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Original Article

Responses of Some Wild Eggplant and Tomato Species to Salt Stress

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ABSTRACT

This study was conducted between 2020 and 2022 to determine the responses of wild genotypes of *Solanum chmielewskii* (Soch), *Solanum neorickii* (Sone), *Solanum pimpinellifolium* (Sopi), *Solanum linnaeanum* (Sola), and *Solanum scabrum* (Sosca), which are considered to have potential for various uses in agricultural production, under salt stress. In the experiment, the genotypes were grown under standard cultivation practices until reaching the five-leaf stage, after which three different salt stress treatments (0 mM, 50 mM, and 100 mM NaCl) were applied. Following the treatments, plant growth status, antioxidative enzyme activities (SOD, CAT and POX), and leaf nutrient contents were evaluated. The findings revealed statistically significant differences ($P < 0.01$) among genotypes and salt stress treatments. Notable increases were observed in enzyme activities, while leaf mineral analyses indicated that Na levels were lower than expected in some genotypes, whereas K levels were higher. These results demonstrate that the examined wild *Solanum* genotypes exhibit distinct physiological and biochemical responses under salt stress and that they possess potential for utilization particularly in regions where salinity problems are prevalent. Based on the findings, the Sopi, Sone, and Soch genotypes were identified as tolerant, while the Soli genotype was determined to be sensitive.

Key words: Wild solanaceae, salt stress, salt tolerance, SOD, CAT

Bazı Yabani Patlıcan ve Domates Türlerinin Tuz Stresine Tepkileri

ÖZ

Bu çalışma, 2020-2022 yılları arasında yürütülmüş ve Solanum chmielewskii (Soch), Solanum neorickii (Sone), Solanum pimpinellifolium (Sopi), Solanum linnaeanum (Soli) ve Solanum scabrum (Sosca) türlerine ait, tarımsal üretimde çeşitli amaçlarla kullanılma potansiyeline sahip olduğu düşünülen yabani genotiplerin tuz stresine verdikleri tepkilerin belirlenmesi amacıyla gerçekleştirilmiştir. Denemede genotipler beş yapraklı oluncaya kadar standart yetiştirme koşullarında kültürel bakım uygulamalarına tabi tutulmuş, ardından 0 mM, 50 mM ve 100 mM NaCl konsantrasyonları ile üç farklı uygulama gerçekleştirilmiştir. Tuz uygulamaları sonrasında genotiplerde bitki gelişim durumu, antioksidatif enzim aktiviteleri (SOD, CAT ve POX) ve yaprak besin elementi içerikleri incelenmiştir. Bulgular, genotipler arasında ve tuz stresi uygulamaları sonucunda istatistiksel açıdan %1 düzeyinde önemli farklılıkların bulunduğunu ortaya koymuştur. Enzim aktivitelerinde belirgin artışlar gözlenmiş, yaprak mineral içeriklerinde ise bazı genotiplerde Na düzeylerinin beklenenden düşük, K içeriklerinin ise daha yüksek olduğu belirlenmiştir. Bu sonuçlar, incelenen yabani Solanum genotiplerinin tuz stresine karşı farklı fizyolojik ve biyokimyasal tepkiler ortaya koyduklarını göstermekte ve bu genotiplerin özellikle tuzluluk sorununun yoğun olduğu bölgelerde kullanım potansiyeline sahip olduklarını ortaya çıkarmaktadır. Bu veriler ışığında ise Sopi, Sone ve Soch genotiplerin toleranslı, Soli genotipinin ise hassas olduğu belirlenmiştir.

Anahtar kelimeler: Yabani solanaceae, tuz stresi, tuz toleransı, SOD, CAT

INTRODUCTION

The growth and development disorder caused by conditions that may adversely affect the optimum growth and development of the plant, which can also call extreme environmental conditions, is called tension or stress. Stress is terminologically divided into two main parts: biotic (living factors) and abiotic (non-living factors) (Mandre, 2002). Salinity (20%) is one of the most important abiotic stress factors after drought (26%) in terms of agricultural production in the world (Blum, 1986., Ekmekçi, 2005). Stress can be caused by salt-containing rocks, mistakes in agricultural irrigation practices and poor drainage in arid and semi-arid climates. Salts accumulated in the soil solution cause adverse effects on the chemical and physical properties of the soil, adversely affect plant growth, and cause significant yield loss in agricultural production (Alam, et al., 2015). The yield losses encountered in crop production are related to the salt content in the soil solution as well as the resistance of plants to salt stress. Salt tolerant plants are defined as plants that have the ability to maintain their growth and development under salt stress conditions (Yıldız, 2010). It is reported that expected yield decreases by 50% with salt stress and more than 50% of agricultural lands are under the threat of salinization (Al-Qwasemeh, 2013).

The physiological defense mechanisms developed by plants at the cellular level to counteract stress exhibit a highly intricate biochemical structure. Research has revealed that plant responses to salt and drought stress differ significantly among species (Terletskaya et al., 2017). It is of great importance to breed plants tolerant to stress factors in order to ensure sustainable food supply in the face of changing global climate factors. This will be possible by understanding the tolerance mechanisms developed by plants (Yıldız et al. 2010).

Salt stress starts with the disruption of cellular activities as a result of irregularities in ion concentrations and osmatic pressure balance in plants (Parida and Das, 2005). With the increase in the amount of Na in the root zone, osmatic pressure increases and osmotic stress occurs. The resulting osmotic pressure imbalance causes a decrease in the amount of water available to plants and this event is defined as “physiological drought” (Tuteja, 2007). In the aftermath of osmotic stress, nutrient deficiency or nutrient imbalance occurs in plants due to the toxic effect of increased Na and Cl ions and competition with essential nutrients such as K^+ , Ca^{+2} and NO^{-3} (Hu and Schmidhalter, 2005). In plants, stress causes overactivation and disruption of electron transport chains in intracellular chloroplasts and mitochondria. Under these conditions, 'Active Oxygen Species (AOS)', which are considered as potentially harmful substances for cell integrity in plants, cause the formation of singlet oxygen (O_2), hydroxyl radical (OH^-), superoxide radical (O^{-2}) and hydrogen peroxide (H_2O_2) (Groß, Durner and Gaupels, 2013). They form enzymes such as superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase (CAT), glutathione reductase (GR), peroxidase (POD), monodehydroxyascorbate reductase (MDAR), dehydroxyascorbate reductase (DHAR) and glutathione peroxidase (GPX) which are enzymatic defense systems against AOS in plants (Mittler et al., 2004).

Plants living in the natural environment have developed some physiological and biochemical defense mechanisms against this stress. These defense mechanisms are; i) Ion homeostasis and partitioning of ion uptake, ii) Synthesis of osmoprotectants and compatible solutes, iii) Synthesis of antioxidant compounds by activation of antioxidant enzymes, iv) Enhancement of polyamine synthesisi, v) Enhancement of nitric oxide production, vi) diversification of hormone production. Although it is logical to look for these characteristics in plants obtained through variety breeding studies, it would be more logical to look for the solution against stress in wild *Solanum* species (Gupta and Huang, 2014; Pailles et al. 2020).

Genotypes of some wild *Solanum* species have been reported to be adapted to saline soils. Wild plants living in the natural environment are directly exposed to salinity and lime stress. Salinity stress occurs because a result of high osmotic pressure due to salts dissolved in the root zone and the plant cannot take ions and enters ion stress. This osmotic pressure difference in the root rhizosphere negatively affects plant growth (Taiz and Zeiger, 2010).

During the vegetative stage, factors such as restrictions in cell expansion caused by salt stress, low soil water potential, nutrient imbalances, and ion toxicity negatively affect shoot and root growth. For instance, at an early vegetative stage (3–4 leaf stage), a 60% reduction in stem elongation rate was observed under saline conditions in *Solanum lycopersicum* cultivars ‘Heinz 1350’ and ‘VF234’. In contrast, wild tomato relatives grown under the same conditions exhibited more limited reductions in stem elongation rates. For example, a 55% reduction was recorded in *S. pennellii* accession Atico, while *S. cheesmaniae* ecotype no. 1400 showed a reduction of only 32% (Tal & Shannon, 1983). These findings demonstrate that wild tomato relatives experience less growth loss under salt stress compared to cultivated varieties. This highlights the potential significance of transferring salt-tolerant genetic traits from wild species to cultivated tomatoes.

A typical characteristic of wild tomato relatives with high salt tolerance is their ability to outperform cultivated tomato varieties under high salt stress conditions, despite exhibiting lower growth under non-saline conditions (Albaladejo et al., 2017). For instance, during the 3–4 leaf stage, under salt stress at a concentration

of 100 mM NaCl (~10 dS m^{-1}) over the first seven days, *Solanum lycopersicum* cv. 'Moneymaker' exhibited higher shoot biomass and growth rate than *S. pennellii* accession PE-47. However, after seven days, *S. pennellii* accession PE-47 outperformed the commercial cultivar. This finding indicates that wild species with high salt tolerance demonstrate superior growth and development compared to cultivated varieties when exposed to prolonged salt stress. The adaptive traits of wild relatives serve as a valuable resource for the development of salt-tolerant cultivated tomato varieties.

Wild tomato species as an invaluable resource for breeding programs aimed at enhancing salt tolerance in cultivated tomatoes. In a hydroponic system, *S. galapagense* and S. cheesmaniae populations were compared with two cultivated tomato varieties (Heinz 1706 and Moneymaker) under saline conditions (200 mM NaCl, ~20 dS m^{-1}) was significantly lower in all wild relative populations compared to cultivated tomato varieties (Pailles et al., 2020).

This study was conducted between 2020 and 2022 in the greenhouses of the Department of Horticulture at Kahramanmaraş Sütçü İmam University. The aim of the study was to evaluate wild *Solanum* species under saline soil conditions, which represent one of the major stress factors in agricultural production, in terms of their diverse morphological and enzymatic characteristics. Through this evaluation, the responses of these species to salinity were revealed, and their potential as genetic resources for various applications in future agricultural production was investigated.

MATERIALS AND METHODS

2.1. Material

The material of the study consisted of wild eggplant from AVRDC (The World Vegetable Center) and wild tomato species from USDA-TGRC (U.S. Department of Agriculture - Tomato Genetics Resource Center). The species were denoted as *Solanum chmielewskii* LA2663 (Soch), *Solanum neorickii* LA1326 (Sone), *Solanum pimpinellifolium* LA0722 (Sopi), *Solanum linnaeanum* VI05421 (Soli), *Solanum scabrum* VI05421 (Soch). The genotypes were selfed in the greenhouse, and the experiment was established once a sufficient number of seeds had been obtained.

2.2.Method

2.2.1 Salt stress Treatments

In order to set up the trial, the seeds were sown in seed tray containing peat-perlite mixture at a ratio of 2:1, and they were watered by deionized water until they had 4-5 true leaves. Salt treatment were began with 0 mM NaCl (control), 50 mM NaCl and 100 mM $NaCl_2$. The plants were given 30 ml of saline water every two days.

2.2.2 Plant Measurements

The experiments were established in a randomized block design with three replications. Each replication consisted of 10 plants, and measurements were performed on three plants per replication. The plants were harvested on the 17^{th} day and measurements were made. Weighing and measurement procedures were carried out at the end of the experiment.

2.2.3 Stem, Root Weights and Height Measurements

Fresh weights were determined in g by weighing 3 plants randomly selected from each replicate on a 1/10000 precision balance, and dry weights were determined in g after drying in an oven at 65°C for 48 hours. Lengths were measured in mm. with a millimeter ruler and digital caliper.

2.2.4 Element Analysis

Three leaves of each genotype, control and salt treated, were taken from each genotype and brought to the laboratory in clean paper bags and each leaf was rinsed first with tap water, then with 0.1 N HCl solution and then with pure water twice and dried with blotting papers. The leaf samples were dried again in the paper bag in an oven at 80 ^{0}C until their weight stabilized. After the leaves were ground and homogenized, they were weighed 0.5 gr and placed in teflon tubes, 8 ml of HNO_3 (65%) and 2 ml of H_2O_2 (30%) were added and burned in a microwave incineration system (CEM MARS 6). Afterwards, the content transferred to falcon tubes was filled to 50 ml with pure water and readings were taken with ICP-OES device (Varol et al, 2018).

2.2.5 Enzyme Analysis

In order to determine the enzyme activities of the plants, superoxide dismutase (SOD) enzyme activity (Köklü Ardıç, 2022), catalase (CAT) and peroxidase (POX) activities were performed in accordance with (Korkmaz,

et al., 2022). For this purpose, salt application was continued for 15 days and then samples were taken for analysis. Analyses were not performed on the same day and the samples were stored in the freezer at - 80 °C.

2.2.6 Determination of superoxide dismutase (SOD) activity

The methods of (Köklü Ardıç, 2022) were used to determine SOD enzyme activity. The samples were crushed in a cold mortar on ice. Weighed 0.25 gr of leaf samples were crushed by adding 3 ml of chilled 0.1 M phosphate buffer (pH: 7.5) containing 10 mM KCl, 2.5 mM DTT, 1 mM EDTA, 1.25 mM PEG 4000 and 1 mM PMSF (dissolved in ethanol). The samples were centrifuged at 4 ℃, 15000 g for 20 min. After centrifugation, the supernatant was passed through 2 layers of Miracloth and 1 layer of filter paper. Pure protein was extracted from the samples by a special filtration process with a PD10 column. The samples were stored at -20℃ until the enzyme readout was completed and protein amounts were determined according to the method of Bradford (1976). For the determination of SOD enzyme activity, all treatments were prepared in 2 sets as dark and light and at least 2 replicate readings were performed in each replicate. For this purpose, 1.15 mL 0.1 M phosphate buffer (pH: 8.0), 500 µL 24 mM riboflavin, 500 µL 150 mM methionine, 250 µL 1.2 mM EDTA, 840 µM 500 µL NBT and 100 µL sample were added to 15 mL capped glass test tubes. The resulting light set was placed under white fluorescent light (4, 23W energy-saving (cold) OSRAM lamps (4x 1500 lumens)). For the dark set, it was placed in an environment with no light at 25℃. The application time for both sets was set as 1 hour and the samples were read at 560 nm in a spectrophotometer. In the calculation of SOD enzyme activity, the activity that inhibits the reduction of NBT by 50% in light was used as enzyme activity in units [U].

2.2.7 Determination of catalase (CAT) activity

For the determination of CAT protein, 0.25 gr of fresh leaf samples (from each replicate of each genotype) were crushed on ice with 3 ml of 50 mM cold phosphate buffer solution (pH: 7.8) containing 1 mM Na-EDTA and 2% PVPP (w/v) in cold porcelain mortars. The samples were centrifuged at 13000 g at 4 ℃ for 10 min and stored in deep freezer (-20 ℃) until analysis. The method described in Bradford (1976) was used for total protein determination. According to Bergmeyer (1970), readings were made by determining the decrease in the amount of H_2O_2 at maximum absorption at 240 nm wavelength in spectrophotometer. For this purpose, 0.1 mM EDTA was added to 50 mM sodium phosphate buffer solution (pH: 7.0) to obtain the reaction medium. Then, 920 µL of reaction liquid, 10 µL of 3% H_2O_2 (total 1 ml) and 70 µL of sample were added to the spectrophotometer cuvette and the enzyme activity was calculated by recording the absorbance change (increase) in every five seconds at 240 nm for 70 seconds. In the blind sample, pure water was used instead of the sample.

2.2.8 Determination of peroxidase (POX) activity

The mashing method was used to obtain catalase protein. Total protein content was determined according to Bradford (1976). The first solution was obtained by adding 0.1 mM 3,3'-diaminobenzedine tetrahydrochloridehydrate (DAB) to 2% gelatin and the second solution was obtained by adding 0.08 M sodium phosphate (NA-P) buffer (pH: 7.0) to 0.05 M citric acid according to the method described in (Dolatabadian et al. 2008) by monitoring the oxidation of guaiacol by H_2O_2. The guaiacol solution obtained by mixing equal volumes of the two solutions was used as the reaction fluid in the analysis. For enzyme activity determination, 920 µL of reaction liquid, 15 µL of 30% H_2O_2 and 65 µL of sample were added to a 1 ml quartz enzyme cuvette and the absorbance change at 465 nM for 70 s was recorded every 5 s in a spectrophotometer set to kinetic measurement mode and the enzyme activity was calculated. In the blind sample, pure water was used instead of sample.

2.2.9 Data Evaluation

Analysis of variance was applied to the data at all stages of the study using JMP 16 statistical analysis package program. According to F test, ns value was determined as statistically insignificant, * value was determined as significant with 5% error probability ($P<0,05$), ** value was determined as significant with 1% error probability ($p<0,01$). In addition, LSD test was performed to reveal the differences between the averages ($p<0,05$).

In the evaluation of the data obtained in the study, the “Weighted rating” method (Akinci and Akinci, 2004) was modified and used. The method, which was first used by Michelson et al. (1958), is a method frequently used in the selection of gene sources and varieties. In this study, the traits used as the basis for weighted rating were root fresh weight, root dry weight, root height, plant height, stem fresh weight, stem dry weight, stem diameter, SOD enzyme, CAT enzyme, POX enzyme and Na, K ions content. For each trait used in the weighted rating, relative scores were given according to the degree of importance. Class values were obtained by dividing the maximum and minimum amounts of the data and the difference between them by the number of genotypes in the trial and subtracting the value obtained from the maximum value gradually. The sum of the weight scores

obtained by multiplying the relative scores by the class value of each trait was taken into consideration for selection.

Table 1. Weighted rating relative score class values

Feature	RS	Class Value	Score
Root Fresh Weight (RWW)	5	6.32<x	6
		6.32 ≥x>5.10	5
		5.10 ≥x>3.87	4
		3.87 ≥x>2.65	3
		2.65 ≥x>1.43	2
		1.43≥x	1
Root Dry Weight (RDW)	5	0.68<x	6
		0.68≥x>0.55	5
		0.55≥x>0.42	4
		0.42≥x>0.28	3
		0.28≥x>0.15	2
		0.15≥x	1
Stem Fresh Weight (SWW)	5	6.55<x	6
		6.55≥x>5.72	5
		5.72≥x>4.88	4
		4.88≥x>4.05	3
		4.05≥x>3.21	2
		3.21≥x	1
Stem Dry Weight (SDW)	5	1.13<x	6
		1.13≥x>0.97	5
		0.97≥x>0.82	4
		0.82≥x>0.67	3
		0.67≥x>0.52	2
		0.52≥x	1
Root Length (RL)	5	31.69<x	6
		31.69≥x>27.71	5
		27.71≥x>23.73	4
		23.73≥x>19.76	3
		19.76≥x>15.78	2
		15.78≥x	1
Leaf Fresh Weight (LWW)	5	63.29<x	6
		63.29≥x>53.69	5
		53.69≥x>44.09	4
		44.09≥x>34.49	3
		34.49≥x>24.89	2
		24.89≥x	1
Catalase (CAT)	15	0.92<x	6
		0.92 ≥x>0.84	5
		0.84 ≥x>0.76	4
		0.76 ≥x>0.68	3
		0.68 ≥x>0.59	2
		0.59 ≥ x	1
Peroxidase (POX)	10	0.85<x	6
		0.85 ≥x>0.69	5
		0.69 ≥x>0.52	4
		0.52 ≥ x>0.36	3
		0.36 ≥ x>0.20	2
		0.20≥x	1
Superoxide Dismutase (SOD)	10	23.42<x	6
		23.42≥x>22.60	5
		22.60≥x>21.79	4
		21.79≥x>20.97	3
		20.97≥x>20.15	2
		20.15≥x	1
Potasium (K)*	10	33.68<x	6
		33.68≥x>27.89	5
		27.89≥x>22.10	4
		22.10≥x>16.31	3
		16.31≥x>10.52	2
		10.52≥x	1
Sodium (Na)*	10	23.78<x	6
		23.78≥x>17.87	5
		17.87≥x>11.96	4
		11.96≥x>6.05	3
		6.05≥x>0.14	2
		0.14≥x	1
SPAD	5	41.35<x	6
		41.35≥x>36.71	5
		36.71≥x>32.07	4
		32.07≥x>27.43	3
		27.43≥x>22.79	2
		22.79≥x	1

* The values were simplified at a ratio of 1/1000. RS: Relative Score, CV: Class Value

RESULTS AND DISCUSSION

3.1 Plant Measurements

3.1.1 Root Fresh Weight

In the experiment in which the effect of salt stress on root wet weight of wild genotypes was examined, decreases were found at the average level with stress. Root wet weight was found to be insignificant in terms of treatment, while genotypes were found to be significant ($p<0,01$). In the index value, which we created by taking the control value as 1, only Sopi genotype provided the highest increase in medium salt level and the highest decrease was realized in Sopi high salt application.

