by taking into account the current crown diameter of the tree.

An analysis of the living space data reveals significant deficiencies in spatial dimensions and associated health issues that fall below established standards. Notably, no monumental plane tree within the study area has been afforded the requisite living space as delineated in the principle decision numbered 110, which designates specific protection areas. The current average living space distance measured at 0.99 m is substantially less than the recommended distance of 7.45 m, derived from average crown widths calculated based on the identified age groups. Although some trees exhibit the use of soil-jointed flooring materials in their living spaces, these joints result in surfaces that exhibit inadequate permeability due to intensive use and compaction (Güneş & Önder, 2022). Non-permeable floor covering materials and soil compaction emerge as primary challenges for plant health in urban environments (Genç & Güner, 2003). According to TSE 13190, practices that would lead to soil compaction within living space should be strictly prohibited. The monumental tree in optimal condition, identified as plane tree number 12, located in Orhan Gazi Park across from the entrance of Koza Han, maintains a living space distance of 2.6 m, making it the only monumental tree that complies with the minimum standard regarding crown diameter. This observation underscores the critical importance of designated living space (protection areas) for the healthy development and sustainability of monumental trees. It is essential to recognize that the living space currently allocated are based on the problematic crown widths of the trees. When calculating according to the appropriate crown widths corresponding to the age of the monumental trees, it becomes evident that a protection area of 12.83 m should be maintained considering the trunks of these trees, in accordance with the standards outlined in Principle Decision Number 110 and the calculated average crown diameters of the twenty trees assessed.

According to Principle Decision No. 110, Genç & Güner (2003), and Yener (2022) in designated protection areas, ground coverings that may adversely affect the root structure and nutritional supply of trees and also inhibit groundwater access to the root system, are prohibited. The protection area for monumental trees is documented alongside the trees themselves, and violations of this regulation necessitate penal action in accordance with pertinent laws and regulations (Çevikçelik, 2021; Sapan, 2024). Alp & Baylan (2017) assert that the protection area for monumental trees should be a minimum of 5 m to the crown projection. Considering the constraints posed by existing historical structures, which cannot be demolished, and the location of the historical trade center characterized by high human movement, the most rational, straightforward, and feasible solution is to employ highly permeable materials for ground coverings around the monumental trees.

The investigation revealed ten distinct problems affecting the monumental plane trees studied, as summarized in Table 3. These issues were found to negatively impact the overall size and health of the monumental trees (Table 3).

As illustrated in Table 3, one of the most significant challenges faced by the monumental plane trees in the study area is the insufficient space allocated for their roots, with 95% of the trees experiencing this issue. According to Principle Decision No. 110 and TSE 13190, the area corresponding to the crown projections of the trees is designated as a protection area, which should ideally remain as soft ground. Martinez & Coelho-Duarte (2023) reported a 50% incidence of root-related problems in their study of 16 *Platanus hispanica* plane trees in Mendoza, Argentina; this rate was observed to be higher in the present study.

A significant issue observed among the monumental plane trees in the study area is the prevalence of deep pruning, which affects 95% of the specimens. Two contributing factors that cause deep pruning of these monumental plane trees are branch dieback and crown top collapse. Branch dieback was observed in 90%, crown top collapse was 35% of the trees included in the scope of the study. Additionally, the proximity of surrounding structures and other trees within the designated protection area further exacerbates the situation. The close proximity of these elements has impeded the natural branching and crown formation of the monumental trees, necessitating pruning interventions. This problem, defined as insufficient crown area, was identified in 55% of the of the assessed trees. This practice has resulted in an imbalance in certain trees and has led to a complete alteration of the natural form in others.

Table 3. Problems detected in monumental plane trees in the Bursa Hanlar Region

Çizelge 3. *Çalışma alanındaki anıt çınar ağaçları ve tespit edilen problemleri*

Monumental Trees	Problems									
	Fungal infections	Sap exudation	Crown top collapse	Deep pruning	Branch dieback	Galls and swellings	Cavities and rots	Insufficient space for roots	Insufficient crown area	Soil compaction and hardening
1. *Platanus orientalis*	✓		✓	✓	✓	✓	✓	✓	✓	
2. *Platanus orientalis*		✓	✓	✓	✓	✓		✓	✓	
3. *Platanus occidentalis*	✓			✓	✓	✓	✓	✓	✓	✓
4. *Platanus occidentalis*	✓			✓	✓			✓	✓	✓
5. *Platanus orientalis*				✓	✓	✓	✓	✓		
6. *Platanus occidentalis*	✓		✓	✓	✓	✓	✓	✓	✓	✓
7. *Platanus orientalis*			✓	✓	✓	✓	✓	✓		
8. *Platanus orientalis*				✓	✓			✓		
9. *Platanus orientalis*				✓	✓			✓		
10. *Platanus orientalis*				✓	✓			✓		
11. *Platanus orientalis*	✓	✓	✓	✓	✓	✓	✓	✓	✓	
12. *Platanus orientalis*						✓				
13. *Platanus occidentalis*	✓			✓	✓	✓	✓	✓		✓
14. *Platanus occidentalis*				✓	✓	✓		✓	✓	✓
15. *Platanus occidentalis*	✓			✓	✓	✓		✓	✓	✓
16. *Platanus orientalis*				✓	✓			✓	✓	✓
17. *Platanus occidentalis*	✓			✓	✓		✓	✓	✓	✓
18. *Platanus orientalis*	✓		✓	✓	✓	✓	✓	✓		✓
19. *Platanus orientalis*			✓	✓	✓	✓	✓	✓		
20. *Platanus orientalis*				✓		✓		✓	✓	
TOTAL (number)	9	2	7	19	18	14	10	19	11	9