Table 2. Effect of salt application on root fresh weight of genotypes (g)

Genotip	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	1.69 b	1.43 b	1.46 b	1.53 B	0.85	0.86
Sone	2.81 a	1.76 b	1.78 b	2.12 A	0.63	0.63
Sopi	2.94 a	3.14 a	1.48 b	2.52 A	1.07	0.50
Soli	2.88 a	1.72 b	1.87 b	2.16 A	0.60	0.65
Sosca	2.54 ab	2.02 ab	1.46 b	2.01 AB	0.79	0.57
Treatment Average	2.58a	2.01ab	1.65b		0.78	0.66
$LSD_{0.05}$	**Treatment: N.S**		**Genoytype: 0.42****		**Treatment x Genotype:2.10****	

3.1.2 Root Dry Weight

In the experiment in which the effect of salt stress on root dry weight of wild genotypes was examined, decreases were determined at the level of averages with increasing stress. Root dry weight was found to be significant (p<0,01) for treatment and genotype. According to the index value formed by taking the control value as 1, the lowest decrease was realized in Sopi genotype with a value of 1.00 in medium salt application, while the highest decrease was realized in Sosca with a value of 0.53, the lowest decrease was realized in Sone with a value of 0.78 and the highest decrease was realized in Sosca with a value of 0.50 in high salt application.

Table 3. Effect of salt application on root dry weight of genotypes (g)

Genotip	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	0.21cd	0.18d	0.15d	0.18c	0.86	0.71
Sone	0.27bc	0.18d	0.21cd	0.22c	0.67	0.78
Sopi	0.31b	0.31b	0.17d	0.26b	1.00	0.55
Soli	0.40a	0.30b	0.28b	0.33a	0.75	0.70
Sosca	0.41a	0.33b	0.21cd	0.32a	0.53	0.50
Treatment Average	0.30a	0.24b	0.20c		0.82	0.69
$LSD_{0.05}$	**Treatment: N.S**		**Genotype: 0.42****		**Treatment x Genotype:2.10****	

3.1.3 Root Length

In the experiment in which the effect of salt stress on root length of wild genotypes was examined, increases were found at the level of averages with stress. While treatment was found insignificant, genotype was found significant (p<0,01). In medium salt application, the highest increase was 1.28 in Sopi and a decrease was detected in Soli. In high salt application, the highest increase was realized in Soli with 1.67, while a decrease of 0.90 was recorded in Sone.

Table 4. Effect of salt application on root length of genotypes (cm)

Genotypes	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	18.56de	21.78b-e	19.17cde	19.84b	1.17	1.03
Sone	26.83a-d	26.44bcd	24.22b-e	25.83a	0.99	0.90
Sopi	27.89a-c	35.67a	28.67ab	30.74a	1.28	1.03
Soli	16.33e	15.78e	27.25a-d	19.79c	0.97	1.67
Sosca	23.78a	24.28cd	23.44bcd	23.83ab	1.02	0.99
Treatment Average	22.40a	24.92a	24.83a		1.10	1.16
$LSD_{0.05}$	**Treatment: N.S**		**Genotype: 5.27****		**Traetment x Genotype:N.S**	

3.1.4 Leaf Fresh Weight

In the experiment evaluating the effects of salt stress on the fresh weight of wild genotypes, mean values indicated a general reduction under stress conditions. Fresh weight was found to be significant at the p<0.05 level for the treatment factor and at the p<0.01 level for the genotype factor. Based on the index values calculated using the control as a baseline of 1, reductions were generally observed; however, genotypes Soch, Sone, and Sopi exhibited increases under moderate salt stress, while the greatest decrease was recorded in genotype Soli. Under high salt stress, Soch, Sone, and Sopi again showed increases above the control level, drawing attention for their positive response, whereas the greatest reduction was observed in genotype Soli.

Table 5. Effect of salt application on leaf fresh weight of genotypes(g)

Genotypes	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	2.38fg	2.69ef	2.94d-f	9.14b	1.13	1.24
Sone	2.25fg	3.39c-e	3.61b-d	7.32b	1.50	1.60
Sopi	1.82g	2.75ef	2.36fg	5.15c	1.51	1.30
Soli	3.62b-d	3.16de	1.7ef	26.06a	0.87	0.47
Sosca	4.15ab	3.94bc	4.76a	26.72a	0.95	1.15
Teratment Average	2,85b	3,19ab	3,28a		1.31	1.36
$LSD_{0.05}$	**Treatment: 0.34***		**Genotype: 0.44****		**Treatment x Genotype:0.76***	

3.1.5 SPAD Value

Analysis of the effects of salt stress on the SPAD values of wild genotypes revealed a distinct reduction in SPAD readings across the experimental means. The variation in SPAD content was statistically significant at the p <0.05 level for the treatment factor and at the p <0.01 level for genotype and genotype × treatment interaction. Using the control value as a baseline of 1 for index calculation, it was evident that all genotypes exhibited lower performance than their respective controls. Under moderate salt stress, genotype Sopi recorded the highest index value (0.91), approaching the control, whereas genotype Sone exhibited the lowest value (0.63). Under high salt stress, genotype Sosca showed the closest value to the control (0.96), while the lowest value was recorded for genotype Soch (0.64).

Table 6. Effect of salt application on SPAD Value of genotypes (cm)

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	66.22bc	58.56d	47.44e	57.41b	0.88	0.72
Sone	61.28cd	59.50d	49.28e	56.69b	0.97	0.80
Sopi	72.89a	72.17ab	57.00d	67.35a	0.99	0.78
Soli	27.89f	25.39f	24.89f	26.06c	0.91	0.89
Sosca	43.33def	46.83def	36.39de	42.18bc	1.08	0.84
Treatmet Average	57.07a	53.91a	44.65b		0.94	0.80
$LSD_{0.05}$	**Treatment: 8.09***		**Genotype: 3.71****		**Treatment x Genotype:6.43***	

3.1.6 Stem Fresh Weight

In the experiment in which the effect of salt stress on stem wet weight of wild genotypes was examined, an increase was found in medium salt application and a decrease was found in high salt application at the average level. While stem wet weight was found to be insignificant in terms of treatment, genotypes were found to be significant (p<0.05). In the index value, which we created by taking the control value as 1, Sone provided the highest increase in medium salt treatment with a value of 1.22 and Soli provided the highest decrease. In high salt application, the least increase was realized in genotype Sone with a value of 1.14 and the most decrease was realized in genotype Soli with a value of 0.64.

Table 7. Effect of salt application on stem fresh weight of genotypes (g)

Genotype	Treatments			Genotype Avarage	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	5.17a	5.07ab	4.67ab	4.97a	0.98	0.90
Sone	4.53ab	5.53a	5.16a	5.07a	1.22	1.14
Sopi	4.8ab	5.25a	3.87bc	4.64a	1.09	0.81
Soli	4.62ab	3.94bc	3.21c	3.92b	0.85	0.69
Sosca	5.23a	5.45a	5.19a	5.11a	1.05	0.94
Treatment Avarage	4.78a	4.95a	4.23a		1.04	0.89
$LSD_{0.05}$	**Treatment: N.S.**		**Genotype: 0.70***		**Treatment x Genotype:N.S.**	

3.1.7 Stem Dry Weight

In the experiment in which the effect of salt stress on stem dry weight of wild genotypes was examined, a decrease was found at the average level. Stem dry weight was found to be significant (p<0.05) in terms of treatments and genotypes. In the index value, which we created by taking the control value as 1, Sone provided

the highest increase with a value of 1.42 and Soli provided the highest decrease with a value of 0.73 in medium salt application. In high salt treatment, the highest increase was realized in Sone genotype with a value of 1.03 and the highest decrease was realized in Sosca genotype with a value of 0.65.

Table 8. Effect of salt application on stem dry weight of genotypes (g)

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	0.97ab	0.80bc	0.63cde	0.80ab	0.82	0.65
Sone	0.77bcd	0.80bc	0.66cde	0.74bc	1.04	1.03
Sopi	0.90b	0.86ab	0.58e	0.78ab	0.96	0.93
Soli	0.83bc	0.61de	0.52e	0.65cd	0.73	0.87
Sosca	1.18a	1.03a	0.84a	1.04a	0.80	0.65
Treatment Average	0.87a	0.77a	0.60b		0.89	0.87
$LSD_{0.05}$	**Treatment: 0.15***		**Genotype: 0.1***		**Treatment x Genotype:N.S.**	

3.1.8 Enzyme Analysis

3.1.8.1 CAT Enzyme Activities

In the experiment in which the effect of salt stress on the enzyme contents of wild genotypes was examined, an increase was found at the level of averages. CAT enzyme was found to be significant at ($p<0.01$) level in terms of treatments and genotypes. In the index value, which we created by taking the control value as 1, Soch provided the highest increase with a value of 1.69 in medium salt application, while Sosca provided the highest decrease with a value of 0.86. In high salt application, the highest increase was realized in genotype Soch with a value of 1.49, while the highest decrease was realized in genotype Sopi with a value of 0.80.

Table 9. Effect of salt application on CAT enzyme activity of genotypes

Genotype	Treatment			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	0.59e	1.00a	0.88abc	0.82b	1.69	1.49
Sone	0.76cd	1.00a	0.80bcd	0.85b	1.32	1.05
Sopi	0.82bc	0.88abc	0.66de	0.79b	1.07	0.80
Soli	0.91ab	0.94ab	0.98a	0.94a	1.03	1.08
Sosca	0.88ab	0.75e	0.75cd	0.79b	0.86	0.86
Treatment Average	0.77c	0.96a	0.83b		1.28	1.11
$LSD_{0.05}$	**Treatment: 0.05****		**Genotype: 0.08****		**Treatment X Genotype:0.15****	

3.1.8.2 POX Enzyme Activities

In the experiment in which the effect of salt stress on the enzyme contents of wild genotypes was examined, an increase was found at the level of averages. POX enzyme was found to be significant at ($p<0.01$) level in terms of treatments and genotypes. In the index value, which we created by taking the control value as 1, Sopi provided the highest increase with a value of 2.96 in medium salt application, while Sosca provided the lowest decrease with a value of 1.05. In high salt application, Soli genotype showed the highest increase with a value of 1.38 and Soch genotype showed the highest decrease with a value of 0.52.

Table 10. Effect of salt application on POX enzyme activity of genotypes

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	0.79b	1.01a	0.41f	0.74a	1.28	0.52
Sone	0.35g	0.68d	0.33g	0.45c	1.94	0.94
Sopi	0.27h	0.80b	0.20ı	0.42d	2.96	0.74
Soli	0.53e	0.68d	0.73c	0.65b	1.28	1.38
Sosca	0.37fg	0.39efg	0.39efg	0.39e	1.05	1.05
Treatment Average	0.49b	0.79a	0.42c		1.87	0.89
$LSD_{0.05}$	**Treatment: 0.05****		**Genotype: 0.02****		**Treatment X Genotype:0.04****	

3.1.8.3 SOD Enzyme Activities

In the experiment in which the effect of salt stress on the enzyme contents of wild genotypes was examined, an increase was found at the level of averages. SOD enzyme was found to be insignificant in terms of treatments and genotypes. In the index value, which we created by taking the control value as 1, Sone provided the highest increase with a value of 1.16 in medium salt application, while Soli provided the highest decrease with a value of 0.95. In high salt application, the highest increase was realized in genotype Sosca with a value of 1.11 and the highest decrease was realized in genotype Soli with a value of 0.98.

Table 11. Effect of salt application on SOD enzyme activity of genotypes

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	21.83ab	22.44ab	21.95ab	22.07a	1.03	1.01
Sone	20.91ab	24.24a	22.37ab	22.51a	1.16	1.07
Sopi	21.86ab	23.22ab	23.11ab	22.73a	1.06	1.06
Soli	21.24ab	20.15b	20.81ab	20.73a	0.95	0.98
Sosca	21.03ab	22.68ab	22.39ab	22.37a	1.08	1.11
Treatment Average	21.46a	22.51a	22.06a		1.05	1.03
$LSD_{0.05}$	**Treatment:N.S.**		**Genotype:N.S.**		**Treatment X Genotype:N.S.**	

3.1.9 Macro Element Analysis

3.1.9.1 Leaf Na Content

In the experiment in which the effect of salt stress on Na content of wild genotypes was examined, intense increases in Na content were detected at the average level. Na content was found to be significant at ($p<0.01$) and ($p<0.05$) levels in terms of treatments and genotypes. In the index value, which we created by taking the control value as 1, Soch provided the least increase with a value of 27.43 in medium salt application, while Soli provided the highest increase with a value of 105.29. In high salt treatment, Sopi genotype had the least increase with a value of 23.25 and Soli had the highest increase with a value of 172.42.

Table 12. Effect of salt application on Na content of genotypes (ppm)

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	0.19d	5.08cd	29.69a	11.65ab	27.43	160.50
Sone	0.34d	11.30bc	27.96a	13.20a	33.73	83.47
Sopi	0.48d	13.35b	11.11bc	8.31b	27.94	23.25
Soli	0.15d	15.52b	25.41a	13.69a	105.29	172.42
Sosca	0.14de	6.78cd	19.43ab	6.53cd	49.00	140.36
Treatment Average	0.29c	11.31b	23.54a		48.60	109.91
$LSD_{0.05}$	**Treatment:N.S**		**Genotype: N.S.**		**Treatment X Genotype:N.S.**	

3.1.9.2 Leaf K content

In the experiment in which the effect of salt stress on K content of wild genotypes was examined, increases in K content were determined at the average level. K content was found to be significant at ($p<0.05$) and ($p<0.01$) levels for treatments and genotypes. In the index value, which we created by taking the control value as 1, Soch provided the highest increase with a value of 1.60 in medium salt application, while Sosca provided the highest decrease with a value of 0.98. In high salt application, Sone genotype showed the highest increase with a value of 1.53 and Soli showed the highest decrease with a value of 0.95.

Table 13. Effect of salt application on K content of genotypes (ppm)

Genotype	Treatments			Genotype Average	İndex	
	Control	50 mM	100 mM		50 mM	100 mM
Soch	18.38f	29.47a	28.00ab	25.29a	1.60	1.52
Sone	18.21f	27.18cd	27.92bc	24.44b	1.49	1.53
Sopi	19.06f	25.45de	25.92de	23.48bc	1.34	1.36
Soli	22.21ef	21.93ef	21.06ef	21.73c	0.99	0.95
Sosca	20.85ef	20.52f-h	20.66fg	20.68d	0.98	0.99
Treatment Average	19.47b	28.76a	29.23a		1.28	1.27
$LSD_{0.05}$	**Treatment: 5.08***		**Genotype: 3.46****		**Treatment X Genotype:5.68****	

3.1.10 Table of İndex

In order to measure the relationship between the responses of the genotypes to salt stress treatments and the control, the values obtained under stress were divided by the control values (Table 13, 14).

Table 14. Medium Salt Treatment Index (50 mM)

Genotype	RWW	RDW	RL	LWW	SWW	SDW	Cat	Pox	Sod	Na	K	SPAD	Average.
Soch	0.85	0.86	1.17	1.13	0.98	0.82	1.69	1.28	1.03	1.00	1.60	0.69	1.09
Sone	0.63	0.67	0.99	1.41	1.22	1.04	1.32	1.94	1.16	1.00	1.49	0.62	1.12
Sopi	1.07	1.00	1.28	1.16	1.09	0.96	1.07	2.96	1.06	1.00	1.34	0.91	1.24
Soli	0.60	0.75	0.97	0.87	0.85	0.73	1.03	1.28	0.95	1.00	0.99	0.71	0.89
Sosca	0.79	0.53	1.02	0.95	1.05	0.80	0.86	1.05	1.08	1.00	0.98	0.84	0.91

Table 15. High Salt Application Index (100 mM)

Genotype	RWW	RDW	RL	LWW	SWW	SDW	Cat	Pox	Sod	Na	K	SPAD	Average.
Soch	0.86	0.71	1.03	1.23	0.90	0.65	1.49	0.52	1.01	1.00	1.52	0.64	0.96
Sone	0.63	0.78	0.90	1.51	1.14	1.03	1.05	0.94	1.07	1.00	1.53	0.67	1.02
Sopi	0.50	0.55	1.03	1.3	0.81	0.93	0.80	0.74	1.06	1.00	1.36	0.72	0.92
Soli	0.65	0.70	1.07	0.75	0.69	0.87	1.08	1.38	0.98	1.00	0.95	0.79	0.91
Sosca	0.57	0.50	0.99	1.15	0.94	0.65	0.86	1.05	1.11	1.00	0.99	0.96	0.89

3.1.11 Weighted Rating

According to the weighted rating score table created at the end of the experiment to distinguish the wild solanum species that are tolerant and sensitive to salt stress, Sopi and then Sone received the highest score in the medium salt treatment. This is in agreement with the index table we created by accepting the control values of salt treatments as 1. According to the high salt treatment data, Sopi and then Soch received the highest score in high salt treatment. According to the index, the genotype found to be sensitive to salt was Sosca, while Soli was found to be sensitive to salt according to the weighted grading priority(Table 15,16).

Table 16. Medium Salt Application Weighed Rating

Genotype	RWW	RDW	RL	SL	SWW	SDW	Cat	Pox	Sod	Na	K	Average
Soch	10	20	15	25	40	30	60	40	40	50	50	**380**
Sone	20	20	20	25	40	30	60	40	60	40	40	**395**
Sopi	30	30	30	30	40	40	50	50	50	30	40	**420**
Soli	20	30	5	10	20	20	60	40	10	30	30	275
Sosca	20	30	20	20	40	50	30	30	50	40	30	360

Table 17. High Salt Application Weighed Rating

Genotype	RWW	RDW	RL	SL	SWW	SDW	Cat	Pox	Sod	Na	K	Average
Soch	20	10	15	20	30	20	50	30	40	10	50	**295**
Sone	20	20	20	20	40	20	40	20	40	10	40	290
Sopi	20	20	25	30	20	20	20	10	50	40	40	**295**
Soli	20	20	20	5	10	10	60	50	20	10	30	265
Sosca	20	20	15	15	40	30	30	30	40	20	30	290

DISCUSSION

Under salt stress conditions, plant traits such as root and shoot fresh and dry weights, leaf number, plant height, root length, and stem diameter generally tend to decrease compared with the control as the severity of stress increases (Turan, 2015). In this study, similar reductions were detected in these parameters relative to the control group with increasing stress levels, which is consistent with the findings of Doğan (2004). However, deviations from this general trend were observed in root length measurements. These results are also in agreement with the findings of Meléndez-Mori et al. (2023). Despite the marked reductions in root fresh and dry weights compared with the control, the increase in root length under salt stress is thought to result from the plant's attempt to extend its root system deeper or over a wider area to reach more favorable environmental conditions. Additionally, the literature indicates that moderate salt stress may trigger osmotic adjustment in some tolerant wild species, thereby maintaining cell turgor and causing a slight increase in water content, particularly in root and shoot tissues (Munns & Tester, 2008; Shabala, 2013). This physiological response may have contributed to the increase in root length observed in the present study.

Salt stress also influences the uptake of minerals by plants, causing an increase in the levels of certain elements while decreasing others. According to Ran et al. (2022), Na content in plants increases under salt stress conditions. The limited accumulation of Na under salt stress is considered a critical parameter for salt tolerance. According to the data obtained in this study, increases in Na content were observed across genotypes (Akinci et al., 2004). The lowest increase in Na content compared to the control was noted in the wild species Sopi and Soch. Moreover, the rise in Na content adversely affected K uptake. As reported by Güden et al. (2024), both increases and decreases in K uptake were observed across genotypes compared to the control.

The increase in K ions under stress conditions can be attributed to the use of wild species in the study, as noted by Albaladejo et al. (2017). Additionally, the high K content in plants under salt stress can be explained by the mechanism of transporting K and P ions from older leaves to younger leaves, as well as the plant's preference for K ions over Na ions. This mechanism is considered an indicator of salt tolerance (Al-Karaki, 2000).

Various studies have also reported that plants increase the activity of certain antioxidant enzymes, such as SOD, CAT, APX, and GR, under salt stress to mitigate the harmful effects of salinity (Sofy et al., 2017; Gharsallah et al., 2016; Mann et al., 2022). Genotypes tolerant to salt stress exhibit significantly higher enzyme activity compared to sensitive genotypes (Harinasut et al., 2003). The findings of this study align with those of Frary et al. (2010), Jbir-Koubaa et al. (2019), and Pradeep (2015), as increases in the activities of SOD, CAT, and POX enzymes were recorded compared to the control.

CONCLUSION

In conclusion, wild Solanum species exhibited varying responses to salt stress applications. The responses of S. pimpinellifolium (Sopi, LA0722), S. chmielewskii (Soch, LA2663), and S. neorickii (Sone, LA1326) to salt stress, based on indices and weighted scoring criteria, indicated that these species are tolerant to salt stress. Conversely, S. linnaeanum (Soli, VI042691) was found to be sensitive to salt stress. Unlike domesticated cultivars, their wild relatives are naturally adapted to saline soils. This adaptability makes wild genotypes a valuable genetic resource for enhancing salt tolerance. Utilizing wild species as rootstocks or developing rootstocks from their hybrids could play a crucial role in increasing resistance to salt stress.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Author Contributions

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Original Article

Determination of Nitrogen and Phosphorus Removal Performance of Sand, Rice Husk and Zeolite Mixture

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ABSTRACT

Growing population, urbanization, and agricultural activities are causing an increase in nitrogen and phosphorus loads in water resources, leading to eutrophication and water quality issues. In this study, the nitrogen and phosphorus removal performance of a mixture of sand, rice husks, and zeolite—which could be used as an alternative filter material in constructed wetland systems—from synthetic wastewater was investigated using laboratory-scale column experiments. The filter material mixture, prepared in equal volumes, was placed in columns; synthetic wastewater containing nitrogen and phosphorus, prepared at different concentrations (50 to 100 mg L^{-1}) under laboratory conditions, was applied at different flow rates (1 and 2.3 mL min^{-1}). Throughout the experiments, samples were collected at different retention times (3, 6, 12, 24, and 48 hours), and analyses of pH, electrical conductivity (EC), total nitrogen (TN), and total phosphorus (TP) were performed. The obtained pH (8.07–9.52) and EC (470.4–1284 µS cm^{-1}) values were found to be compliant with relevant discharge standards. The highest phosphorus removal efficiency (99%) was achieved at a concentration of 50 mg L^{-1} and a flow rate of 1 mL min^{-1}, resulting in an effluent concentration of 0.50 mg L^{-1}, while the lowest removal efficiency (62%) was observed at a concentration of 100 mg L^{-1} and a flow rate of 2.3 mL min^{-1}, resulting in an effluent concentration of 38.0 mg L^{-1}. For nitrogen removal, the highest performance (90.1%) was achieved at a concentration of 100 mg L^{-1} and a flow rate of 2.3 mL min^{-1}, resulting in an effluent concentration of 9.99 mg L^{-1}, while the lowest removal performance (4%) was measured at a flow rate of 1 mL min^{-1}, resulting in an effluent concentration of 68.34 mg L^{-1}. In conclusion, the study demonstrated that the mixture of sand, rice husks, and zeolite provides high efficiency in nitrogen and phosphorus removal and can be used as a sustainable, low-cost, and environmentally friendly alternative filter material in constructed wetland systems. However, it was determined that increasing concentration and retention time did not produce the expected positive effect, particularly in phosphorus removal. Furthermore, it was found that low flow rates and appropriate pH conditions enhance adsorption efficiency, and it was assessed that pH optimization is necessary, particularly in wastewater with high pH values. It is believed that the findings obtained at the laboratory scale will make significant contributions to the applicability of natural filter materials for nutrient removal in constructed wetland technologies if supported by long-term and pilot-scale studies.

Key words: Adsorption, Column Tests, Treatment

Kum, Çeltik Kavuzu ve Zeolit Karışımının Azot ve Fosfor Giderim Performansının Belirlenmesi

ÖZ

Artan nüfus, kentleşme ve tarımsal faaliyetler, su kaynaklarında azot ve fosfor yüklerinin artmasına neden olmakta ve buna bağlı olarak ötrofikasyon ile su kalitesi problemlerini beraberinde getirmektedir. Bu çalışmada, yapay sulak alan sistemlerinde alternatif filtre materyali olarak kullanılabilecek kum, pirinç kabuğu ve zeolit

karışımının sentetik atık sulardan azot ve fosfor giderim performansı laboratuvar ölçekli kolon deneyleri ile araştırılmıştır. Eşit hacimlerde hazırlanan filtre materyali karışımı kolonlara yerleştirilmiş; laboratuvar koşullarında farklı konsantrasyonlarında (50 ile 100 mg L^{-1}) hazırlanan ve azot ile fosfor içeren sentetik atık sular, farklı debilerde (1 ve 2.3 mL dak^{-1}) uygulanmıştır. Denemeler boyunca farklı bekleme sürelerinde (3, 6, 12, 24 ve 48 saat) alınan numunelerde pH, elektriksel iletkenlik (EC), toplam azot (TN) ve toplam fosfor (TP) analizleri gerçekleştirilmiştir. Elde edilen pH (8.07–9.52) ve EC (470.4–1284 µS cm^{-1}) değerlerinin ilgili deşarj standartlarıyla uyumlu olduğu belirlenmiştir. Fosfor gideriminde en yüksek performans (%99), 50 mg L^{-1} konsantrasyon ve 1 mL min^{-1} debide 0.50 mg L^{-1} çıkış konsantrasyonu ile elde edilirken, en düşük giderim performansı (%62), 100 mg L^{-1} konsantrasyon ve 2.3 mL dak^{-1} debide 38.0 mg L^{-1} çıkış konsantrasyonu ile belirlenmiştir. Azot gideriminde ise en yüksek performans (%90.1), 100 mg L^{-1} konsantrasyon ve 2.3 mL dak^{-1} debide 9.99 mg L^{-1} çıkış konsantrasyonu ile elde edilirken, en düşük giderim performansı (%4), 1 mL dak^{-1} debi koşullarında 68.34 mg L^{-1} olarak ölçülmüştür. Sonuç olarak, kum, pirinç kabuğu ve zeolit karışımının azot ve fosfor gideriminde yüksek verimlilik sağladığını ve yapay sulak alan sistemlerinde sürdürülebilir, düşük maliyetli ve çevre dostu alternatif bir filtre materyali olarak kullanılabileceğini göstermiştir. Bununla birlikte, artan konsantrasyon ve bekleme süresinin özellikle fosfor gideriminde beklenen düzeyde olumlu bir etki oluşturmadığı belirlenmiştir. Ayrıca düşük debi ve uygun pH koşullarının adsorpsiyon verimini artırdığı tespit edilmiş olup, özellikle yüksek pH değerine sahip atık sularda pH optimizasyonunun gerekli olduğu değerlendirilmiştir. Laboratuvar ölçeğinde elde edilen bulguların, uzun süreli ve pilot ölçekli çalışmalarla desteklenmesi durumunda doğal filtre materyallerinin yapay sulak alan teknolojilerinde besin elementi giderimine yönelik uygulanabilirliğine önemli katkılar sağlayacağı düşünülmektedir.

Anahtar kelimeler: Adsorpsiyon, Arıtma, Kolon Denemeleri

INTRODUCTION

The world population is increasing every day. In addition, industrialization and water consumption are increasing worldwide. Consequently, waste in solid, liquid, and gaseous forms is reaching levels that disrupt the balance of life and threaten human existence.

The reckless use of human natural resources, particularly available water resources, increases water consumption and leads to water waste. Water resources are among the most essential resources necessary for sustaining live on earth. Water resources, which are essential for the life of every living being, are becoming increasingly polluted (Kılıç, 2008). Freshwater resources, which are extremely limited in the world, determine the future of both people and countries. Therefore, one of the most important fundamental issues is to have good organization in every area, from the protection of water resources to their operation, and from the distribution of water to its removal. In fact, the protection of water resources within a holistic structure should also be considered an indicator of the integrity of nature (Soylu et al., 2006). It is of great importance to protect water resources and pass them on to future generations. Domestic and industrial wastewater are the main factors causing pollution of water resources, which have many different applications. Owing to legal regulations aimed at protecting the environment and the increasing demand for water in businesses, minimizing wastewater generation, recovering valuable materials, and reusing water have become increasingly important (Murathan et al., 2013).

Türkiye, a country not rich in water resources, will increasingly feel this pressure due to its growing population. Especially in large cities, unplanned growth and increasing population density require water-related problems to be addressed not with short-term and superficial solutions, but with long-term and strategic ones (Aksungur and Firidin, 2008). Türkiye has a total area of approximately 78 million hectares. Of this area, 24 million hectares are cultivated for agriculture, 21.5 million hectares are pastures and meadows, 23 million hectares are forests and scrublands, and the remainder consists of unused water surfaces and rocky terrain. The total is 112 billion m^3 per year, consisting of an average of 94 billion m^3 of surface water and 18 billion m^3 of groundwater (DSI, 2025). More than 70% of the world's water is used for agricultural irrigation. Therefore, although it only covers a portion of irrigation water needs, there is great potential for the use of treated wastewater in irrigation (WWAP, 2003). Agricultural activities are one of the most significant sources of water pollution in Türkiye. Fertilizers and pesticides are used intensively in agricultural areas to increase production. The fertilizers and pesticides used are carried by rain or irrigation water, polluting surface waters and groundwater resources (Olhan and Ataseven, 2009). The use of treated wastewater in agriculture has many advantages. First, it contributes to increased production. This is because treated wastewater contains plant nutrients. The nutrient richness of treated wastewater has led to an increase in its reuse for agricultural purposes (Filibeli et al., 2017).

Many risk factors associated with the reuse of water in agricultural irrigation have been identified. Some risk factors have short-term effects, while the severity of the effects of other risk factors varies depending on the

potential for contact with animals, humans, or the environment. Other risk factors have effects that increase over time and with the continuous use of treated water (e.g. as soil salinity and the effects of toxic chemicals) (Toze, 2006). Dissolved nitrogen in water is one of the main parameters that cause pollution in surface and groundwater. Although nitrate is the most common form of dissolved nitrogen found underground, it can also be found in the form of ammonium, nitrite, nitrous oxide, and organic nitrogen. Bacteria found in aerobic environments convert ammonia into nitrite or nitrate ions (Akosman and Özdemir, 2018). Nitrogen fertilizers commonly used in agricultural applications, industrial waste, and waste from livestock operations increase the nitrogen content of soil, water, and produced goods, causing environmental pollution (Sünal and Erşahin, 2012).

In addition to high-cost advanced biological treatment plants for wastewater treatment, less expensive constructed wetlands are being built for use in rural areas. Constructed wetlands provide habitats for many organisms and have the capacity to utilize solar energy and self-renew. They contribute to the natural balance of the atmosphere by consuming CO_2 and producing O_2 in the environment. They can remove organic matter, suspended solids, toxic substances, heavy metals, and biological elements from wastewater and have high treatment capacities (Bütünoğlu, 2018). Constructed wetlands are systems that enable the regular control of water flow, retention time, and wastewater level by placing porous materials such as stones, gravel, and sand within an impermeable clay layer (Esmeray and Armutcu, 2020). Constructed wetlands perform physical, chemical, and biological treatments through interactions between the fill material, plants, and air space, aided by microorganisms present in the soil structure (Dutta and Mia, 2010).

Constructed wetlands are constructed by filling impermeable ground with bedding materials such as sand or gravel that can support rooted plants. In these systems, water does not come into contact with the atmosphere because it flows through the filling materials (Demirörs, 2006). In constructed wetlands, natural materials such as soil, clay, and sand, processed materials such as zeolite or pumice, and waste materials such as fly ash or blast furnace slag can be used as filter materials. Depending on the basic pollutant parameters and pollutant concentrations in wastewater, these materials are often used in combination with each other (Gökalp and Taş, 2018).

The addition of zeolite to water treatment systems increases sludge activity while also improving the removal efficiency of suspended solid particles and the phosphate precipitation effect of trivalent cations. Zeolites are highly absorbent porous minerals composed primarily of silicon and aluminum. Similar to sponges that absorb water, zeolites are useful for their ability to capture and retain various unwanted materials (Miteva and Stoyanova, 2020). With their high ion exchange and heavy metal removal efficiencies, these materials have been used to improve the physical, chemical, and biological properties of soil and are evaluated for fertilization applications. Thus, zeolite enables the controlled release of nutrients into the soil. Furthermore, the production of zeolite-based fertilizers results in lower carbon dioxide emissions into the environment (Jarosz et al., 2022).

Rice constitutes half of the food supply for 1.6 billion people worldwide. Rice production results in excessive amounts of rice husks as waste material (Pourshakiba, 2012). Rice is obtained by processing paddy. During the separation of the husks, which are a waste product of rice production, from the grains, two types of husks are formed. The first husk is a thin membrane surrounding the rice grain, known as the bran. It is rich in nutrients and is used as animal feed. The second husk is the outermost shell of rice grain. This husk is also called the hull or husk (Sadıç, 2008). The composition of rice husks contains up to 46.9% organic carbon. The nitrogen content is 1.6% and the moisture content is 9.3% (Çakirer, 2015).

Fertilizers derived from industrial sources are commonly used to address phosphorus deficiency in soil. While plants consume the phosphorus applied during the year, the remainder accumulates in the soil as “residual phosphorus.” Only a small portion of this residual phosphorus dissolves in water as phosphate, while an estimated 80% reaches freshwater sources and the ocean in granular form. Industrial and domestic waste contains high levels of phosphorus (Kılıç and Korkmaz, 2012). All organisms involved in the biological processes of wastewater treatment require phosphorus for reproduction and the synthesis of new cells. In this regard, domestic wastewater contains much more phosphorus than the amount necessary for the stabilization of the organic matter it contains. This situation can be understood by looking at the amount of phosphorus in the effluent of biological wastewater treatment plants. In Türkiye, according to the urban wastewater treatment regulation, at least 80% of total phosphorus must be removed in discharges to sensitive water bodies with low water circulation (Kaya, 2013).

Ammonia-based fertilizers are used to meet the nitrogen requirements of plants. However, the use of these fertilizers has caused environmental problems has caused. While some of the ammonia applied as fertilizer is used by plants, part of it is used by bacteria in the soil for cellular respiration, resulting in the release of nitrite. Nitrite, which is oxidized by other microorganisms, is converted into nitrate and, owing to its chemical properties, can easily mix with groundwater. Groundwater carries nitrates to sea and oceans, causing water pollution (Serin, 2014).

Recent studies have focused on various filter materials such as peat soil, sand, gravel, blast furnace slag, coal furnace slag, limestone, rice husk, pumice, zeolite, and vermiculite for nitrogen and phosphorus removal from wastewater (Gökalp and Kanarya, 2018; Uzun et al., 2021; Atıcı, 2023; Aşık and İrik, 2025; Demir et al., 2025; İrik and Kanarya, 2025).

In previous studies, the removal performance of various wastes has generally been investigated using the materials in their pure forms. This study was conducted to determine the performance of a homogeneous mixture of sand, rice husk, and zeolite materials in removing nitrogen and phosphorus from wastewater.

MATERIALS AND METHODS

The study was contained in the form of column tests, in which filter materials were subjected to artificially generated wastewater. The filter materials consisted of sand, rice husk, and zeolite (50 cm^3 each), mixed to form a total of 150 cm^3 of material. Before being transferred to the columns, the materials used in the study were sieved through screens with pore diameters of 1 and 2 mm, and the materials retained between the two screens were used.

The columns contain pores with a pore diameter of 1 mm to prevent clogging caused by the filter material. This study was conducted on a pilot scale in the form of column tests representing constructed wetlands to avoid harming the environment.

Sand is a granular material composed of fragmented rock and mineral particles. It is finer than gravel and coarser than silt. Sand can also refer to a textural soil or soil type. That is, it is a soil containing more than 85% sand-sized particles by mass. The composition of sand varies depending on rock sources and conditions. In inland environments and non-tropical coastal environments, the most common component of sand is silica (SiO_2), usually in the form of quartz (Apaydın, 2007).

Rice husks are bio-waste materials used as adsorbents in studies. While rice husks exhibit good and economical adsorbent properties, they pose significant environmental problems in the management and disposal of agricultural waste (Kalderis et al., 2008; Asadi et al., 2008). Rice husks are insoluble in water, have a silica-cellulose structure, are woody, abrasive, and contain 20% silica material. The important substances in their structure are cellulose, hemicellulose, lignin, hydrated silica, and ash. The chemical components of rice husks are SiO_2, H_2O, Al_2O_3, Fe_2O_3, K_2O, Na_2O, CaO, and Mg (Foo and Hameed, 2009).

Zeolite is a hydrated aluminum silicate with a crystalline structure originating from volcanic rock, which has micro-pores and can be widely used as an adsorbent and catalyst. There are 42 different types of zeolites according to their compositions (Altan et al., 1998). Zeolites are used in agriculture as soil conditioners, fertilizer additives, water retainers, and for aeration purposes; in plant production as a growing medium; in landscaping and garden design; in animal husbandry as feed additives and bedding material; in purification for mechanical and chemical filtration; in the retention of toxic waste; as filter material in pools and spas, as aquarium material, cat litter, cleaning materials, in the textile industry, paper and energy sectors, as toxin binders in the health sector, as catalysts in aquaculture and chemistry, as well as in waste and wastewater treatment (Çağın et al., 2006).