Deep pruning significantly compromises the aesthetic integrity of monumental trees, and also poses substantial risks to their health by inducing wound formation. As per TSE 13190 standard, monumental trees should only be subjected to intentional pruning when their physiological needs and location necessitate such interventions. Furthermore, our study revealed that two-thirds of the examined trees exhibited branch desiccation. In contrast, Martinez and Coelho-Duarte (2023) identified a 44% incidence of crown top collapse and branch dieback in a study involving a different species of plane tree in Argentina, a rate that was surpassed in our findings. Contributing factors to this phenomenon include insufficient root space, soil compaction, and hardening (45%). It is posited that these deficiencies are primary contributors to the myriad of issues observed in monumental trees. The sealing of the soft ground within the tree's crown projection—through concrete, asphalt, or impermeable soil compaction—disrupts the essential water and air circulation, leading to developmental disorders due to deficiencies in water and oxygen (Genç & Güner, 2003). The TSE 13190 standard explicitly prohibits activities that would result in soil compaction within the living area of monumental trees. When a tree is unable to obtain sufficient water, nutrients, and oxygen from its root zone, it experiences top collapse and branch desiccation. Attempts to rectify these issues through pruning only exacerbate the problem, resulting in a

gradual loss of the original dimensions of the tree, which constitutes its primary function. Although many monumental trees may not exhibit obvious signs of distress, it is believed that the most significant issues arise from these underlying deficiencies.

One of the identified issues is the prevalence of galls and swellings formed on the trunks, accounting for 70% of cases. This phenomenon primarily results from physical interventions related to human activities, improper pruning, and exposure to diseases and pests affecting the tree trunk. The allowance of harmful activities within the conservation space established under principle decision number 110, coupled with inadequate control measures for diseases and pests, facilitates the occurrence of such damage. It is imperative to safeguard the monumental trees within the Bursa Hanlar District from these interventions and to mitigate the formation of galls and swellings by adhering to maintenance protocols in accordance with TS 13190 standards, as stipulated by principle decisions number 110 and 666. However, it appears that insufficient care is being administered. The occurrence of galls and swellings observed in our study was similarly noted at a rate of 75% in research conducted by Martinez & Coelho-Duarte (2023) on a different plane tree species in Argentina. Furthermore, the cavities and rots observed in our study, at a rate of 50%, aligns closely with findings from Martinez & Coelho-Duarte (2023), which reported a rate of 63% in Mendoza, Argentina.

In our study, fungal infections were identified in 45% of the trees, while sap exudation was observed in 10%. Both conditions were determined to be associated with mechanical injuries sustained by the trees.

Our results indicate significant differences in tree height and trunk diameter between the current and expected dimensions of the monumental plane trees within the study area. It has been noted that monumental trees meeting or closely approaching the expected dimensions are subjected to only 2-3 of the identified issues. In contrast, those trees that fall significantly short of the expected dimensions experience the majority of the identified problems. This observation underscores the extent to which the challenges faced by monumental trees impact their growth dimensions.

As a consequence of the various issues identified in the monumental plane trees within the study area, it has become evident that their current status diverges from the anticipated condition. However, as articulated by Çevikçelik (2021), Bulut, (2024) and Sapan (2024), adherence to the preventive measures outlined in Principle Decision No. 666 of the Supreme Council for the Protection of Cultural and Natural Assets, which addresses the “Definition and Protection of Monumental Trees as Natural Assets that Must Be Protected” is crucial. Additionally, the implementation of specialized maintenance protocols for monumental trees in accordance with TS 13190 "Monumental Trees - Protection and Maintenance Rules," as mandated by law, is essential to mitigate many of the challenges currently faced.

To ensure the sustainable transfer of monumental trees inherited from the past to future generations, it is compulsory that these trees are maintained diligently and regularly by specialized teams. This maintenance is essential for preserving their dimensions, which confer their status as monumental trees (Çevikçelik, 2021; Sapan, 2024).

The rules for the protection and maintenance of monumental trees are outlined in the TS 13190 standard, titled “Monumental Trees – Protection and Maintenance Rules.” This standard delineates various maintenance protocols, including nutrient supplementation, wound care, cavity filling, soil aeration, safeguarding the soil within the root zone, procedures for addressing soil compaction in the root area, disease and pest prevention, and pruning techniques specific to monumental trees. Compliance with this standard, which mandates that all monumental trees in Türkiye be maintained by expert teams, is essential (TSE, 13190).

According to Çevikçelik (2021), the legal procedures surrounding trees with such characteristics aims to ensure that these living natural assets benefit from protective measures established within the legislation. The associated laws, regulations, and directives aim to provide adequate living conditions for monumental trees, establish specialized care requirements, and implement penalties for individuals who harm these trees.