Columns made of glass material with a standard inner diameter of 3 cm and a length of 60 cm were used in this study. A LongerPump brand 12-channel peristaltic pump was used in the experiment to ensure that a specified amount of liquid was transferred into the columns within a specified time, and the apparatus used in the experiment is shown in Figure 1. Nine columns were used at a time in the experiments, and each study was conducted with three replicates.

In the study, synthetic wastewater was prepared using potassium nitrate (KNO_3) and potassium dihydrogen phosphate (KH_2PO_4) at a concentration of 1000 mg L^{-1} as a stock solution. Synthetic wastewater was prepared at concentrations of 50 and 100 mg L^{-1} using the prepared stock solution. The synthetic wastewater prepared under laboratory conditions using a peristaltic pump was applied at flow rates of 1 and 2.3 mL min^{-1}.

In order to better determine the effectiveness of the materials used, retention was performed at 3, 6, 12, 24, and 48 hours after the system was started. After measuring the pH and EC of the samples taken at different times, they were filtered through filter paper with a pore size of 0.45 µm to determine the total phosphorus and nitrate content.

Samples collected throughout the study were filtered through filter paper. pH and EC analyses were measured using a Hanna brand HI-5522 model pH and EC meter. Phosphorus content was determined using a Hanna brand phosphorus analyzer. Ten milliliters of each sample was taken, 10 drops of Hanna brand HI93717A-0 model reagent were added, and one packet of Hanna brand HI93717B-0 model powder was added, and a reading was taken from the device. The phosphorus content was determined based on the findings. For nitrate determination, 10 ml of the samples were taken, 0.2 ml ISA (Ionic Strength Adjuster) was added to them, and

they were mixed. Nitrate analysis was performed using the Hanna HI-4113 ion probe on the Hanna HI-5522 ion meter device. The findings obtained were divided by 4.43 to determine the nitrogen content in the nitrate.

Figure 1. The system used in the study

Using the findings obtained in the study, the nitrogen and phosphorus removal efficiencies of the materials were determined as percentages. At this stage, Equation 1 was used.

$$RP = \frac{C_{in}-C_{out}}{C_{in}} x100 \quad (1)$$

Where; RP: Removal Performance (%); C_{in}: Concentration of influent (mg L^{-1}); Cout: Concentration of effluent (mg L^{-1}).

RESULTS AND DISCUSSION

Change in pH Value During the Treatment Process

The pH values of solutions prepared at different concentrations (50 and 100 mg L^{-1}) were determined to be 5.03 and 4.99. As a result of the study, the pH values of the effluent water varied between 8.07 and 9.52 depending on the different concentrations loaded with phosphorus and nitrogen mixtures and different retention times. The Water Pollution Control Regulation published by the Ministry of Environment, Urbanization, and Climate Change states that pH values must be between 6 and 10 for wastewater to be discharged into receiving environments (SKKY, 2004). According to the findings, it was determined that this criterion was met (Table 1, Figure 2).

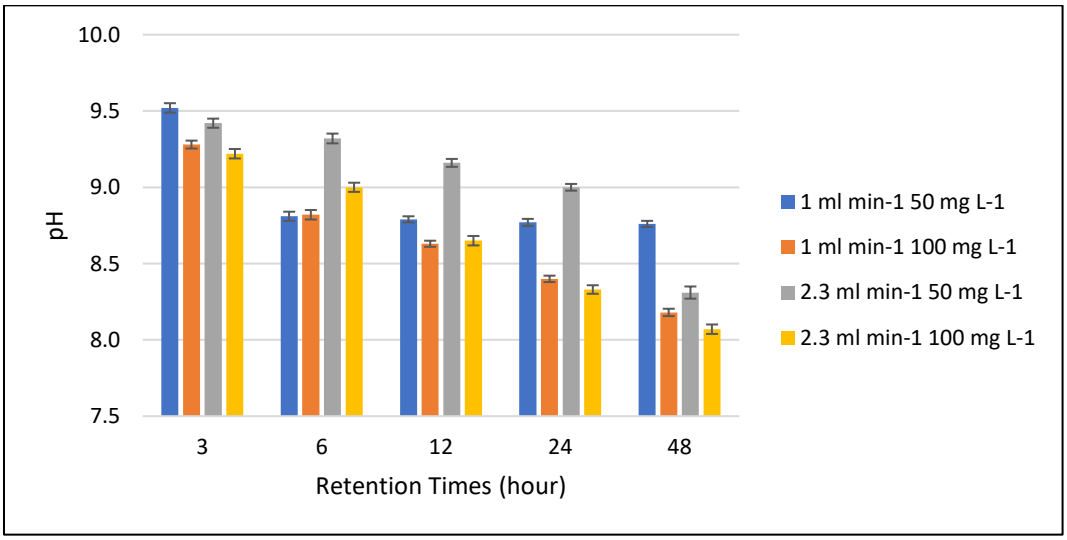

Figure 2. pH changes during study

As shown in Figure 2, the effect of nitrogen and phosphorus-containing solutions applied at different concentrations on pH values varied depending on the retention times. These changes increased initially because the pH values of the materials were higher after contact with the prepared solutions and then tended to

decrease. During the study, decreases and increases in pH values were observed due to the material was washed. The pH data obtained at different flow rates and after different retention times are presented in Table 1.

Table 1. pH changes during study

Flow Rate (mL min^{-1})	Conc. (mg L^{-1})	Retention Times (hour)				
		3rd	6th	12th	24th	48th
1	50	9.52±0.031	8.81±0.03	8.79±0.02	8.77±0.023	8.76±0.02
	100	9.28±0.026	8.82±0.031	8.63±0.02	8.4±0.021	8.18±0.024
2.3	50	9.42±0.03	9.32±0.032	9.16±0.026	9.00±0.22	8.31±0.04
	100	9.22±0.031	9.00±0.03	8.65±0.031	8.33±0.028	8.07±0.031

During the study, pH values ranged from 9.22 to 9.52 at the end of the 3rd hour, 8.81 to 9.32 at the end of the 6th hour, 8.63 to 9.16 at the end of the 12th hour, 8.33 to 9.00 at the end of the 24th hour, and 8.07 to 8.76 at the end of the 48th hour. The lowest pH value was observed in the sample taken at 48 hours from the material treated with a solution at a flow rate of 2.3 mL min^{-1} and a concentration of 100 mg L^{-1}, while the highest pH value was observed in the sample taken at 3 hours from the material treated with a solution at a flow rate of 1 mL min^{-1} and a concentration of 50 mg L^{-1}. The pH analysis results obtained in the study show that the values decrease with increasing concentration and time. The pH values complied with the criteria of the relevant regulation for the discharge of treated wastewater into receiving environments.

Demir et al. (2025), in their column test study, used zeolite, vermiculite, and mixtures of both materials in different ratios as filter materials and did not observe a standard change in pH values. Atıcı (2023) used zeolite, sawdust, and mixtures of both materials in different ratios as filter materials in column tests. It was observed that pH values decreased depending on the concentration of the applied solution and did not show significant change over time.

Change in EC (µS cm^{-1}) Value During the Treatment Process

The EC values of the solutions prepared at different concentrations (50 and 100 mg L^{-1}) were determined to be 436.89 and 1016.42. The analyses conducted in the study revealed that EC values ranged between 470.4 and 1300 µS cm^{-1}. The relevant ministry stated in its announcement that the ideal EC value should be below 2000 µS cm^{-1} (SKKY, 2004). The findings indicate that this criterion was met (Table 2, Figure 3).

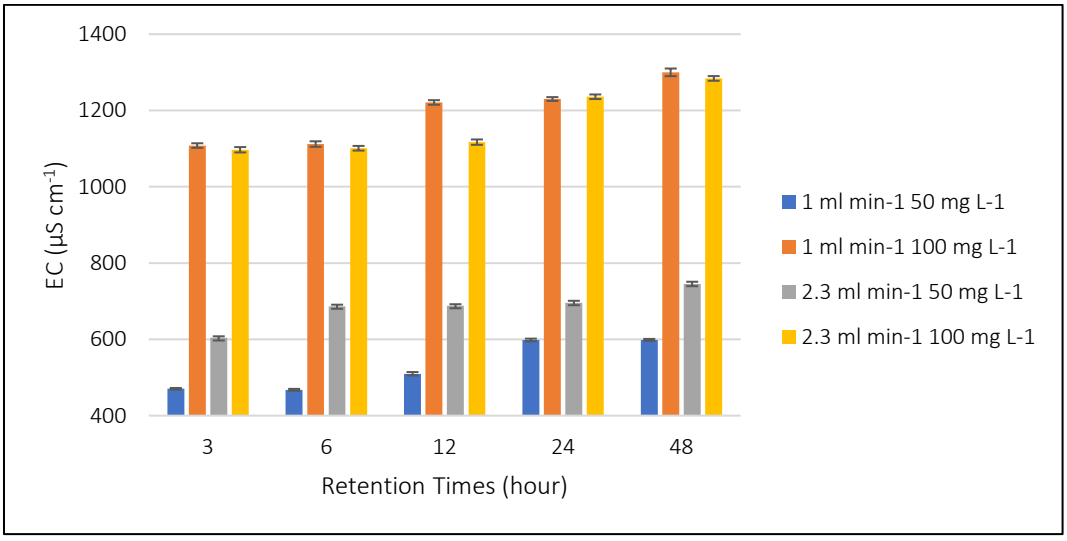

Figure 3. EC (µS cm^{-1}) changes during study

As can be seen from Figure 3, it was determined that the effect of nitrogen and phosphorus-containing solutions applied at different concentrations on EC values varied depending on the retention times. These changes increased because the EC values of the materials were higher after the prepared solutions encountered the materials. The EC data obtained at different flow rates and after different retention times are presented in Table 2.

Table 2. EC (µS cm^{-1}) changes during study

Flow Rate (mL min^{-1})	Conc. (mg L^{-1})	Retention Times (hour)				
		3rd	6th	12th	24th	48th
1	50	470.4±2.12	467.6±2.55	509.8±4.51	598.4±3.55	598.6±2.52
	100	1108±6	1112±7.21	1221±6	1230±5	1300±10
2.3	50	604±4	686.3±4.59	688.5±3.61	695.5±5.57	745.5±5.51
	100	1097±7	1101±6.11	1117±7.02	1236±6	1284±6.11

During the study, EC values (µS cm^{-1}) ranged from 470.40 to 1108.00 at the end of the 3rd hour, from 497.60 to 1112. 00 at the end of the 6th hour, between 509.80 and 1221.00 at the end of the 12th hour, between 598.40 and 1236.00 at the end of the 24th hour, and between 598.60 and 1300.00 at the end of the 48th hour. The lowest EC value was observed in the sample taken at the 3rd hour of the material treated with a solution at a concentration of 50 mg L^{-1} at a flow rate of 1 mL min^{-1}, while the highest EC value was observed in the sample taken at the 48th hour of the material treated with a solution at a concentration of 100 mg L^{-1} at a flow rate of 1 mL min^{-1}. The EC analysis results obtained in the study show that the values increase over time. The EC values were found to comply with the criteria of the relevant regulation for the discharge of treated wastewater into receiving environments.

In their column tests, Demir et al. (2025), determined that different materials did not affect EC levels in pollution but had an effect on the retention process and observed that EC results increased over time depending on the retention period. Atıcı (2023), in column tests, evaluated the EC analysis results and found that the values were proportionally close to each other with the change in materials and that the results obtained were in compliance with the regulation. The data we have obtained within the discharge limits specified in the Water Pollution Control Regulation published by the Ministry of Environment, Urbanization, and Climate Change does not indicate any problems with wastewater discharge.

Change in Total Phosphorus (mg L^{-1}) Value During the Treatment Process

After applying solutions prepared at different concentrations (50 and 100 mg L^{-1}) to the columns, the analyses revealed that the total phosphorus values ranged between 0.50 and 38.0 mg L^{-1}. The relevant ministry's published regulation states that the TP value of treated wastewater must be below 10 mg L^{-1} (SKKY, 2004). According to the findings, it was determined that this criterion was mostly met (Table 3, Figure 4).

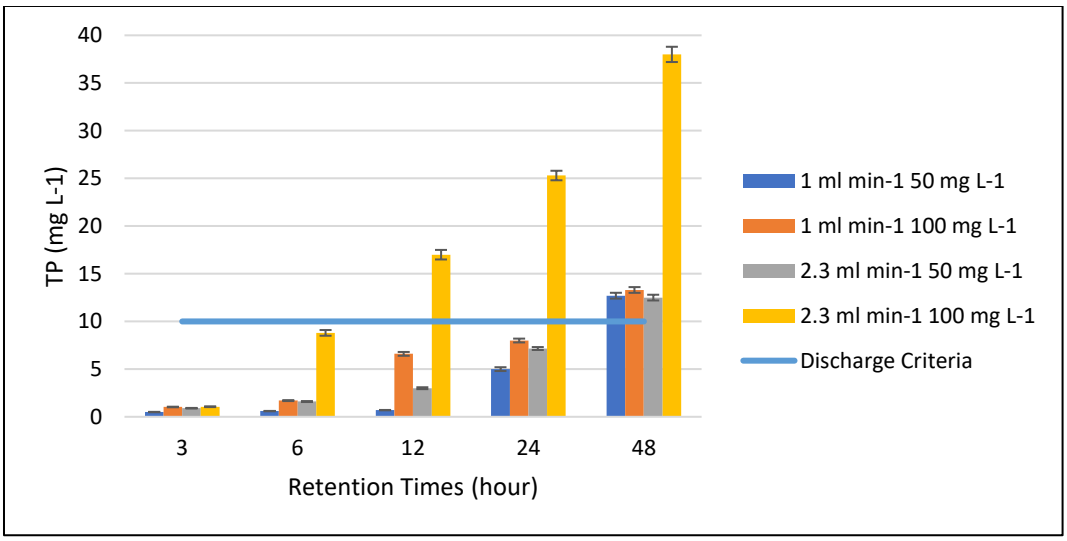

Figure 4. Changes in TP (mg L^{-1}) during the study

As can be seen in Figure 4, it was determined that phosphorus-containing solutions applied at different concentrations varied according to their retention times. After the prepared solutions met the material, the TP values increased due to the materials reaching saturation over time. The TP values obtained at different flow rates and after different retention times are given in Table 3.

Table 3. Changes in TP (mg L^{-1}) during the study

Flow Rate (mL min^{-1})	Conc. (mg L^{-1})	Retention Times (hour)				
		3rd	6th	12th	24th	48th
1	50	0.5±0.02	0.6±0.02	0.7±0.02	5±0.2	12.7±0.305
	100	1.03±0.031	1.7±0.05	6.6±0.2	8±0.2	13.3±0.3
2.3	50	0.9±0.031	1.6±0.05	3±0.1	7.16±0.153	12.5±0.3
	100	1.06±0.04	8.8±0.3	17±0.5	25.3±0.5	38±0.8

During the study, TP values (mg L^{-1}) ranged from 0.50 to 1.06 at the end of the 3rd hour, from 0.60 to 8.80 at the end of the 6th hour, from 0.70 to 17.00 at the end of the 12th hour, 5.00 to 25.30 at the end of the 24th hour, and 12.50 to 38.00 at the end of the 48th hour. The lowest TP value was observed in the sample taken at 3 hours from the material treated with a solution at a concentration of 50 mg L^{-1} at a flow rate of 1 mL min^{-1}, while the highest TP value was observed in the sample taken at 48 hours from the material treated with a solution at a concentration of 100 mg L^{-1} at a flow rate of 2.3 mL min^{-1}. The TP analysis results obtained in the study show that the values increase over time. It was observed that TP values complied with the relevant regulation criteria for the discharge of treated wastewater into receiving environments up to 24 hours at a flow rate of 1 mL min^{-1}, 12 hours at a flow rate of 2.3 mL min^{-1} with a concentration of 50 mg L^{-1}, and 6 hours with a concentration of 100 mg L^{-1}. As the flow rate, the concentration of the applied solution, and the retention time increased, the limit was approached, and it was determined that the criterion could not be met thereafter. The total phosphorus change obtained as a result of the study was similar to the results obtained by Uzun et al. (2021) and Demir et al. (2025).

Change in Total Nitrogen (mg L^{-1}) Value During the Treatment Process

Following the application of solutions prepared at different concentrations (50 and 100 mg L^{-1}) to the columns, analyses revealed that total nitrogen values ranged between 9.99 and 68.34 mg L^{-1}. The relevant ministry's published regulation states that the TN value of treated wastewater must be below 40 mg L^{-1} (SKKY, 2004). According to the findings, it was determined that this criterion was mostly met (Table 4, Figure 5).

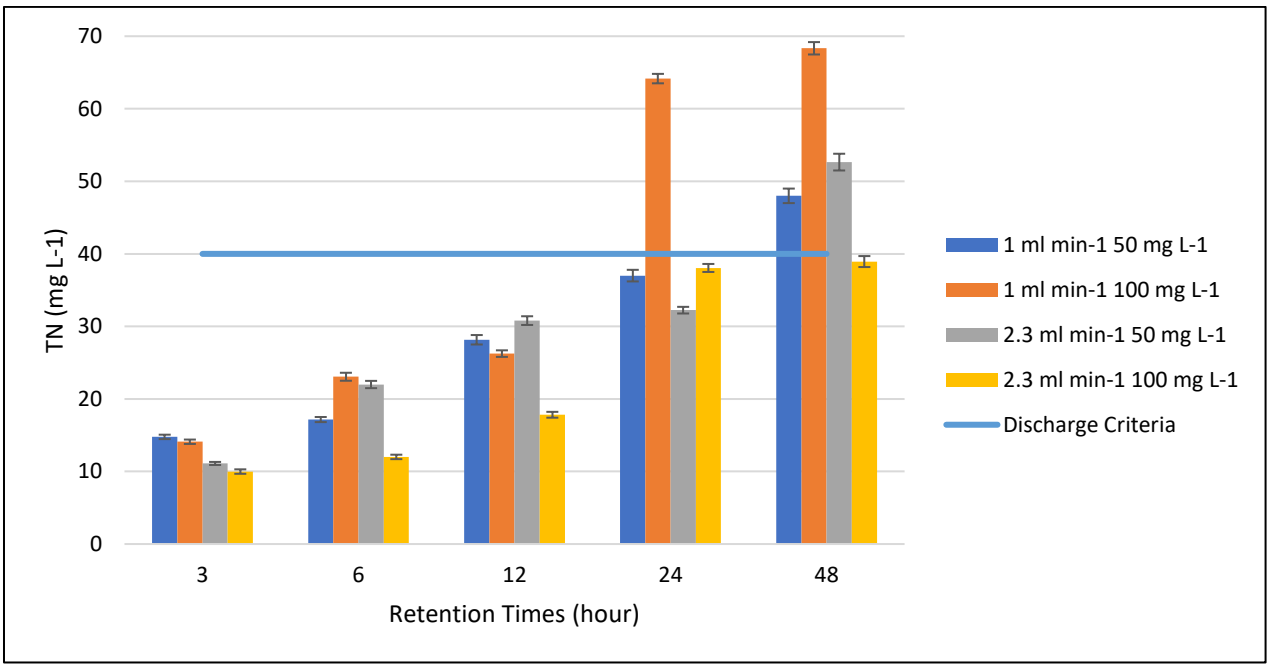

Figure 5. Changes in TN (mg L^{-1}) during the study

As can be seen in Figure 5, it was determined that nitrogen-containing solutions applied at different concentrations varied according to their retention times. After the prepared solutions met with the material, the values increased due to the materials reaching saturation over time. The TN values obtained at different flow rates and after different retention times are given in Table 4.