RECOMMENDATIONS

Located within the UNESCO World Heritage-listed Bursa Hanlar District, the monumental plane trees, along with the site's structural and vegetative elements, constitute an integral component of cultural and natural heritage. The same level of attention devoted to the preservation and restoration of architectural structures should also be extended to these monumental trees. As living elements of our natural heritage, monumental plane trees derive their ecological and symbolic significance from being maintained within appropriate habitat dimensions. Representing both the identity of 'Green Bursa' and the legacy of the Ottoman Empire, these trees serve as key landmarks and attraction points for ecotourism.

Based on the findings of the study, the following practices are recommended for the conservation of monumental plane trees to ensure their continued vitality and preservation of their monumental characteristics;

• To address the insufficient spatial requirements for roots observed in 95% of trees, it is imperative to expand the soil area wherever feasible. Additionally, the region extending to the crown edge line (the protective zone of the monumental tree) should be safeguarded against construction activities, and the introduction of other plant species in this area should be avoided.

• Completely sealing the living space surrounding the trunk of the trees with impermeable materials poses a significant risk to the long-term vitality of the trees. For such cases, it is essential to maximize the available green space and ensure adequate ventilation for the roots.

• It is advisable to aerate and loosen the soil of monumental trees that are unable to draw necessary water and absorb necessary oxygen due to soil compaction.

• Any cavities and rots that develop on monumental trees should be addressed by specialized teams. Depending on the severity of the issue, the most suitable open or closed treatment method should be employed. Furthermore, measures should be implemented to prevent individuals from filling these cavities with waste thereby exacerbating the tree's condition.

• Pruning should only be conducted when there is a valid reason, and any proposed pruning should be discussed and justified beforehand.

• Wounds inflicted on trees due to pruning or other causes should be treated promptly and appropriately.

• It is recommended that authorized institutions and organizations establish dedicated units for the management of monumental trees, focusing on their pruning, maintenance, and protection, staffed by trained personnel overseen by subject matter experts.

• The maintenance and oversight of monumental trees should be conducted on a regular and ongoing basis.

• Initiatives should be undertaken to enhance public awareness regarding the significance and preservation of monumental trees, as well as to mitigate potential human-induced damage.

• "Article 65, Paragraph 1 of Law No. 2863 (1983) prescribes legal penalties for intentional acts that harm registered monumental trees, including demolition, degradation, destruction, and physical damage. Unauthorized construction or interventions within their protection zones are also subject to sanction.

Offenders may face imprisonment from two to five years and judicial fines of up to five thousand days. This provision is designed to act as a legal deterrent for the protection of natural heritage.

• The responsibility for maintaining and protecting monumental trees is assigned to Municipalities and Special Provincial Administrations. This is based on Article 7/1-o and 7/2-d of the Metropolitan Municipality Law No. 5216, Article 14/1-b of the Municipality Law No. 5393, and Article 526 of the Special Provincial Administration Law No. 5302. These duties are coordinated by the Ministry of Environment and Urbanization, as stated in Article 10 of Law No. 2863 on the Protection of Cultural and Natural Assets. Monumental trees located within conservation areas (defined by crown diameter projections) are legally recognized as cultural and natural assets. If these trees are not preserved in the appropriate form or health, the responsible institutions may be held liable under the principle of administrative service fault (Çevikçelik, 2021; Sapan, 2024).

Data Availability

Data is available upon reasonable request.

Author Contributions

Conception and design of the study: SÇÇ, KE; sample collection: SÇÇ; analysis and interpretation of data: SÇÇ, KE; statistical analysis: SÇÇ, KE; visualization: SÇÇ; writing manuscript: SÇÇ, KE.

Conflict of Interest

There is no conflict of interest among the authors in this study.

Ethics Statement

We declare that there is no need for an ethics committee for this research.

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Review
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Effects of pesticides on *Apis mellifera* L. (Hymenoptera: Apidae) and their residues in honey

Pestisitlerin *Apis mellifera* L. (Hymenoptera: Apidae) üzerindeki etkileri ve baldaki kalıntıları

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ABSTRACT

Objective: This review critically examines recent studies on the toxicological effects of pesticides in honey bee (*Apis mellifera* L. (Hymenoptera: Apidae)) and the subsequent residue levels in honey.

Material and Methods: The review synthesizes findings from various recent studies that investigate the acute and chronic toxicity of commonly used insecticides, acaricides, fungicides, and herbicides in honey bee behaviour, physiology, and colony health.

Results: The evidence suggests that even sub-lethal doses can impair foraging ability, navigation, and reproductive success, leading to long-term effects on colony stability.

Conclusion: Further research is required to elucidate the complex interactions between pesticides, bees, and environmental factors. Simultaneously, the development of more sustainable pest management strategies is vital to safeguarding pollinator health and preserving biodiversity.

Keywords: Acaricides, fungicides, herbicides, honey, honey bee, insecticides

ÖZ

Amaç: Bu derleme, bal arılarında (*Apis mellifera* L. (Hymenoptera: Apidae)) pestisitlerin toksikolojik etkilerine ve balda kalıntı düzeylerine ilişkin son çalışmaları eleştirel bir bakış açısıyla incelemektedir.

Materyal ve Yöntem: Bu derleme, yaygın olarak kullanılan insektisit, akarisit, fungisit ve herbisitlerin bal arılarının davranışları, fizyolojileri ve koloni sağlığı üzerindeki akut ve kronik toksisitelerini inceleyen çeşitli güncel çalışmalardan elde edilen bulguları sentezlemektedir.

Araştırma Bulguları: Elde edilen bulgular, ölümcül olmayan dozların dahi arıların yiyecek arama yetilerini, yön bulma becerilerini ve üreme başarılarını olumsuz etkileyebileceğini, bunun da koloni stabilitesi üzerinde uzun vadeli sonuçlara yol açabileceğini ortaya koymaktadır.

Sonuç: Pestisitler, arılar ve çevresel faktörler arasındaki karmaşık etkileşimlerin anlaşılabilmesi için daha fazla araştırma yapılması gereklidir. Aynı zamanda, tozlayıcıların sağlığını ve biyolojik çeşitliliğini korumaya yönelik daha sürdürülebilir zararlı kontrol yöntemlerinin geliştirilmesi oldukça hayatidir.

Anahtar sözcükler: Akarisit, fungisit, herbisit, bal, bal arısı, insektisit

INTRODUCTION

Pesticides, encompassing both chemical and biological forms, are vital tools in modern agricultural practices, primarily used to manage pests such as insects, weeds, fungi, and rodents (Kuşaksız & Çimer, 2019; Dede et al., 2022; Leite et al., 2022; Chaudhary et al., 2024; Jeschke 2024; Yaraşır et al., 2024a). Despite their significant role in enhancing agricultural output, the impact of these substances on non-target organisms has generated considerable concern (Du et al., 2022; Ádám et al., 2024; Kaur et al., 2024; Yaraşır et al., 2024b; Harbi et al., 2025). Of particular concern is the toxic effect of pesticides in honey bee populations, which has been linked to disruptions in their physiology, behavior, and overall colony health. Neonicotinoids, including imidacloprid and clothianidin, are key contributors to this issue, with evidence demonstrating their adverse effects on the behavior and physiological functions of the honey bee, *Apis mellifera* L. (Hymenoptera: Apidae). Prolonged exposure to these compounds leads not only to acute toxicity but also to sublethal effects, which compromise the bees' foraging efficiency, cognitive abilities, and immune system functioning (Colin et al., 2019; Cook 2019; Colin et al., 2020). Research suggests that the combined use of neonicotinoids with other substances, such as miticides, can intensify these negative outcomes, further impairing cognitive functions critical to colony survival (Williams et al., 2015; Chakrabarti et al., 2020; Colin et al., 2020).

The resulting oxidative stress can disrupt essential bee activities, ultimately influencing colony productivity and overall health (Pettis et al., 2013; Chakrabarti et al., 2014). Additionally, the organ responsible for metabolizing various compounds and maintaining physiological balance in honey bees may also be adversely affected by pesticide exposure, underscoring the broader impact these substances have on bees' foraging behavior, brood care, and hive maintenance (Cook, 2019; Das et al., 2024; Frizzera et al., 2024).

The consequences of pesticide exposure extend beyond individual bees, affecting complex interactions within the hive ecosystem. For example, neonicotinoid exposure has been linked to increased vulnerability to pathogens, such as *Nosema ceranae*, which can lead to higher incidence of disease (Pettis et al., 2012; Pettis et al., 2013).

This interaction between pesticide exposure and pathogen susceptibility creates a precarious health environment for honey bees, decreasing the resilience of colonies and contributing to elevated mortality rates (Naggar & Baer, 2019). Furthermore, pesticide residues can accumulate in hive products, including honey and beeswax, raising concerns not only for bee health but also for human safety (Mullin et al., 2010; Sánchez-Bayo & Goka, 2014; Lucas et al., 2022).

Examining the broader environmental context, research highlights a concerning correlation between intensive agricultural practices that heavily rely on pesticide use and the decline in bee populations, especially in highly cultivated regions (Mallinger et al., 2015; Heard et al., 2017). Pesticide residues in pollen and nectar can adversely affect larval development, leading to long-lasting toxic effects even after initial exposure has ceased (Chakrabarti et al., 2014; Sansar, 2021). Consequently, it is crucial to monitor pesticide levels in bee habitats to safeguard their health and well-being, which emphasizes the urgent need for regulatory frameworks to minimize harmful pesticide exposure (Mullin et al., 2010; McArt et al., 2017; Tosi et al., 2022). As pollinators are vital for both ecosystem stability and agricultural productivity, understanding and mitigating the risks posed by these chemicals is essential for the development of sustainable pest management strategies (Lucas et al., 2022; Bütüner et al., 2024; Dede et al., 2024; Harran et al., 2024; Li et al., 2024). This study aims to review recent findings on the toxic effects of pesticides on *A. mellifera* and the effects of their residues on the honey they produce, and to highlight the need for sustainable pest management practices.

Toxic Effects of Pesticides on Honey Bees

The toxicological impact of pesticides on bee populations, particularly honey bees, has garnered significant attention due to their essential role in pollination and global food production. Research surrounding pesticide toxicity reveals a complex array of effects, including not only direct lethality but also sublethal consequences that adversely affect bee health, behavior, and colony survival (Das et al., 2024; Margaoan et al., 2024; McGruddy et al., 2024; Rinkevich et al., 2025).