Table 4. Changes in TN (mg L^{-1}) during the study

Flow Rate (mL min^{-1})	Conc. (mg L^{-1})	Retention Times (hour)				
		3rd	6th	12th	24th	48th
1	50	14,77±0,306	17,16±0,351	28,16±0,651	37±0,8	48±1
	100	14,1±0,3	23,06±0,551	26,25±0,451	64,16±0,651	68,34±0,854
2.3	50	11,11±0,208	21,99±0,503	30,8±0,6	32,24±0,458	52,65±1,153
	100	9,99±0,306	12,01±0,306	17,82±0,404	38,06±0,551	38,94±0,755

During the study, TN values (mg L^{-1}) were 9.99 to 14.77 at the end of the 3rd hour, 12.01 to 23.06 at the end of the 6th hour, 17.82 to 30.80 at the end of the 12th hour, 32.24 to 64.16 at the end of the 24th hour, and 38.94 to 68.34 at the end of the 48th hour. The lowest TN value was observed in the sample taken at the 3rd hour of the material treated with a solution at a flow rate of 2.3 mL min^{-1} and a concentration of 100 mg L^{-1}, while the highest TN value was observed in the sample taken at the 48th hour of the material treated with a solution at a flow rate of 1 mL min^{-1} and a concentration of 100 mg L^{-1}. The TN analysis results obtained in the study show that the values increase over time. For treated wastewater to be discharged into receiving environments, TN values must comply with the criteria of the relevant regulation at a flow rate of 1 mL min^{-1} at a concentration of 50 mg L^{-1} up to 24 hours and at a concentration of 100 mg L^{-1} up to 12 hours. At a flow rate of 2.3 mL min^{-1}, compliance with the relevant regulation criteria was observed at the end of the 24th hour. As the flow rate, the concentration of the applied solution, and the retention time increased, the limit was approached, and it was determined that the criterion could not be met thereafter. The total nitrogen change obtained as a result of the study was found to be similar to the results obtained by Aşık and İrik (2025) and Demir et al. (2025).

CONCLUSION

The use of soil or filter materials is recommended for nitrogen and phosphorus removal in natural treatment systems (Mann, 1990). Therefore, this study was conducted in the form of column tests in the laboratories of the Department of Biosystems Engineering, Faculty of Agriculture, Erciyes University, to investigate the performance of different filter materials in removing nitrogen and phosphorus pollution. Using a homogeneous mixture of sand, rice husk, and zeolite materials, samples were taken after 3, 6, 12, 24, and 48 hours of retention time with synthetic wastewater containing nitrogen and phosphorus produced under laboratory conditions at two different concentrations (50 and 100 mg L^{-1}). The solutions prepared at concentrations of 50 and 100 mg L^{-1} were applied to the filter materials at flow rates of 1 and 2.3 mL min^{-1} for 48 hours, and pH, EC, total nitrogen, and total phosphorus analyses were performed on a total of 135 samples. The obtained pH (8.07–9.52) and EC (470.4–1284 µS cm^{-1}) values were determined to meet the relevant discharge standards.

The highest phosphorus removal performance (99%) was achieved at a concentration of 50 mg L^{-1}, a flow rate of 1 mL min^{-1}, and 0.50 mg L^{-1} at 3 hours. The lowest phosphorus removal performance (62%) was detected at a concentration of 100 mg L^{-1}, a flow rate of 2.3 mL min^{-1}, and 38.0 mg L^{-1} at 48 hours. The highest performance in nitrogen removal performance (90.1%) was achieved at a concentration of 100 mg L^{-1}, a flow rate of 2.3 mL min^{-1}, and 9.99 mg L^{-1} at 3 hours; the lowest removal performance (4%) was measured at a flow rate of 1 mL min^{-1}, a concentration of 100 mg L^{-1}, and 68.34 mg L^{-1} at 48 hours.

The results show that the mixture of sand, rice husk, and zeolite had high nitrogen and phosphorus removal efficiencies and can therefore be used as an alternative filter material in constructed wetlands. Since the study was conducted on a laboratory scale, it is thought that applications conducted over longer periods and at different concentrations will reveal the material's performance in more detail. It has been determined that applying wastewater at low pH and low flow rates increases adsorption efficiency, and pH adjustment is recommended, especially for wastewater with high pH values. Furthermore, using natural filter materials mixed in appropriate ratios will increase phosphorus and nitrogen removal efficiency in constructed wetlands.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

***Kübra BERKKAN*:** Data curation; formal analysis
***Hasan Ali İRİK*:** Conceptualization; funding acquisition; investigation; project administration; writing—review and editing.
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Original Article

Phenotypic Responses of Forage Kochia under Different Environment Conditions

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ABSTRACT

Phenotypic plasticity is a key factor in plant adaptation to heterogeneous environments. However, the extent to which plastic responses vary among traits under stress-prone conditions remains poorly understood. This study examined plasticity, stability, and phenotypic integration at the trait level in forage kochia *(Bassia prostrata),* a perennial semi-shrub species tolerant to drought and saline soils, commonly used in rangeland improvement. Plants were grown in three different environmental systems: a stress-prone area (SASs), an irrigated site (IC), and an organically amended site (FWM). Nine morphological and color-related traits were evaluated. Plasticity indices, coefficients of variation (CV), and Finlay–Wilkinson regression were used. Trait associations were calculated using Spearman's rank correlation and adjusted with the Benjamini–Hochberg procedure. Trait correlation networks were constructed for each environment, and network metrics were calculated. Most traits exhibited high plasticity indices. Regression slopes (β) were low, indicating that genotype performance ranking was largely maintained. Within-environment variation was high in the SASs environment. In the IC environment, stem color showed extreme variation, while leaf hairiness consistently had the lowest CV values across all three environments.Network analysis revealed that during the SASs environment, vegetative and generative traits separated into two distinct components; during the IC environment, a fully connected network was formed; and during the FWM environment, a sparse network with only two independent correlations was observed. These findings suggest that the ecological success of forage kochia in different environmental systems may arise from the combination of flexible trait means and consistent genotypic ranking.

Key words: Climate Change, Forage Shrub , Plant Adaptation, Salinity Stress

Farklı Çevre Şartlarında Bozkır Otunun Fenotipik Tepkileri

ÖZ

Fenotipik plastisite, bitkilerin heterojen çevrelere uyumunda önemli bir faktördür. Ancak, stres eğilimli koşullar altında plastik tepkilerin özellikler arasında ne ölçüde değiştiği yeterince anlaşılmamıştır. Bu çalışmada, mera ıslahında yaygın olarak kullanılan, kuraklığa ve tuzlu topraklara toleranslı bir tür olan bozkır otunda (*Bassia prostrata)* özellik düzeyinde plastisite, stabilite ve fenotipik entegrasyon incelenmiştir. Bitkiler üç farklı çevre sisteminde yetiştirilmiştir: stres eğilimli alan (SASs), sulanan alan (IC) ve organik madde uygulanan alan (FWM). Dokuz morfolojik ve renk ile ilişkili özellik değerlendirilmiştir. Plastisite indeksleri, varyasyon katsayıları (CV) ve Finlay–Wilkinson regresyonu kullanılmıştır. Özellik ilişkileri Spearman sıra korelasyonu ile hesaplanmış ve Benjamini–Hochberg yöntemiyle düzeltilmiştir. Her çevre için özellik ağları oluşturulmuş ve ağ metrikleri hesaplanmıştır. Çoğu özellik yüksek plastisite indeksleri sergilemiştir. Regresyon eğimleri (β) düşük bulunmuş, genotiplerin performans sıralamasının büyük ölçüde korunduğu görülmüştür. SASs çevresinde CV değerleri yüksek olmuş, IC çevresinde gövde rengi aşırı varyasyon göstermiş, yaprak tüylülüğü ise her üç çevrede en düşük CV değerlerine sahip olmuştur. Ağ analizleri, SASs çevresinde vejetatif ve generatif özelliklerin iki ayrı bileşene ayrıldığını , IC çevresinde tam bağlantılı bir ağ oluştuğunu, FWM çevresinde ise seyrek bir ağ yapısı sergilendiğini

göstermiştir. Bulgular, bozkır otunun farklı çevre sistemlerindeki ekolojik başarısının, esnek özellik ortalamaları ile tutarlı genotipik sıralamanın birleşiminden kaynaklanabileceğini düşündürmektedir.

Anahtar kelimeler: İklim Değişikliği, Çalı yem bitkileri, Bitki Adaptasyonu, Tuzluluk Stresi

INTRODUCTION

Rangeland ecosystems are increasingly exposed to environmental constraints such as drought, soil salinity, and nutrient limitation, which threaten forage productivity and ecosystem stability, particularly in semi-arid regions (Reynolds et al., 2007). In arid and semi-arid regions such as Türkiye, sensitivity is increasing due to the effects of climate change. In this process, large natural grazing areas are negatively affected by salinity, alkalinity, and water scarcity. As a result, serious degradation is occurring and the carrying capacity of grazing lands is decreasing (Gökkuş, 2020). Under these conditions, the use of perennial shrub and semi-shrub species that are tolernat to stress factors such as drought and salinity is of strategic importance for the sustainability of grazing land rehabilitation.

Forage kochia (*Bassia prostrata* (L.) A.J. Scott Syn. *Kochia prostrata*) is a perennial, semi-shrub species belonging to the *Chenopodiaceae* family, widely recognized for its high tolerance to drought, salinity, and poor soil conditions (Glenn et al., 1999; Waldron et al., 2011). It has been increasingly recommended in Türkiye for the improvement of degraded rangelands, particularly in arid and salt-affected areas owing to its deep root system. Previous studies conducted in different regions of Central Anatolia have highlighted its agronomic potential and adaptability under marginal conditions.

Despite its growing importance in rangeland management, most existing studies on forage kochia have focused on descriptive evaluations of growth performance, forage yield, or basic morphological traits under specific environments (Acar and Koç, 2019; Koç Koyun and Acar, 2021, Koç Koyun, 2024). However, the extent to which phenotypic traits of this species vary among contrasting environmental conditions, and how such responses are coordinated across multiple traits, remains poorly understood. Few studies have examined trait-level plasticity, stability, and phenotypic integration as complementary dimensions of environmental adaptation in perennial rangeland species.

Phenotypic plasticity, defined as the ability of a genotype to modify its phenotype in response to environmental variation. Also, it plays a central role in plant adaptation to heterogeneous environments (Valladares et al., 2007). However, high plasticity does not necessarily mean a functional advantage unless trait responses are stable and traits are integrated (Nicotra et al., 2010). Therefore, combining plasticity indices with stability analyses and trait correlation networks provides a more comprehensive framework for understanding both how plants cope with environmental changes and their yield potential in different environments as a result of plantation.

The study aims to examine phenotypic integration models using correlation networks with the phenotypic plasticity and stability of traits. Therefore, this study compares the phenotypic responses of forage kochia and the patterns of trait integration across three contrasting environmental conditions: a stress-prone saline site (SASs), an irrigated consition site (IC), and an organically amended site (FWM). The SASs and FWM sites are rain-fed and represent realistic rangeland improvement scenarios, while the IC site receives supplemental irrigation. These three conditions differ in multiple factors (soil, water, management) as would occur in practice. Rather than isolating a single variable, this study adopts a whole-system comparison to assess phenotypic responses under integrated environmental contrasts. Unlike multi-environment trials that typically use different sets of genotypes across environments, this study uses the same set of genetic individuals across all three contrasting systems. This design helps to reduce genotypic variation as a confounding factor.

MATERIALS AND METHODS

Plant material and experimental environments

The study was conducted over a six-year period (2018-2023) by growing the same set of genetic individuals in three contrasting environments sequentially: first a salt-affected, stress-prone (SASs) site (2018-2019), then an irrigated condition (IC) site (2020-2021), and finally an organically improved area fertilized with farmyard manure (FWM) site (2022-2023). At each transition, plants were uprooted and replanted in the next site. Each environment was established in a separate field site with its own soil properties, water regime, and agronomic practices (including planting distance). These differences are inherent to the contrasting systems that were compared, as the objective was to assess phenotypic responses under realistic, whole-environment conditions rather than to isolate individual factors.

Firstly, the plants were planted as seedlings in 2017 in a problematic area (37°43’12” N, 32°37’52”E) with spacing of 1.4 m x 1 m. The SASs environment was characterized by saline–alkaline soil conditions. According to soil analysis, the soil had a pH of 7.8, high organic matter content (5.41%), very high lime content (68.4%), severe salinity (ECe = 9.03 dS m^{-1}), and high boron concentration (57.36 mg kg^{-1}). The soil texture was clay loam, and potassium, calcium, and magnesium levels were above optimal ranges. Plants were grown under natural rainfall without irrigation. Mean annual temperature and total precipitation were 13.78°C and 443 mm in 2018 and 12.85°C and 367 mm in 2019.

Secondly, surviving plants were transplanted in 2020 to an experimental field at Selçuk University, Faculty of Agriculture (38°02'07"N 32°30'50"E), with a spacing of 1 m × 1 m. The IC soil was clay loam, slightly alkaline (pH 7.54), with lower organic matter (1.43%), lower lime content (43%), no salinity (ECe = 2.61 dS m^{-1}), and no boron toxicity (0.90 mg kg^{-1}). Plants were irrigated during the summer seasons, receiving approximately 300 mm of water annually in 2020 and 2021. Mean annual temperature and precipitation were 13.1°C and 292 mm in 2020 and 12.5°C and 360 mm in 2021, respectively.

Thirdly, an organically improved area fertilized with farmyard manure (FWM) was located within the same experimental field but without irrigation. In 2021, plants were transplanted with a spacing of 1.5 m between rows and 1 m between plants. A mixture of sheep and cattle manure was applied at a rate of 10 t ha^{-1}. The manure had an organic matter content of 6.41% and a pH of 7.09. Mean annual temperature and precipitation were 12.1°C and 289 mm in 2022 and 13.0°C and 348 mm in 2023, respectively.

At the end of each growing season, all plants were cut to a uniform height of 8 cm above ground to standardize above-ground starting biomass (Acar and Koç, 2019), and also at each transplantation (from SASs to IC and from IC to FWM), the root system of each plant was trimmed to a uniform length of approximately 25 cm before replanting to reduce variation in root system size and minimize transplant shock. These standardizations (above-ground cutting and root trimming) were applied to minimize age-related and size-related variation across measurement years

In the SASs site, 25 distinct genotypes that had successfully flowered were initially selected as the starting plant material. These 25 genotypes were divided into three groups based on morphological similarity (plant height, stem diameter, stem color, leaf color, and leaf hairiness) to ensure that within-group variation was minimized, as these groups were intended to serve as physical blocks in the experimental layout.

After the SASs environment, the surviving plants were transplanted to the IC site, where 18 of the 25 genotypes remained viable. Following the IC environment, the plants were transplanted to the FWM site, where 15 of the 18 genotypes survived to flowering. Consequently, the final analyses (plasticity indices, trait correlations, and network metrics) were conducted on the 15 genotypes that completed all three environmental periods. This reduced dataset was used to avoid excessively high variation that would have arisen from including genotypes that did not survive across all environments.

In each environment, the experimental layout consisted of blocks corresponding to the initial three morphological groups, with a row length of 5 m per block. Plot sizes varied among environments (SASs: 7 m^2; IC: 5.0 m^2; FWM: 7.5 m^2) due to differences in row spacing, reflecting the agronomic and logistical requirements of each contrasting system. The same 15 genotypes were used across all three environments (SASs, IC, FWM) after transplantation. Unlike herbaceous annuals, research with shrubs and semi-shrubs such as forage kochia requires different experimental considerations due to their growth habit and larger space requirements. In such cases, small plots of 1 to 6 plants are considered satisfactory for most studies (Dias and Resende, 2001).

Trait measurements

Morphological and reproductive traits were recorded annually during the flowering period (August–October). The following traits were measured: plant height (PH), canopy diameter (CD), stem diameter (SD), leaf length (LL), leaf width (LW), leaf hairiness (LH), stem color (SC), stigma color (STC), and anther color (AC) (Koç Koyun and Acar, 2021).

Plant height was measured from the soil surface to the highest point of the canopy, and canopy diameter was calculated as the mean of the maximum and minimum horizontal diameters, both recorded in centimeters. Stem diameter was measured on five newly developed shoots using a digital caliper and recorded in millimeters (Aygün and Olgun, 2015). Leaf length and width were measured on five fully developed leaves per plant. Leaf hairiness was determined on a scale of 1 to 9 based on visual observation. Stem color and Stigma and anther colors scales were used and visualized in Figure 1.

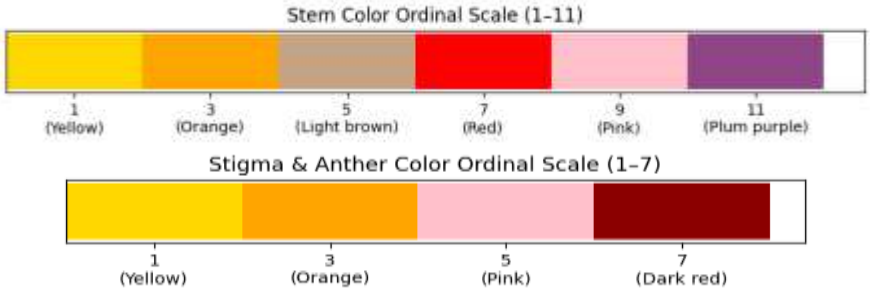

Figure 1. Stem color and stigma & anther color ordinal scale (Koç Koyun, 2021).

This experimental dataset was previously published in a conference paper focusing on descriptive trait performance (Koç Koyun, 2024). However, this study presents a new analytical framework by clearly measuring trait-level plasticity, stability, and phenotypic integrative ability under the three contrasting conditions.

Statistical Analyses

Plasticity at the trait level was calculated using the plasticity index (PI) of Valladares et al. (2006):

$PI = (X_{max} - X_{min}) / X_{max}$, (Eq 1)

where X_{max} and X_{min} are the maximum and minimum mean trait values across environments. Coefficient of variation (CV) values were calculated separately for each environment and trait to assess within-environment variation (Sokal and Rohlf, 1995). Heatmaps were used to visualize CV patterns across environments.