A central issue identified in this context is the dependence of beekeepers on toxic pesticides to manage pests, particularly, the parasitic mite *Varroa destructor* (Arachnida: Varroidae), a major threat to honey bee populations. According to McGruddy et al. (2024), many beekeepers express concerns about the toxicity of these necessary treatments, which, despite their efficacy in pest control, pose significant risks to the health of honey bees. Additionally, Sadia et al. (2024) underscore that improper pesticide use is a global threat to honey bee populations, exacerbating the ongoing decline of these crucial pollinators. This highlights the systemic challenge of balancing effective pest management with the preservation of bee health. Beyond lethality, the impact of pesticides includes various sublethal effects, particularly on cognitive functions such as learning and memory. In addition, Haran et al. (2024) explore the biochemical mechanisms through which pesticides disrupt vital energy metabolism in honey bees, particularly through the inhibition of succinate dehydrogenase. This metabolic disruption not only affects individual bees but can also have cascading consequences for the entire colony, potentially contributing to broader phenomena such as hive depopulation syndrome (HDS). Contributing factors such as climate change and habitat degradation further exacerbate the challenges faced by bee populations (Bava et al., 2024). The studies carried out by Morrison et al. (2025) showing declines in bee populations correlate strongly with increased pesticide exposure, with multispecies research indicating reduced reproduction and survival rates under sublethal pesticide conditions. The consequences for agriculture are significant, as the decline in pollinator populations poses a direct threat to crop yields and food security; with Das et al. (2024) linking reduced pollinator visitation rates to decreases in crop output. Furthermore, ongoing research has highlighted potential mitigation strategies, including the use of natural compounds to counteract pesticide toxicity. Recent studies suggest that certain polyphenolic compounds may offer protective effects against pesticide-induced toxicity in honey bees (Bava et al., 2024). This points to the urgent need to develop non-toxic pest management alternatives that safeguard both agricultural productivity and pollinator health.

In a similar study, Haran et al. (2024) explored the mechanisms by which pesticides inhibit respiratory enzymes in honey bees, suggesting that disruptions to mitochondrial function could exacerbate population declines and, in turn, influence honey stability and quality. These findings underscore the importance of reassessing pesticide regulations to minimize their toxic effects on bee health and, by extension, the quality of honey.

Toxic effects of insecticides and acaricides

Insecticides, particularly neonicotinoids and pyrethroids, as well as commonly used acaricides such as cyflumetofen, have been shown to exert both lethal and sublethal effects on *A. mellifera*. These include impaired foraging behaviour, reduced cognitive function, disrupted gene expression, and increased mortality. Sublethal exposures may alter detoxification enzyme activity, interfere with neurological pathways, and suppress immune responses. The combined or sequential use of insecticides and acaricides can also result in synergistic toxicity (Mullin et al., 2010; Lucas et al., 2022; Chen et al., 2024; Frizzera et al., 2024). For instance, Li et al. (2024) comparatively examined the toxic effects of chlorantraniliprole, one of the widely used diamide insecticides, on two honey bee species: *A. mellifera* and *Apis cerana* (Hymenoptera: Apidae). The findings revealed that *A. cerana* exhibited greater sensitivity to chlorantraniliprole (48-hour LC_{50} value: 109.709 mg/L) and that prolonged exposure to low

doses impaired both sucrose responsiveness and climbing activity in the species. Alterations in antioxidant enzyme activities and differences in the expression of immunity-related genes indicated significant biochemical and molecular adaptive responses between the species. Notably, *A. mellifera* showed suppression of immune-related and endoplasmic reticulum stress response genes at low chlorantraniliprole concentrations, whereas *A. cerana* exhibited more limited genetic changes. The study underscores the species-specific toxic effects of chlorantraniliprole in honey bees and highlights the necessity of accounting for such interspecies differences in pesticide risk assessments and safety regulations. Similarly, Chen et al. (2024) aimed to address the gap in the existing literature regarding mixed pesticide toxicity by investigating the toxic effects of pesticides in honey bees at both individual and combined levels. The study assessed the acute and chronic toxicities of abamectin and lambda-cyhalothrin under laboratory conditions. The results demonstrated that abamectin exhibited higher acute toxicity to honey bees compared to lambda-cyhalothrin; however, the mixture of abamectin and lambda-cyhalothrin produced an antagonistic effect at the acute level. Additionally, the combination was found to induce notable disruptions in the gut microbiota of honey bees, along with significant impairments in the expression of immunity-related genes and the activity of detoxification enzymes. Also, Frizzera et al. (2024) demonstrated that the seemingly benign individual effects of pesticides may lead to severe outcomes when considered in conjunction with other environmental stressors. In their study, the effects of sulfoxaflor in honey bees were tested within a multifactorial framework that included additional stress factors such as parasite presence, suboptimal temperatures, and nutritional scarcity. The results indicated that although field-realistic exposure to sulfoxaflor did not cause direct mortality, it led to significant changes in the expression of specific genes. These findings underscore that the sublethal effects of pesticides may not be detectable through conventional single-factor toxicological approaches, thereby highlighting the necessity of multifactorial evaluations in pesticide risk assessments.

The study by El Agrebi et al. (2024) developed a novel *in vivo* model to evaluate the effects of exposure to pesticides and beeswax additives on gene expression in honey bee larvae under realistic conditions. In their study, larvae were reared in beeswax contaminated with acrinathrin, chlorpyrifos-ethyl, and stearin, and the expression of genes related to immunity and detoxification was analyzed. The results showed that exposure to acrinathrin triggered an immune response and significantly upregulated the expression of the CYP6AS14 gene. In contrast, exposure to chlorpyrifos-ethyl led to the suppression of expression in most of the tested immune and detoxification genes. Stearin exposure, particularly at higher concentrations, resulted in increased larval mortality and marked alterations in both immune and detoxification responses. Similarly, Choi et al. (2024) investigated the acute and chronic exposure of honey bee larvae to lambda-cyhalothrin and spinetoram pesticides. Both pesticides adversely affected the development of honey bees and caused changes in enzyme activities. Lambda-cyhalothrin and spinetoram, increased the activities of detoxification and antioxidative enzymes, while also impacting neurotransmission enzymes. Similarly, Bixby et al. (2024) investigated the effects of neonicotinoid-type pesticides on *A. mellifera*. The study covered a field experiment conducted in 2020 and 2021 in blueberry fields in British Columbia. Honey bee colonies were placed in areas both near and far from highbush blueberry fields, and pesticide levels in these areas were determined. The study found that neonicotinoids, particularly clothianidin and thiamethoxam, caused toxic effects on bee colonies, with these pesticides exceeding international safety limits. Additionally, colonies exposed to these pesticides exhibited both lethal and sublethal effects, leading to losses in honey production and issues with colony health. However, the study by Kadala et al. (2024) emphasizes that current pesticide risk assessment systems do not adequately consider the effects of low doses on off-target species. The study on honey bees found that newly emerged bees were more sensitive to deltamethrin, a common pyrethroid insecticide, compared to 6-day-old bees. Lethal doses were observed at lower levels in D1 bees, with an LD_{50} value of 11 ng/bee. Moreover, even at non-lethal low doses (0.75, 1.5, and 3 ng/bee), significant reductions in mobility and increased periods of immobility were detected in D1 bees. At the cellular level,

it was demonstrated through patch-clamp experiments that deltamethrin slowed the kinetics of voltage-gated sodium channels (NaV). Similar effects were observed with two other pyrethroids, such as cypermethrin. The study suggests that combining behavioural tests with cellular toxicity measurements could contribute to more accurate assessments of the toxic effects of pesticides.

Another study carried out by Pham et al. (2025) highlighted the economic importance of beekeeping in Vietnam and the threat posed by pesticide use to this sector, investigating the pesticide toxicities in different honey bee species. The study evaluated the oral toxicities of five commonly used agricultural insecticides (bifenthrin, imidacloprid, thiacloprid, thiamethoxam, and chlorantraniliprole) on four honey bee species, the Asian honey bee, *A. cerana*, the European honey bee, *A. mellifera*, the giant honey bee, *Apis dorsata* (Hymenoptera: Apidae), and the red dwarf honey bee, *Apis florea* (Hymenoptera: Apidae). The findings revealed significant differences in toxicity among the pesticides and bee species. Among the managed species, *A. cerana* exhibited the highest tolerance to all insecticides, while the wild species *A. dorsata* and *A. florea* displayed greater sensitivity. The study emphasised that relying solely on *A. mellifera* in pesticide risk assessments is insufficient and that other honey bee species should also be incorporated into protection strategies.

On the other hand, the acute exposure of *A. mellifera* to cyflumetofen, a pesticide used on plants such as apples, coffee, and citrus, was investigated by Reis et al. (2024). The study revealed histopathological and cytological damage in the bees' stomach, hypopharyngeal glands, and fat tissue. The stomach epithelium exhibited cellular changes indicative of cell death and autophagy. While the hypopharyngeal glands produced more secretions, no changes were observed in the fat tissue. These findings suggest that cyflumetofen negatively affects honey bees, potentially impairing their survival and pollinator behaviour.

In the study conducted by Oliveira et al. (2024), the sensitivity of the honey bee *A. mellifera* to chronic exposure to teflubenzuron and the associated histopathological changes in the midgut tissue were evaluated. Worker bees were orally exposed to field-realistic concentrations of teflubenzuron, resulting in a mortality rate of 81.54%. Severe structural alterations were observed in the midgut epithelium, including vacuolisation, cell lysis, apocrine secretion, nuclear pyknosis, loss of cellular integrity, and damage to the peritrophic matrix. These findings indicate that, despite Teflubenzuron being classified as safe for non-target insects, chronic exposure may exert significant toxic effects in honey bees. Also, in the study conducted by Rükün et al. (2025), the effects of sublethal doses of imidacloprid exposure on honey bees, *A. mellifera*, on colour memory and visual preferences were investigated. In the study, free-flying worker bees were trained to visit a yellow artificial flower feeder and then released into an area with flowers of different colours. Bees exposed to imidacloprid doses greater than 4% of the LD_{50} value were observed to lose their preferential visits to yellow flowers, likely reverting to basic feeding preferences. Despite the expectation that colour discrimination would be easy, it was found that the bees had lost this ability. Additionally, pesticide exposure led to an increase in the expression of the genes Lop1, UVop, and Blop, while the expression of the CaMKII and CREB genes decreased. The study suggests that memory loss may be the underlying mechanism for the altered colour preferences in bees. In this regard, the study highlights that pesticides may also cause disruptions in the nervous system of bees, leading to cognitive memory impairments.