Finlay–Wilkinson regression analyses were performed to evaluate trait stability and environmental responsiveness (Finlay and Wilkinson, 1963). The regression slope (β) was used as an indicator of trait stability when values were close to zero, with higher β values indicating greater environmental sensitivity. Although Finlay–Wilkinson regression is often applied in multi-environment trials with more than three environments (Lian and de Los Campos, 2016), the method can be used with as few as two environments (Rio et al., 2024). Therefore, the use of three environments in this study is within the methodological limits of the approach. Nevertheless, the results are interpreted descriptively, focusing on relative trends rather than statistical inference

To examine trait associations, Spearman's rank correlation coefficient was used for all pairwise comparisons within each environment (Zar, 1972). For each pair of traits, the Spearman correlation coefficient ρ (or r_s) was calculated. Because multiple pairwise comparisons were performed (36 tests per environment), the resulting p-values were adjusted to control the false discovery rate (FDR) using the Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995), where m = 36 is the total number of tests and $p_{(1)} \leq p_{(2)} \leq \ldots \leq p_{(m)}$ are the p-values sorted in ascending order. The largest index k satisfying the following condition was identified:*

$p_{(k)} \leq (k / m) \times \alpha$ (Eq 2)

where α = 0.05. All hypotheses corresponding to $p_{(1)}, \ldots, p_{(k)}$ were rejected as statistically significant. This procedure ensures that the expected proportion of false positives among the rejected hypotheses (the false discovery rate) is ≤ α. Only correlations with $|\rho| \geq 0.5$ and FDR-adjusted $p < 0.05$ were considered statistically significant and retained for subsequent network analysis.

In network graphs, nodes represent traits, and edges represent significant correlations. Edge color indicates the direction of the correlation (positive or negative), and edge thickness is proportional to the strength of the correlation ($|\rho|$). For each network, the following metrics were calculated: number of nodes and edges, network density ($2E / [N(N–1)]$), number of connected components, node degree, weighted degree (sum of $|\rho|$), betweenness centrality, closeness centrality, eigenvector centrality, and local clustering coefficient (for IC and FWM).

Statistical analyses (CV, regression, and Spearman correlation) were conducted using JMP Pro 17 (SAS Institute Inc., Cary, NC, USA) (Sall et al., 2017). Heatmaps and network visualizations were generated using Python (Van Rossum and Drake, 2009). Trait correlation networks were constructed using the NetworkX library (Hagberg et al., 2008), and figures were created with Matplotlib (Hunter, 2007)

RESULTS AND DISCUSSION

Results

Trait-level plasticity and stability

Phenotypic plasticity was assessed using the plasticity index, CV, and β for stability, while environmental sensitivity was evaluated using β and R^2 values (Table 1). Phenotypic plasticity indices (PI) were consistently high

across all investigated traits, ranging from 0.89 for leaf hairiness (LH) to 0.99 for canopy diameter (CD), indicating high variability in trait means across the three environments. Regression slopes (β) ranged from 0.15 to 0.53, with most traits exhibiting β values below 0.5 (Table 1). The lowest β value (0.15) was observed for leaf length (LL), while the highest (0.53) was for leaf hairiness (LH), suggesting that genotype rank orders for most traits remained relatively stable across environments, with leaf hairiness being the most responsive in terms of rank change. Leaf hairiness (LH) also showed consistently low CV across all environments.

Table 1. Phenotypic plasticity, stability and environmental responsiveness of functional traits across environments. PI and regression parameters are dimensionless, while CV values are expressed as percentages.

Trait	PI	SASs_CV	IC_CV	FWM_CV	β (Slope)	R^2	P
PH	0.95	54.81	30.47	33.26	0.39	0.07	0.0116
CD	0.99	84.91	56.35	29.45	0.20	0.23	0.001
SD	0.96	96.31	69.78	51.51	0.21	0.20	0.001
LL	0.98	55.93	27.23	31.92	0.15	0.35	0.001
LW	0.94	45.57	36.62	78.37	0.22	0.19	0.001
LH	0.89	8.07	22.07	21.50	0.53	0.04	0.0608
SC	0.97	81.76	166.56	109.75	0.41	0.06	0.0169
STC	0.92	14.53	68.82	46.83	0.31	0.13	0.0016
AC	0.92	60.53	32.79	66.35	0.20	0.28	0.001

Plant Height (PH), Canopy Diameter (CD), Stem Diameter (SD), Leaf Length (LL), Leaf Width (LW), Leaf Hairiness (LH), Stem Color (SC), Stigma Color (STC) and Anther Color (AC)

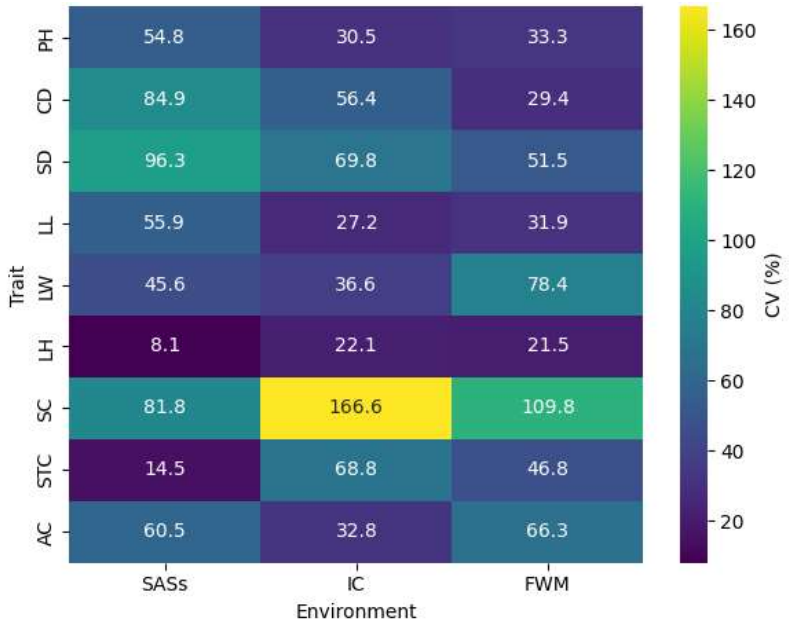

Figure 2. Heatmap of within-environment coefficients of variation (CV) for all traits under stress (SASs), irrigated (IC), and organic amendment (FWM) conditions

Within-environment coefficients of variation (CV) differed markedly among environments and traits (Figure 2). During the SASs environment, CV values were consistently higher compared to the IC and FWM environments for most traits. During the SASs environment, very high variability was observed for all traits except stigma color (STC) and leaf hairiness (LH). During the IC environment, variability was moderate, although stem color (SC) showed a CV of up to 166%. During the FWM environment, CV values ranged from moderate to high depending on the trait (Figure 2).

Environment-level trait correlation networks

The significant trait correlations (FDR-adjusted $p < 0.05$, $|\rho| \geq 0.5$) used in network analysis are summarized in Table 2, and the resulting networks are shown in Figure 3. For the SASs environment, 15 significant correlations were retained, involving 8 traits. The network had a density of 0.536 and consisted of two separate connected components (Figure 3A, Table 3). One component included all vegetative traits (PH, CD, SD, LL, LW, SC), while the other contained only the two floral color traits (AC and STC). Node-level centrality metrics (Table 4) showed that CD, PH, LL, and SD had the highest degree (5 each) and eigenvector centrality (>0.42), indicating that these traits were the most influential within the vegetative module.

In the IC environment, 6 significant correlations were retained, involving 5 traits (CD, SD, STC, LL, PH). The network was fully connected (one component) with a density of 0.600 (Figure 3B, Table 3). Stigma color (STC) had the highest weighted degree (1.913), while canopy diameter (CD) showed the highest betweenness centrality (0.50). Both STC and CD had degree values of 3, together with SD (Table 4).

In the FWM environment, only 2 significant correlations were retained, involving 4 traits (CD–PH and STC–LH). The network consisted of two independent components, each containing a single correlation, with an overall density of 0.333 (Figure 3C, Table 3). No node had a degree higher than 1 (Table 4).

Table 2. Trait correlations used to construct environment-level networks.

Environment	Trait 1	Trait 2	Spearman ρ	FDR-adjusted p
SAS	CD	PH	0.932	0.004
SAS	SD	PH	0.675	0.002
SAS	SD	CD	0.732	0.001
SAS	LL	PH	0.775	0.001
SAS	LL	CD	0.785	0.001
SAS	LW	SD	0.658	0.001
SAS	LL	SD	0.636	0.001
SAS	SC	CD	-0.645	0.001
SAS	SC	PH	-0.634	0.001
SAS	SC	SD	-0.573	0.005
SAS	LW	CD	0.551	0.005
SAS	LW	LL	0.547	0.005
SAS	SC	LL	-0.549	0.007
SAS	AC	STC	0.599	0.008
SAS	LW	PH	0.505	0.015
IC	SD	CD	0.763	0.004
IC	STC	CD	0.671	0.016
IC	STC	SD	0.637	0.023
IC	STC	LL	0.606	0.032
IC	LL	SD	0.490	0.043
IC	CD	PH	0.474	0.049
FWM	CD	PH	0.561	0.047
FWM	STC	LH	0.537	0.040

Only correlations with FDR-adjusted $p < 0.05$ and $|\rho| \geq 0.5$ are shown. The full correlation matrices (including non-significant correlations) are provided in Supplementary Table S1. Plant Height (PH), Canopy Diameter (CD), Stem Diameter (SD), Leaf Length (LL), Stem Color (SC), Stigma Color (STC) And Anther Color (AC)

Table 3. Global network metrics for SASs, IC, and FWM environments

Metric	SASs	IC	FWM
Number of nodes (N)	8	5	4
Number of edges (E)	15	6	2
Network density	0.536	0.600	0.333
Number of connected components	2	1	2
Average clustering coefficient	—	0.60	0
Components structure	Vegetative (6 nodes) + Floral (2 nodes)	Fully connected	CD–PH + STC–LH (two separate pairs)

Density = 2E / [N(N-1)]. Clustering coefficient not calculated for SASs due to component separation; for FWM, no triangles exist (C=0 for all nodes)

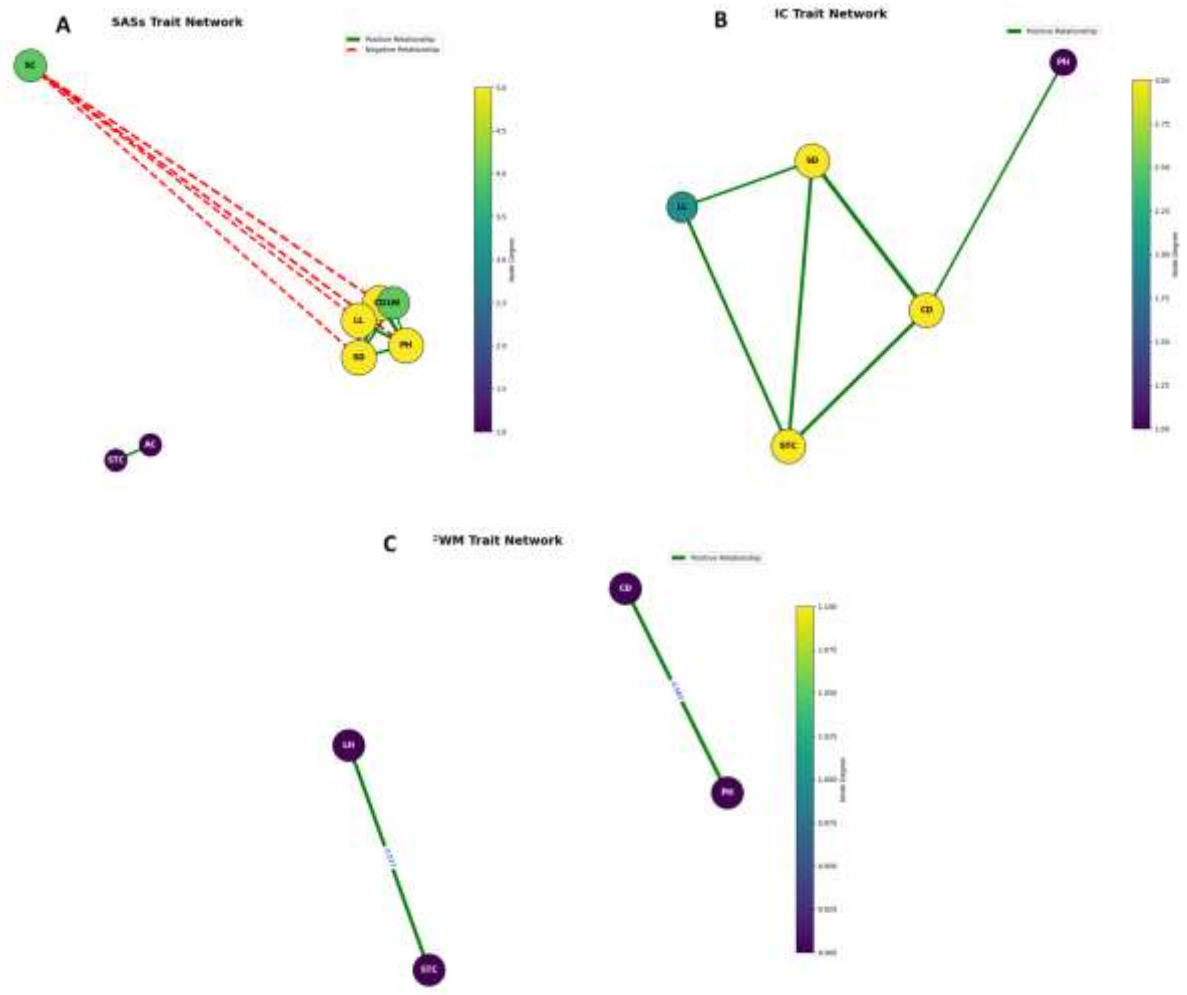

Figure 3. Network of trait correlations for A: stress-prone areas (SAS), B: irrigated condition areas (IC), and C: organic fertilization (FWM) environments.

Table 4. Node-level centrality metrics across environments

Trait	SASs Degree	SASs WD	SASs Eigen	SASs Betw.	IC Degree	IC WD	IC Eigen	IC Betw.	FWM Degree	FWM Eigen	FWM WD
CD	5	3.644	0.466	0.012	3	1.907	1.000	0.50	1	1.000	0.561
PH	5	3.521	0.454	0.012	1	0.474	0.329	0	1	1.000	0.561
SD	5	3.274	0.421	0.012	3	1.889	0.855	0.08	—	—	—
LL	5	3.292	0.428	0.012	2	1.096	0.655	0	—	—	—
LW	4	2.261	0.318	0	—	—	—	—	—	—	—
SC	4	2.400	0.339	0	—	—	—	—	—	—	—
STC	1	0.599	0.000	0	3	1.913	1.000	0.08	1	1.000	0.537
AC	1	0.599	0.000	0	—	—	—	—	—	—	—
LH	—	—	—	—	—	—	—	—	1	1.000	0.537

FWM: betweenness centrality = 0 for all nodes (each component has only one edge)
(—):The relevant feature indicates that it does not have a significant correlation in that environment.
WD = Weighted Degree, Eigen = Eigenvector Centrality, Betw = Betweenness

Discussion

In this study, the phenotypic plasticity, trait stability, and trait integration patterns of forage kochia *(Bassia prostrata)* were compared across three different environmental systems (SASs, IC, FWM). High plasticity indices (PI) were obtained for all traits, indicating that trait means differed substantially among environments. In contrast, regression slopes (β) were generally low, suggesting that genotypes responded to different environmental conditions in similar directions and largely maintained their relative performance rankings (Nicotra et al., 2010). Such a response may be advantageous in heterogeneous environments: the population may exhibit flexible trait means while preserving adaptive ranking among genotypes.

The preservation of adaptive ranking among genotypes across different environments (low genotype × environment interaction) can provide predictability for breeding programs and may be considered an indicator of wide adaptation ability (Kendal, 2015; Khalili and Pour-Aboughadareh, 2016). This strategy can also be regarded as one of the adaptation mechanisms observed in rangeland species (Pichancourt and van Klinken, 2012). Plants capable of modifying their phenotypes under changing environments can generally maintain or enhance their survival and reproductive success; this ability may allow the species to expand its ecological niche. The development of different ecotypes in changing environments can influence survival, competitive dynamics, and evolutionary capacity (Grenier et al., 2016; Hess et al., 2022).

CV values showed a wide range across the three environmental systems. During the IC environment, stem color (SC) exhibited very high variation; however, when SC was excluded, the CV range of the remaining traits was similar to those observed in the SASs and FWM systems. In all three environments, leaf hairiness (LH) consistently had the lowest CV values, indicating that LH is the most consistent trait across environments. This trait appears to be less affected by environmental change and may be maintained independently of other traits as an adaptation to reduce water loss under stress conditions (Ehleringer and Mooney, 1978).

A closer examination of SC revealed that this trait exhibited higher variation in the IC system compared to the other two systems (SASs and FWM). This suggests that under stressful conditions, plants may display color tones within a narrower range through anthocyanin synthesis (Naing and Kim, 2021). During the irrigated IC environment, plants exhibited genotype-specific colors, and this trait showed high diversity among genotypes. Such plastic responses can be considered as an effective ecological strategy for coping with abiotic and biotic stress factors (Jacob and Legrand, 2021).

During the SASs environment, the trait network separated into two distinct components: one contained all vegetative traits (CD, PH, LL, SD, LW, SC), while the other contained only the floral color traits (AC and STC). This decoupling between vegetative and generative traits suggests that plants prioritize vegetative functions over reproductive investment. This interpretation is consistent with resource allocation theory, which posits that environmental stress (e.g., resource impoverishment) favors individual strategies that enhance survival at the expense of reproduction (Bonser and Aarssen, 2009; Weiner, 2017). The high degree and eigenvector centrality of vegetative traits (particularly CD, PH, LL, and SD) suggest that these traits form a tightly interconnected module and may reflect coordinated responses to water and salt stress. Prioritizing vegetative growth under stressful conditions can be interpreted as a strategy that favors individual survival. Therefore, the separation of vegetative

and generative traits in the SASs network suggests that the plant reduces reproductive investment and gives priority to vegetative functions.

During the FWM environment, the network was extremely sparse, consisting of only two independent correlations (CD–PH and STC–LH). The correlation between leaf hairiness (LH), which showed low within-environment variability, and stigma color (STC) is noteworthy. Although no direct relationship between these two traits has been reported in the literature, a study conducted in a different species (sorghum) reported a genetic linkage between leaf tip hairiness and stigma morphology (Rangaswami Ayyangar & Venkataramana Reddy, 1939). While this finding raises the possibility of an underlying genetic basis for the relationship observed in our species, further studies are certainly needed to test this hypothesis.

In contrast, during the IC environment, the network was fully connected, with stigma color (STC) and canopy diameter (CD) emerging as central nodes. The high weighted degree and eigenvector centrality of STC under irrigated conditions suggest that when water stress is absent, reproductive traits become more integrated with vegetative traits. This pattern is consistent with the idea that under favorable conditions, plants can allocate resources to both growth and reproduction simultaneously (Bloom et al., 1985; Chapin et al., 1990).

Several limitations of this study should be acknowledged. First, the three environmental periods were applied sequentially rather than simultaneously, and the sites differed in location, year, and agronomic practices (including planting distance). Therefore, causal attribution of the observed differences to specific environmental factors is not possible. Instead, the comparisons in this study provide a descriptive assessment of the whole-system conditions prevailing in each environment. Second, transplanting plants between environments may have induced carry-over effects and transplant shock. In addition to all these potential limitations (carry-over effects, transplant shock, age), there is growing evidence that prior stress experiences can alter plant physiology (Li et al., 2022; Tan et al., 2024). This phenomenon is sometimes referred to as 'stress memory' (Crisp et al., 2016). However, the existence and benefit of this concept remain debated (Auler & do Amaral, 2025). Moreover, it has been suggested that such memory may not always be advantageous for plants and could even be detrimental by hindering recovery and development (Crisp et al., 2016). In the present study, standardizations such as root trimming (25 cm) and above-ground cutting (8 cm) were applied to minimize all these potential effects (whether carry-over or memory-related), and the potential influence of these factors is acknowledged as a limitation when interpreting the results.Third, the use of only three environments limits the generalizability of the Finlay–Wilkinson slopes; therefore, the slopes were interpreted as descriptive statistics reflecting relative trends rather than as inferential estimates.