Toxic effects of fungicides

Although traditionally considered less harmful to pollinators, fungicides have been increasingly recognised, for their sublethal toxicity in honey bees. Certain compounds, such as chlorothalonil and propiconazole, can disrupt detoxification pathways, suppress immune-related gene expression, and alter gut microbiota composition. Moreover, fungicides may synergize with insecticides, amplifying their toxic effects. These findings suggest that fungicides, especially when encountered in mixtures, can compromise

bee health and should be more thoroughly assessed in pollinator risk evaluations (Mullin et al., 2010; Schuhmann et al., 2022; Drummond et al., 2024). In this context, the study carried out by Rienkevich et al. (2025) investigated the diversity of pesticides encountered by honey bees in their foraging areas and colonies, as well as the potential effects of the fungicide chlorothalonil in particular. The research evaluated the impact of chlorothalonil on its direct toxicity on honey bees, its synergistic effects with insecticides, its influence on detoxification enzyme activity, and the expression of specific genes (esterase and cytochrome P450). The findings revealed that there was no significant increase in mortality among bees exposed to either a 10 µg topical dose or a 5 ppm oral dose under laboratory conditions. Moreover, the synergistic or antagonistic interactions between chlorothalonil and other pesticides were found to be minimal (less than a twofold effect). No notable changes were observed in detoxification enzyme activity or gene expression. These results suggest that chlorothalonil may contribute to colony losses not through direct toxicity or synergism, but potentially via other physiological mechanisms. Similarly, Liu et al. (2025) emphasised that current pesticide risk assessments do not reflect real field conditions, given that pollinator insects are frequently exposed to pesticide mixtures in agricultural ecosystems. In this context, the combined toxic effects of the mesoionic insecticide triflumezopyrim and the triazole fungicide triadimenfon, which are commonly found together in the environment, were investigated in honey bees. The study demonstrated that the co-application of triflumezopyrim and triadimenfon induced acute synergistic toxicity in *A. mellifera*. Furthermore, significant changes were observed in biochemical parameters related to oxidative stress (MDA), neural function (AChE), detoxification pathways (GST), digestion (trypsin), and immunity, as well as in the expression of genes (abaecin, CRBXase, CYP6AS14, and CYP306A1). Additionally, both pesticides were found to alter the molecular conformations of catalase (CAT) and acetylcholinesterase (AChE), thereby affecting the activities of these enzymes. The results indicated that the combined presence of triflumezopyrim and triadimenfon could exacerbate physiological damage in *A. mellifera*, providing valuable insights into the ecotoxicological effects of pesticide mixtures.

The interaction between pesticides and other environmental factors has also been the focus of extensive research. For instance, Wang et al. (2025) studied the combined effects of microplastics and difenoconazole in honey bees, reporting an enhanced oxidative stress response. This suggests that the cumulative effects of multiple stressors contribute significantly to the deterioration of bee health and honey production. Similarly, research by Drummond et al. (2024) emphasized the necessity of contextualizing pesticide risks within the broader agricultural context, revealing that off-farm sources of pesticide exposure contribute substantially to the overall pesticide load experienced by honey bee populations.

Toxic effects of herbicides

Herbicides are primarily aimed at plant targets; their residues have been detected in honey, raising concerns about environmental contamination and food safety. Glyphosate, one of the most widely used herbicides, has frequently been found in honey samples worldwide. These residues typically result from foraging activity in treated landscapes and may reflect broader ecological exposure. While concentrations are often below legal limits, the chronic presence of herbicides in hive products highlights the need for expanded monitoring and inclusion of herbicides in pollinator-focused risk assessments (Cullen et al., 2019; Belsky & Joshi, 2020; Mohamed et al., 2023; Battisti et al., 2024; Ilić et al., 2024; Pawar et al., 2024; Xue et al., 2024). For instance, research by Kaakinen et al. (2024) demonstrated that glyphosate and glyphosate-based herbicides impair cognitive functions in honey bees, with effects that are likely to extend to bumblebees, as well. Furthermore, the accumulation of pesticides in both urban and agricultural environments presents additional risks, as evidenced by Ilić et al. (2024), who employed advanced biomonitoring techniques to trace pesticide exposure to agricultural sources. These findings highlight the pressing need for more rigorous monitoring of pesticide application near bee habitats. Similarly, Vommaro & Giglio (2024) investigate the cytotoxic and genotoxic effects of a pendimethalin-based herbicide, widely

used in agricultural fields, on *A. mellifera* worker bees. In laboratory experiments, the bees were exposed to a single dose of the herbicide, and morphological changes in the digestive system, Malpighian tubules, and circulating hemocytes were analyzed. The results demonstrated that the herbicide induced significant damage to the cellular structures of the bees, including nuclear anomalies. These findings underscore the potential risks posed by herbicides to pollinators. In this regard, the use of herbicides in agricultural areas should be subject to specific regulations, and adjustments should be made regarding their application due to the toxic effects they have on non-target organisms.

Toxic Effects of Pesticides Residues in Honey

Pesticide residues in honey are a significant concern for both food safety and environmental health. Various pesticides, including insecticides, acaricides, fungicides and herbicides, can accumulate in honey due to contamination from treated crops or direct exposure during foraging. Residue levels depend on factors such as pesticide type, application timing, and environmental conditions (Irungu et al., 2016; Scripcă & Amariei, 2021; Jaramillo-Zárate & Londoño-Giraldo, 2023). While many of these residues remain below toxic thresholds, long-term exposure could pose risks to human health and bee populations. Monitoring and regulating pesticide residues in honey are essential for ensuring both consumer safety and pollinator health (Irungu et al., 2016; Darko et al., 2017; Hrynko et al., 2018; Jaramillo-Zárate & Londoño-Giraldo, 2023). In light of these findings, ongoing research advocates for the adoption of integrated pest management strategies that balance agricultural productivity with bee welfare. Recommendations include the use of less harmful alternatives and the implementation of stricter regulatory frameworks for pesticide use (Haran et al., 2024; Bartlett et al., 2024). As highlighted by Sadia et al. (2024), addressing the conflict between pesticide usage and its implications for food security is urgent, as reducing pesticide exposure could promote sustainable apiculture practices and enhance the quality of bee-derived products.

Furthermore, Stevanović et al. (2024) reported a concerning prevalence of pesticide residues in honey, with over 35% of samples from Western honey bee colonies containing detectable levels of harmful chemicals. This contamination poses significant implications, as pesticide residues not only degrade the taste and nutritional value of honey but also introduce potential health risks for consumers, from increased exposure to environmental contaminants (Fasasi et al., 2024). Silva et al. (2024) further corroborated these findings, revealing that a substantial proportion of honey samples in Brazil contained pesticide residues, raising concerns about public health if regulatory measures remain insufficient.

Research has highlighted the intricate relationship between pesticide toxicity and honey bee behavior. In a study conducted by Stevanović et al. (2024), pesticide residues were analysed in honey samples of various botanical origins, and the potential risks of these residues to public health were assessed. The findings revealed that none of the analyzed pesticides were detected in pine honey samples, whereas residues of pesticides such as chlorpyrifos, clothianidin, dimethoate, and thiamethoxam were identified at varying levels in other types of honey. However, hazard quotient (HQ) calculations indicated that the levels of detected residues remained within the acceptable limits for human health. Pine honey was identified as the safest type due to the absence of pesticide residues, which is attributed to the lack of direct pesticide application in forested areas. Nevertheless, other honey types also posed no significant risk to consumer health owing to their low levels of pesticide contamination. The study further emphasised both the toxic effects of pesticide use in agricultural production on bees and the resulting residue levels in honey products. In this regard, the research highlights that pesticide contamination may not only affect bees directly but can also be present in honey. Cappellari et al. (2024) investigated the influence of landscape structure and seasonality on the levels of pesticide contamination in pollen collected by honey bees. The research was carried out across 13 locations in northern Italy with varying land-use characteristics, where approximately 400 pesticide compounds were analysed, and this analysis resulted in the detection of 97 distinct substances. The findings revealed that nearly all pollen

samples contained at least one pesticide residue, with insecticides and acaricides identified as particularly toxic. Assessments using the Pollen Hazard Quotient (PHQ) indicated that 15% of the samples reached moderate-to-high or high toxicity levels, posing potentially serious threats to bee health. Moreover, PHQ values were found to increase with the proportion of agricultural and urban land cover, with this effect being especially pronounced at the beginning of the season. The study highlights the significant risks of pesticide exposure via pollen, shaped by the complex interactions between pesticide categories, seasonal variation, and landscape composition.

Villalba et al. (2024) reported that chlorpyrifos and banned pollutants were detected in honey, beeswax, and pollen samples from honey bees in Argentina. Chlorpyrifos was found at higher levels, especially in spring, and dangerous concentrations were observed in beeswax. Beeswax was the most contaminated matrix with organochlorine pesticides. The study emphasizes that the distribution of pesticides aligns with environmental factors and highlights the need for sustainable monitoring.

CONCLUSION

Toxicological effects on *A. mellifera* pose a multifaceted challenge at the intersection of ecological health and modern agricultural practices. Pesticide exposure, particularly from neonicotinoids, pyrethrins, and fungicides, can have both lethal and sublethal effects on bees, affecting foraging behavior, cognitive function, and overall colony health. These effects can extend beyond individual bees, potentially leading to colony collapse, disrupting pollination services that are vital for crop production and maintaining biodiversity.

Furthermore, the accumulation of pesticide residues in honey is a significant concern because honey serves both as a food source for humans and as a medium for understanding pesticide exposure in bee populations. It has been determined that various pesticide residues, including insecticides, fungicides, and herbicides, can be transferred to bees during foraging and ultimately to honey. Monitoring pesticide levels in honey is therefore critical not only for food safety, but also to assess the broader ecological consequences of pesticide use on bee health and the sustainability of pollination services. Recent studies have shown that it is vital to develop evidence-based strategies to reduce these risks, including promoting integrated pest management (IPM) practices and establishing regulatory standards to limit pesticide residues in both the environment and hive products. These efforts are important to ensure the sustainability of honey bee populations and the protection of the essential ecosystem services they provide, which are crucial for agricultural productivity and ecological balance.

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Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: AKB, İAS; analysis and interpretation of data: AKB, İAS; writing manuscript: AKB; writing-editing manuscript: AKB, İAS.

Conflict of Interest

There is no conflict of interest, between the authors in this study.

Ethical Statement

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