The major strength of this study is that the same set of genetic individuals was used across all three environments. To our knowledge, this is one of the few studies to simultaneously examine phenotypic plasticity, trait stability, and phenotypic integration in a perennial semi-shrub using this approach**.** This approach eliminated genotypic variation as a confounding factor and allowed a direct assessment of phenotypic plasticity. This design is particularly valuable for outcrossing perennial species, for which the production of inbred lines or clonal replicates is not feasible.

CONCLUSION

This study demonstrates that forage kochia exhibits high phenotypic plasticity across different environmental systems, while the relative performance ranking of genotypes is largely maintained. During the stress-dominated SASs environment, within-environment coefficients of variation were markedly high. Stability analyses based on Finlay–Wilkinson regression revealed that most traits exhibited a conservative response to environmental change. Trait integration patterns varied among environments: during the SASs environment, vegetative and generative networks became decoupled, whereas during the IC environment, fully integrated networks were formed. This suggests that the ecological success of forage kochia in heterogeneous rangeland systems may arise from the combination of flexible trait means and consistent genotypic ranking. The combination of high plasticity indices and low regression slopes suggests a dual strategy—flexible trait means accompanied by consistent genotypic ranking—that may contribute to the ecological success of this species in heterogeneous rangeland systems.

These findings may have practical implications for selecting genotypes to be used in salt-affected and organically amended rangeland areas. The high genotypic variation observed during the SASs environment suggests that a broad genetic base should be evaluated in selection studies conducted in saline areas. In contrast, the weakening of trait correlations during the FWM environment may indicate that traits become more independent following organic amendment, and that a different selection strategy should be followed in such improvement programs. Therefore, multi-environment breeding trials that directly test genotype performance across different environmental systems are needed to validate the findings of this study and to test the practical recommendations derived from them.

Declaration of interests

The Author declare that there is no conflict of interest.

Author Contributions

***Nur KOÇ KOYUN*:**Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; writing— original draft; writing—review and editing.

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Original Article

Determination of Agro-Morphological Characteristics and Relationships Between Characters in Green Lentil Varieties

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ABSTRACT

Lentils are preferred for their drought resistance and their ability to be cultivated successfully in marginal areas. Due to their significant contribution to closing the protein gap in recent years, their preference rate has increased notably. However, obtaining high-yielding varieties can take many years. Even so, it is essential to understand the relationships between plant traits to guide breeding studies effectively. This study was conducted to determine the grain yield and specific yield components of green lentil varieties and to reveal the relationships between these characteristics under the ecological conditions of Mucur, Kırşehir. The research was conducted in a farmer's field in Medetsiz village, Mucur district, Kırşehir province, over two years (2021 and 2022). Ten green lentil varieties developed by various research institutes and the private sector were utilized. The experiment was conducted according to a randomized block design with 3 replications. The variables examined included plant height, first pod height, biological yield, number of pods per plant, number of grains per plant, thousand-grain weight, and grain yield per plant. Data normality was assessed using the Anderson-Darling test, and homogeneity of variances was assessed using the Bartlett test. Pearson correlation was conducted to determine the level of relationship between the variables. The results indicated that the variables were normally distributed and had homogeneous variances. According to the correlation analysis, significant positive relationships were identified between first pod height and plant height, number of pods per plant and biological yield, number of grains per plant and biological yield, yield per plant and number of grains per plant, and yield per plant and thousand grain weights were determined to be positive and significant. The highest yield was obtained from the Ceren variety, at 0.91 g/plant, whereas the lowest was recorded from the Karagül variety, at 0.71 g/plant.

Key words: Lentil, Variety, Yield, Character, Correlation

Yeşil Mercimek Çeşitlerinde Agro-Morfolojik Özellikler ile Özellikler Arası İlişkilerin Belirlenmesi

ÖZ

Mercimek bitkisi özellikle kurak koşullara dayanım ve marjinal alanlarda başarılı bir şekilde yetiştirilebilme özelliği nedeniyle tercih edilmektedir. Son yıllarda ortaya çıkan protein açığının kapatılabilmesi için yapılan çalışmalara büyük katkısı olması nedeniyle tercih edilme oranında belirgin artışlar olmaya başlamıştır. Ancak yüksek verimli çeşitlerin elde edilmesi uzun yıllar alabilmektedir. Bu gerçekleşse bile karakterler arasındaki ilişkilerin bilinmesi ve buna göre çalışmaların yönlendirilmesi faydalı olmaktadır. Bu kapsamda Mucur/Kırşehir ekolojik koşullarında bazı yeşil mercimek çeşitlerinin tane verimi ile bazı verim öğeleri yanında incelenen özellikler arası ilişkilerin ortaya konulması amacıyla yürütülen çalışma Kırşehir ili Mucur ilçesine bağlı Medetsiz köyünde çiftçi arazisi koşullarında 2021 ve 2022 yıllarında iki yıl süreyle gerçekleştirilmiştir. Farklı araştırma enstitüleri ile özel sektör tarafından geliştirilmiş 10 adet yeşil mercimek çeşidinin kullanıldığı çalışma tesadüfi blokları deneme desenine göre 3 tekerrürlü olarak kurulmuştur. Çalışmada incelenen değişkenler bitki boyu, ilk bakla yüksekliği,

biyolojik verim, bitkide bakla sayısı, bitkide tane sayısı, bin tane ağırlığı ve bitkide tane verimi olmuştur. Verilerin normal dağılım varsayımlarını yerine getirip getirmedikleri Anderson-Darling yöntemi ile belirlenirken, varyansların homojenliği ise Bartlett testi ile yapılmış, değişkenler arasındaki ilişkinin seviyesini belirleyebilmek için ise Pearson korelasyonu uygulanmıştır. Çalışma sonucunda değişkenlerin normal dağılıma sahip oldukları ve varyanslarının homojen oldukları görülmüştür. Gerçekleştirilen korelasyon analizi sonuçlarına göre ilk bakla yüksekliği ile bitki boyu; bitkide bakla sayısı ile biyolojik verim; bitkide tane sayısı ile biyolojik verim; bitkide tane verimi ile bitkide tane sayısı ve bin tane ağırlığı arasındaki ilişkiler pozitif ve önemli olarak tespit edilmiştir. Çalışmada en yüksek bitkide tane verimi 0.91 g/bitki ile Ceren çeşidinden elde edilirken, en düşük verim ise 0,71 g/bitki ile Karagül çeşidinde ortaya konulmuştur.

Anahtar kelime: Mercimek, Çeşit, Verim, Karakter, Korelasyon

INTRODUCTION

Lentil (*Lens culinaris* L.), one of the foremost food grain legumes in the Vicieae tribe of the Leguminosae family—one of the largest families in the plant kingdom—was domesticated thousands of years ago, together with chickpeas. Research has shown that small-seeded lentils originated in the high-altitude areas of Afghanistan and the Himalayan and Hindu Kush mountains; medium-seeded varieties in the mountainous lands of Central Anatolia; and large-seeded varieties in the Mediterranean, a major genetic center (Karaköy and Sözen, 2023). Today, lentil cultivation is predominantly carried out in temperate and subtropical climates worldwide. In Türkiye, however, it is practiced in all regions except for the Eastern Black Sea (Çiftçi et al., 1997).

Obtaining high yields per unit area and reducing fallow land are among farmers' primary goals in crop production. In this respect, lentils, considering their climatic requirements, can be included in cereal-legume rotations in both arid and semi-arid areas, contributing organic matter to the soil. Lentils, especially compared to other field crops that depend on natural rainfall, allow the land to be cleared quickly because of their early harvest. Due to their ability to leave a rich soil structure for the subsequent crop, lentils hold an important position among edible grain legume types.

Worldwide, lentils have a cultivation area of 6.422 million hectares, a production of 7.887 million tons, and a yield of 1,228.2 kg ha^{-1}. In Türkiye, they rank second after chickpeas with a cultivation area of 242,195 hectares, a production of 405,000 tons, and a yield of 1,672.2 kg ha^{-1} (FAO, 2024). In Kırşehir province, which is located in the center of the Central Anatolia Region and represents our study area, lentil production accounts for 18.22% of total edible grain legume production. At the provincial level, 35,483 hectares of chickpeas, 13,082 hectares of lentils, and 239 hectares of dry beans are cultivated. Green lentils, which rank second after chickpea in terms of cultivation area, yield 660 kg per hectare, which remains below the national average of 1,672 kg. The high use of local varieties and farmers' failure to follow proper cultivation techniques are the primary reasons why yields per unit area have not increased in Kırşehir.

Lentils are a vital food source for addressing hunger and malnutrition worldwide due to their high protein content (23-31%) and rich vitamin (A, B, D, and K) and mineral (Na, Cu, K, Mg, P, Ca, Fe, Mn, Zn) profiles. Furthermore, the levels of essential amino acids such as methionine, threonine, and lysine in their protein content are close to those found in animal proteins. In lentils, the proportions of these amino acids were determined to be 1.4, 3.5, and 7.3 grams per 100 grams of protein, respectively. Lentils are a rich source of soluble fiber, which helps lower cholesterol, balance blood sugar, and increase satiety, thereby contributing to weight loss and alleviating digestive system disorders (Rehinan et al., 2004). High digestibility is also considered an important attribute. In breeding such a significant plant, understanding the relationships among characteristics will enhance the success of the studies to be conducted. Due to their nutritional value, lentils are considered one of the most important plant-based protein sources, particularly for mitigating climate change. Therefore, in addition to drought-related research, determining the relationships between characteristics is of great importance for this species.

Research on many field crop species, including edible grain legumes such as lentils, reveals that evaluating parameters that directly affect yield is essential, as is examining those that influence yield in the studied genotypes. Therefore, correlation analysis is a key approach for determining yield and its contributing elements (Noor et al., 2003). Correlation analysis is a statistical method used to determine the strength and direction (positive/negative) of the relationship between two parameters; in this analysis, whether the characteristics are dependent or independent variables is not considered. The Pearson correlation coefficient, the canonical correlation coefficient, and the partial correlation coefficient are types used for different purposes and calculated in various ways. The most prominent among these is the Pearson correlation coefficient, denoted by the letter *r*, which ranges from -1 to +1 ($-1 \leq r \leq +1$). A value of 0 indicates no relationship between the variables, 1 indicates a strong and perfect positive relationship, and -1 indicates a strong and perfect inverse relationship.

In a study conducted on 9 lentil genotypes, positive and significant correlations were determined between grain yield and plant height (0.338**), yield and number of pods per plant (0.419**), yield and number of grains per plant (0.239*), and grain yield per plant (0.301*); while a negative but significant correlation (-0.322**) was determined between yield and number of grains per pod, as stated by Bildirici and Çiftçi (2001). Toklu et al. (2009) reported that the number of pods per plant, the number of seeds per plant, and the 1000-seed weight affect seed yield. Karadavut and Palta (2010), in a study spanning three years and four different environments, revealed significant correlations among chemical performance. Sözen and Karadavut (2017) stated that there is a high, positive correlation between the number of grains in the plant and yield, whereas Kakde et al. (2005) said that the direction of the observed relationship between yield and the characteristics affecting it can be determined by environmental effects.

The aim of this study is to determine the yield and yield components of green lentil varieties, developed by various research institutes and the private sector, under the ecological conditions of Kırşehir, as well as the relationships between these components. Determining these relationships could inform future breeding studies.

MATERIALS AND METHODS

The study, conducted over two years in 2021 and 2022 under the ecological conditions of Mucur/Kırşehir, was carried out in arid conditions on farmland in Medetsiz village of Mucur district, Kırşehir province ower two -years. The soil surface was cleaned, and soil samples from 3-5 cm thick and 30 cm deep were taken from four different locations, mixed, and a 2 kg soil samples was placed in a plastic bags and Samples were analyzed at a soil analysis laboratory belonging to a private company. When the soil characteristics of the farmer's land where the research was conducted were evaluated, it was found to be poor in organic matter and was rich in potassium, phosphorus, and calcium, and the experimental area had a slightly alkaline, clay-loam soil structure. The climate data for the study location are given in Table 1. When the table is evaluated, it can be seen that in the experimental area, the average temperature for the growing seasons was lowest in March (4.6 °C and 8.1 °C) and the highest in July (25.1 °C and 25.7 °C) in both years. These values were similar to the average values over many years. In terms of rainfall amounts, March (95.5 mm) of the first year and May (42.5 mm) of the second year were the months with the highest rainfall, and in both years, except for March 2021 and May 2021, the rainfall amounts were similar to the long-term rainfall amounts. Regarding the amount of humidity, there were no significant changes in either year, and relative humidity values were determined in the range of 40.5-65.4%.

Table 1. Climate data for Kırşehir province.

Months	Average Temperature (ºC)			Total Rainfall (mm)			Average Relative Humidity (%)		
	2021	2022	Long Years	2021	2022	Long Terms	2021	2022	Long Terms
March	4.6	8.1	5.5	95.5	15.5	37.8	65.4	61.5	66.5
April	12.1	10.9	10.8	19.5	25.4	42.5	56.4	55.0	62.5
May	18.2	15.9	15.5	9.5	42.5	46.5	45.2	56.5	60.5
June	19.4	20.7	19.8	35.5	38.0	37.2	55.0	49.1	54.2
July	25.1	25.7	23.4	1.1	9.8	8.5	40.5	41.0	46.5
Average	15.9	16.3	15.0				52.5	52.6	58.1
Total				161.1	131.2	172.5			

In the study, which was conducted over two years, 10 different green lentil varieties registered by various Agricultural Research Institutes and the private sector were used as material. Information on the green lentil varieties used in the study was given in Table 2.

Table 2. Green lentil varieties included in the study.

Varieites	Registering Institution	Varieites	Registering Institution
Ankara Yeşili	Field Crops Central Research Institute / Ankara	Meyveci 2001	Field Crops Central Research Institute / Ankara
Bozok		Yusufhan	
Ceren		Kayı 91	Transition Zone Agricultural Research Institute / Eskişehir
Gümrah		Sultan	
Karagül		Şahan (Çiftçi)	Olgunlar Company /Adıyaman

The research, conducted over two years, was set up using a Randomized Complete Block design with 3 replications. Seeds were sown on March 25, 2021, and March 28, 2022. Seeds was sown at 30 cm row spacing, and 5-8 cm on the rows opened with a marker, and no space was left between the plots. The plot areas were arranged as 5 x 1.2 = 6 m², with each plot consisting of 4 rows. All agricultural procedures were performed on an area of 0.6 m x 4 m = 2.4 m². The experimental plot was fertilized with 15 kg of DAP (Diammonium Phosphate/18-46-0) containing 3.0 kg of pure nitrogen and 6.0 kg of pure phosphorus for two years, starting with the planting process. In the study, irrigation water wasn't apllied both of the two years. weed control was carried out twice each year after the plants first emerged. Observations on plant height (cm), first pod height (cm), biological yield (g), number of pods per plant, number of seeds per plant, 1000-seed weight (g), and seed yield per plant were taken. 10 green lentil plants harvested for each plant traits from each plot. The data were combined over the years and subjected to analysis of variance. To determine which parameter(s) caused the significant differences among the data points an LSD test (P>0.05) was performed, followed by Pearson correlation analysis of the obtained data to identify relationships between the characters. All analyses were performed using the SPSS 22 V statistical software package.

RESULTS AND DISCUSSION

Descriptive statistics for the variables were given in Table 3. The largest range of the variation among the characteristics was in plant height (27 cm). This wide range in plant height has been explained by differences in the responses of green lentil varieties to environmental influences. It is thought that the extremely low rainfall and the heterogeneity in the soil structure in the areas where the plants are located have been effective in this change. The smallest range of variation was observed in yield per plant. The main reason for this is that the yield is quite low in all green lentil varieties, and this low yield values are similar to each other. The low yield per plant is mainly due to the fact that the plants could not properly complete the grain filling stage, especially after flowering, because of the very low rainfall observed. The fact that the standard deviation, standard error, and variance are highest for plant height indicates that the range of variation has a direct effect on the variance.

Table 3. Descriptive statistics for features.

Features	N	Range of Variation	Average	Standard Error	Standard Deviation	Variance
Number of pods per plant	30	10	21,01	0,337	1,848	3,415
Biological yield	30	9	15,48	0,339	1,857	3,447
The first pod height	30	5	6,56	0,156	,852	0,726
Plant height	30	27	26,31	1,130	6,191	38,330
Number of seeds per plant	30	25	23,98	0,990	5,423	29,413
1000-seeds weight	30	25	23,98	0,990	5,423	29,413
Yield per plant	30	1	0,80	0,033	0,182	0,033

Descriptive statistics for the green lentil varieties included in the study were given in Table 4. When the table was examined, it could be seen that plant height ranges from 19.13 cm (Şahan) to 23.00 cm (Kayı 91). When the values were examined, it was generally observed that the varieties were very close in plant height. The fact that no statistically significant difference was observed in the analysis of variance also demonstrates this. In studies conducted on plant height, Kaçar and Azkan (1997) obtained values of 19.9-27.9 cm, Bildirici and Çiftçi (2001) obtained values of 22.2-25.8 cm, Bozdemir (2007) obtained 28.9-38.0 cm, Öktem (2016) obtained 37.3-45.1 cm, Alabay (2019) obtained 25.03-29.83 cm, and Küçükay et al. (2019) obtained values of 27.5- 32.8 cm. The values obtained in our study (19.13-23.00 cm) are lower than those obtained in studies conducted on this property. It was concluded that this is due to the influence of environmental and climatic factors, as well as the genetic capabilities of the varieties.

The first pod height is a character directly affected by plant height. As plant height increases, the height of the first pod increases as well. The first pod height values ranged from 13.70 (Yusufhan) to 17.87 (Kayı 91) cm. The observed differences in first pod height were not statistically significant. This was considered an expected result. The observed similarity in plant height was also seen here. In studies conducted on this feature, Türk and Atikyılmaz (2000) 14-30 cm, Toğay (2002) 12.18-14.76 cm, Erman et al. (2005) 10-16 cm, Demirhan (2006) 10.0-16.0 cm, Bozdemir (2007) 14.4-20.1 cm, Kayan and Olgun (2012) 18.07 cm, Alabay (2019) 11.33-12.16 cm, Küçükay et al. (2019) 9.23-20.2 cm and Tekin (2019) 12.27-18.90 cm obtained values. The values obtained in this study (13.70-17.87) fell within the ranges reported by other researchers for this characteristic and were similar to those reported in the studies conducted.

Biological yield is an indicator of the amount of biological material a plant produces above ground. It is also important because it can determine the plant's tolerance to environmental conditions. Biological yield values ranged from 5.97 g (Kayı 91) to 7.50 g (Ceren). No significant difference was observed in terms of the values obtained by green lentil varieties. As can be seen, the varieties had low biological yields. The reason plants cannot grow sufficiently or utilize soil nutrients is low soil moisture content. In studies conducted on this feature, Şakar et al. (1997) 3.00-9.40 g, Biçer et al. (2001) 1.525-4.932 g, Bucak et al. (2003) 3.36-4.64 g, Erman et al. (2005) 5.93-7.68 g, Biçer and Şakar (2008a) 2.93 g, Biçer and Şakar (2011) 5.39 g, Kayan and Olgun (2012) 4.48 g, Canbolat (2014) 3.41-3.82 g and Alabay (2019) 3.56 g obtained values. The values obtained in the study (5.97-7.50) fall within the ranges reported by other researchers on this characteristic and are similar to those in our study.

The variation in the number of pods per plant is higher than that of other characteristics. The number of pods per plant ranged from 21.33 (Kayı 91) to 31.20 (Ceren), and the observed difference was determined to be significant. While a high number of pods per plant is certainly desirable, it is not significant on its own. Because what matters is not the quantity of seeds, but that they reach maturity and have the necessary weight. Otherwise, there will be many empty seeds. In this study, considering yield and thousand-seed weights, it was observed that the pods were generally filled with one or fewer seeds, but they didn't reach full filling. In studies conducted on this feature, Biçer et al. (2001) 12.1-43.8 pods, Erman et al. (2005) 9.5-34.5 pods, Demirhan (2006) 9.50-34.50 pods, Biçer and Şakar (2007a) 22.5-41.1 pods, Bozdemir (2007) 10.3-15.1 pods, Güneş (2016) 41.00-49.22 pods, Mekonnen et al. (2014) 27.80-43.3 pods, Toklu et al. (2017) 12.0-74.3 pods, Küçükay et al. (2019) 10.8-113.6 pods, Tekin (2019) 12.07-28.07 pods obtained values. The values obtained in the study (21.33-31.20 units) fall within the ranges reported by other researchers on this characteristic and are similar to those in our study.

Table 4. Descriptive statistics for varieties.

Varieties	Plant height	The first pod height	Biological yield	Number of pods per plant	Number of seeds per plant	1000-seeds weight	Yield per plant
Bozok	20.33	15.33	6.50	23.53 d	23.47 ab	32.76 b	0.79 c
Sultan	21.40	15.30	6.41	29.27 a	23.33 ab	35.04 ab	0.79 c
Kafkas	23.00	17.87	5.97	21.3 de	22.93 b	32.00 b	0.73 d
Ankara Yeşili	20.70	15.10	6.79	28.5 ab	27.42 a	32.98 b	0.88 ab
Ceren	21.07	15.73	7.50	31.20 a	26.00 a	35.27 ab	0.91 a
Karagül	22.87	16.93	6.05	25.00 c	17.83 c	39.36 a	0.71 d
Meyveci 2001	20.77	14.47	6.54	25.2 bc	24.83 a	34.99 ab	0.85 b
Gümrah	21.40	16.27	6.44	24.0 cd	23.0 ab	34.40 ab	0.80 c
Çiftçi	19.13	14.13	6.42	26.3 bc	25.93 a	29.30 c	0.74 d
Yusufhan	19.43	13.70	6.96	27.0 bc	24.42 a	34.58 ab	0.83 bc

Another characteristic affected by the number of pods per plant is the number of seeds per plant. Statistically significant differences were found in the number of seeds per plant. The number of seeds per plant ranged from 17.83 (Karagül) to 27.42 (Anakara Yeşili). The number of seeds in a plant is related to the number of pods in the plant. If the pod develops well, the plant's seed count will also be higher. In studies conducted on this feature, Kaçar and Azkan (1997) reported 10.4-16.5 units, Stoilova and Pereira (1998) 9.7-75.5 units, Şakar and Biçer (2001) 115.4-118.6 units, Koç (2004) 23.9-57.4 units, Erman et al. (2005) 12.8-54.3 units, Demirhan (2006) 12.8-54.3 units, Kayan and Adak (2006) 23-38 units, Biçer and Şakar (2007a) 33.1-57.9 units, Alabay (2019) 20.4-24.13 units, Küçükay et al. (2019) obtained values between 40.96-64.7 units and Tekin (2019) obtained values between 20.12-47.28 units. The values obtained in the conducted study (17.83-27.42 adet units) are within the range of values obtained by other researchers working on this characteristic and are similar to our study.

When green lentil varieties were examined in terms of thousand-seed weight, it was observed that the values vary between 29.30 (Şahan) and 39.36 (Karagül) g. The observed difference was deemed significant. In studies conducted on this feature, Kaçar and Azkan (1997) reported 38.1-72.4 g, Stoilova and Pereira (1998) 18-68 g, Toğay (2002) 37.06-59.14 g, Bucak et al. (2003) 33.06-40.64 g, Koç (2004) 25.25-50.50 g, and Erman et al. (2005) 26.3-65.5 g, Demirhan (2006) 26.3-65.5 g, Bozdemir (2007) 54.8-74.4 g, Biçer and Şakar (2010) 36.27 g, Kayan and Olgun (2012) 52.4 g, Katiyar and Kant (2015) 28.3 g, Güneş (2016) 35.03-38.66 g, Öktem (2016) 33.55-46.1 g, Küçükay et al. (2019) 29.1-36.4 g, Tekin (2019) 25.93-43.60 g, Faqeer et al. (2020) 60.09 g were obtained. The values obtained in the study (29.30-39.36 g) fall within the ranges reported by other researchers on this characteristic and are similar to those in our study.

One of the most important yield parameters, yield per plant, ranged from 0.73 g (Kayı 91) to 0.91 g (Ceren), and the difference between the values was significant. The fact that the Ceren variety had the highest yield indicates that it was more tolerant of environmental conditions compared to others. Values between 2.32-24.88 g (Şakar and Biçer, 2001), 0.83-1.56 g (Demirhan, 2006), 0.7-1.8 g (Biçer and Şakar, 2007a), 2.13 g (Roy et al., 2013), 13.8-27.9 g (Hussain et al., 2014) and 0.49-2.07 g (Küçükay et al., 2019) were obtained for this characteristic. The values obtained in this study (0.73-0.91 g) fall within the range above and are consistent with the findings.

In many field crop species, the interrelationships of morpho-agronomic elements can determine the yield data of the cultivated plants. In breeding programs, it is extremely important to know the intensity of the effects of factors influencing yield, both individually and in combination. In this context, the correlation coefficient (r) can provide comprehensive information for determining the direction and intensity of relationships between elements. The results of the correlation analysis, conducted to assess relationships among the variables in the green lentil varieties included in this study, were shown in Table 5.

Table 5. Results of correlation analysis between variables.

Variables	Plant Height	The first pod height	Biological yield	Number of pods per plant	Number of seeds per plant	1000-seeds weight	Yield per plant
Plant Height	1.000	0.956**	0.062	0.150	-0.048	0.332	0.119
The first pod height		1.000	0.078	0.117	-0.041	0.273	0.100
Biological yield			1.000	0.735**	0.702**	0.108	0.779**
Number of pods per plant				1.000	0.804**	0.099	0.856**
Number of seeds per plant					1.000	-0.265	0.888**
1000-seeds weight						1.000	0.175
Seed yield per plant							1.000

When the table was examined, a highly significant and positive correlation was determined between plant height and first pod height (r= 0.956**); insignificant and positive correlations were found between biological yield (r= 0.062), number of pods per plant (r= 0.150), thousand-seed weight (r= 0.332) and seed yield per plant (r= 0.119); and an insignificant but negative correlation was found between the number of seeds per plant (r= -0.048). As expected, plant height and first pod height showed a very high and significant correlation. In the study conducted by Aydoğan et al. (2006) between 2002 and 2004 to develop high-quality winter lentil varieties, a significant and positive relationship (0.756**) was found between yield and plant height.

Positive and insignificant correlations were found between first pod height and biological yield (r= 0.078), number of pods per plant (r= 0.117), thousand-grain weight (r= 0.273), and grain yield per plant (r= 0.100). An insignificant but negative correlation was found between first pod height and the number of grains per plant (r = -0.041). In a study conducted by Aydoğan et al. (2003) to characterize native green lentil populations collected from 12 provinces, the highest correlation values were found between the number of pods per plant and the number of grains per plant (0.738**), biological yield and grain yield (0.593**), and biological yield and plant height (0.387**).

Highly significant and positive correlations were found between biological yield and the number of pods per plant (r= 0.735**), number of seeds per plant (r= 0.702**), and seed yield per plant (r= 0.779**), while an insignificant and positive correlation was observed with thousand-seed weight (r= 0.108). In a study conducted in Cairo to determine the relationships between yield and yield components in 19 lines and 4 lentil varieties, Khattab (1999) showed that there were positive correlations between seed yield and plant height, number of pods per plant, number of seeds per plant, number of branches per plant, and biological yield. In addition, strong and positive correlations were observed between plant height, number of branches per plant, number of pods per plant, and biological yield.

A highly significant and positive correlation was found between the number of pods per plant and the number of seeds per plant (r= 0.804**) and seed yield per plant (r= 0.856**); while a non-significant and positive correlation was found with thousand-seed weight (r= 0.099). In a study that determined the degree and direction of relationships among the characteristics examined in terms of the lines/varieties considered in the ecological conditions of Van, it was reported by Bildirici and Çiftçi (2001) that positive and significant relationships were

found between grain yield and the number of pods per plant (r= 0.419**), the number of grains per plant (r= 0.239*) and the grain yield per plant (r= 0.301*).

While highly significant and positive correlations were found between the number of seeds per plant and seed yield per plant (r=0.888**), an insignificant and negative correlation was detected with thousand-grain weight (r=-0.265). In addition, insignificant and negative correlations were found between thousand-grain weight and grain yield per plant (r = 0.175). Chauhan and Singh (2001), in their study conducted in India for 2 years to determine the interrelationships of 21 lentil genotypes in terms of 17 parameters, reported that grain yield showed a positive and strong correlation with pod number, plant height and biological yield.

CONCLUSION

According to the results of the study conducted in 2021 and 2022 to determine green lentil varieties suitable for the ecological conditions of Mucur/Kırşehir, the two-year average grain yield per plant of green lentil varieties ranged between 0.73 and 0.91 g. The highest grain yield per plant was obtained from the Ceren variety, while the lowest grain yield per plant was observed in the Kayı 91 variety. The study results indicate that variety selection is crucial for green lentil cultivation under drought conditions. Simply growing lentils will not be sufficient, as differences among varieties in yield and yield-influencing characteristics are significant. A high correlation was found between the number of pods per plant and the number of seeds and biological yield per plant. As these values increase, yield also increases; therefore, it is necessary to focus on these variables. Based on these results, the Ceren and Ankara Yeşili varieties, which had the highest grain yield values, performed more successfully. In terms of humidity levels, there were no significant changes in either year, and relative humidity ranged from 40.5% to 65.4%.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Ufuk KARADAVUT: Conceptualization; methodology; investigation; data curation; analysis; software; writing—original draft; writing—review and editing.

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Original Article

Standardization of Culture Media and Propagation Cycle For in Vitro Multiplication of *Coffea arabica* via Organogenesis

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ABSTRACT

Coffee is the most traded produce in the international market after oil. However, its production is constrained by low propagation rate as the fruits serve as a beverage and a seed. Plant tissue culture has been used to rapidly propagate different crops because it permits true-to-type multiplication with a high ratio. This study propagated single node cuttings (SNC) of *Coffea arabica* in vitro using different growth media over five cycles. Nodal cuttings from 8 weeks coffee seedlings were disinfected and cultured in Murashige and Skoog media supplemented with different concentrations of plant growth regulators (M1: 4 mg/L Benzylaminopurine; M2: 4 mg/L Benzylaminopurine+2 mg/L Naphthaleneacetic acid; M3: 4 mg/L Naphthaleneacetic acid+4 mg/L Benzylaminopurine; M4: 4 mg/L Naphthaleneacetic acid acid+8 mg/L Benzylaminopurine; and M5: 8 mg/L+8 mg/L Benzylaminopurine) for 8 weeks in five cycles. The experiment was a 5 (media) by 5 (cycles) factorial arranged in a CRD (r=3). Data were collected on the number of roots (NOR), the number of nodes (NON), and the number of leaves (NOL). All data were analysed using ANOVA and means were separated using LSD at $\alpha_{0.05}$. The NOL, NON, and NOR differed significantly among media and ranged from 1.6±0.3 (M3) to 3.0±0.3 (M4), 2.0±0.3 (M5) to 4.9±0.3 (M1), and 0.6±0.5 (M1) to 6.4±0.5 (M5), respectively. The NOL differed significantly among culture cycles and ranged from 2.2±0.3 (M4) to 3.2±0.3 (M2). The interaction between media and culture cycle was significant on the NOL. 4 mg/L Naphthaleneacetic acid+8 mg/L Benzylaminopurine enhanced leaf and root production while 4 mg/L Benzylaminopurine enhanced nodal formation.

Key words: *C. arabica*, Nodal culture, Plant Growth Regulator, Micropropagation, Culture media.

C.Arabica'nın Organogenez Yoluyla in Vitro Çoğalması İçin Kültür Ortamının ve Yayılma Döngüsünün Standardizasyonu

ÖZ

Kahve, uluslararası pazarda petrolden sonra en çok ticareti yapılan üründür. Ancak meyveler içecek ve tohum görevi gördüğünden, üretimi düşük üreme oranı nedeniyle kısıtlanmaktadır. Bitki doku kültürü, yüksek oranda gerçek tipte çoğalmaya izin verdiği için farklı mahsulleri hızlı bir şekilde çoğaltmak için kullanılmıştır. Bu çalışma, beş döngü boyunca farklı büyüme ortamları kullanarak C. arabica'nın tek düğüm kesimlerini (SNC) in vitro olarak çoğalttı. 8 haftalık kahve fidelerinden elde edilen düğüm kesimleri dezenfekte edildi ve farklı

konsantrasyonlarda bitki büyüme düzenleyicileri (M1: 4 mg/L Benzilaminopurin; M2: 4 mg/L Benzilaminopurin+2 mg/L Naftalinasetik asit; M3: 4 mg/L Naftalinasetik asit+4 mg/L Benzilaminopurin; M4: 4 mg/L Naftalinasetik asit +8 mg/L Benzilaminopurin; ve M5: 8 mg/L+8 mg/L Benzilaminopurin) beş siklusta 8 hafta süreyle. Deney, bir CRD'de (r=3) düzenlenmiş 5'e (medya) x 5'lik (döngü) bir faktöriyeldi. Kök sayısı (NOR), düğüm sayısı (NON) ve yaprak sayısı (NOL) hakkında veriler toplandı. Tüm veriler ANOVA kullanılarak analiz edildi ve ortalamalar $\alpha_{0.05}$'te LSD kullanılarak ayrıldı. NOL, NON ve NOR medya arasında önemli ölçüde farklılık gösterdi ve 1,6±0,3 (M3) ila 3,0±0,3 (M4), 2,0±0,3 (M5) ila 4,9±0,3 (M1) ve 0,6±0,5 (M1) ila 6,4±0,5 (M5) arasında değişiyordu. sırasıyla. NOL, kültür döngüleri arasında önemli ölçüde farklılık gösterdi ve 2,2±0,3 (M4) ile 3,2±0,3 (M2) arasında değişiyordu. Ortam ve kültür döngüsü arasındaki etkileşim NOL'de anlamlıydı. 4 mg/L Naftalinasetik asit+8 mg/L Benzilaminopurin yaprak ve kök üretimini artırırken , 4 mg/L Benzilaminopurin düğüm oluşumunu artırdı.

Anahtar kelimeler: C. arabica, Nodal kültür, Bitki Büyüme Düzenleyicisi, Mikro çoğaltma, Kültür ortamı.

INTRODUCTION

Coffee (*Coffea arabica* L.) belongs to the family Rubiaceae, and the genus Coffee is mostly grown in subtropical and tropical regions of the world. Coffee is an important crop in the global market as one of the world's leading beverage and most traded produce in the international market after oil. Coffee cultivation has been reported in over 80 countries around the world of which about 70% of the producers are categorized as smallholder farmers (Khemira et al., 2024). Besides being a source of income for millions of people, it represents an avenue for the generation of foreign currency. However, the caffeine concentration in coffee depends on the coffee specie, environmental factors, and the processing method. Hence, out of the several known species of coffee, only *Coffee arabica* (arabica) and *Coffee canephora* (robusta) are the two most important and traded species accounting for about 70% and 20% global trade, respectively.

In the coffee year 2022/2023, the global total of coffee produced was 168.2 million bags, out of which Africa produced 17.9 million bags, with Kenya being the highest producer in Africa. Globally, coffee output and export is increasing every year, while it is decreasing in Africa (Krishnan, 2017). This decline could be linked to the large continental interest in producing the most consumable species (*Coffee arabica*) as it attracts larger market and pricing, because an improved production of *Coffee arabica* is location and altitude (greater than 800 m above sea level) specific. In Nigeria, unlike other African countries where *Coffee arabica* can be grown, there is an issue of rapid seedling multiplication owing to the sole reliance in the use of zygotic seed, a part that also serve for consumption, and over time, the zygotic seeds might lead to the creation of a hybrid due to cross fertilization (Ibrahim et al., 2024). The zygotic seeds also requires period of dormancy before germination, which might not serve the farmers seedling need in time. However, apart from the use of zygotic seed in seedling propagation, the in vitro propagation of coffee provides a faster and true-to-seed alternative to the dependence on zygotic seeds which is labourous and expensive (Dumaslan et al., 2023).

Plant tissue culture has been used because its permits true-to-type production and high multiplication ratio as the multiplication rate for seed propagation is 1:1 in 8 months, while micropropagation has a rate of 1:4 in 2 months. Somatic embryos of *Coffea arabica* can be induced directly from the mesophyll cells of leaf explants or indirectly from the callus mass-produced on the explants. However, the latter is the most common technique in coffee mass propagation (Tefera et al., 2007). In coffee, multiplication of Coffee arabica using organogenesis has had low efficiency because of several technical difficulties such as explant sterilization, high concentration of phenol in the explant, apical dormancy, and low rate of shoot multiplication (Raghramuhu et al. 1989). Most studies show that vegetative multiplication of *Coffee arabica* genotypes is mainly achieved by indirect somatic embryogenesis (Andrea Silva de Almeida, 2020). While the cost-effectiveness of somatic embryogenesis for commercial coffee propagation remains unsatisfactory, profitability could be enhanced by optimizing the multiplication protocol thus decreasing the production cost per somatic seedling (Etienne et al., 2013). To meet the market demand for clean and disease-free seedlings, it is important to standardize the optimum concentrations of plant growth regulators in the culture medium for the in vitro multiplication of Nigerian Blue Mountain variety of Coffee Arabica, hence the aim of this study are therefore to optimize the effect of different plant growth regulators in coffee in vitro culture and develop an effective protocol for introduction, multiplication, rooting and acclimatization of *Coffee arabica* (var. Blue mountain) in Nigeria.

MATERIALS AND METHODS

Experimental location

Tissue culture laboratory of the Mai Shayi Coffee Roasters Ltd, Jos, Plateau State, Nigeria

Experimental Materials: Plant Growth Regulators (PGRs):

α-Naphthaleneacetic acid (NAA) and Benzylaminopurine (BAP) were sourced from Sigma Aldrich.

Culture vessel: Test tubes (for disinfection and introduction) and Weck glasses (for multiplication).

Genotypes: *Coffea arabica* (Blue Mountain).

Hormone Stock Preparation Auxins

About 100 mg of auxin (NAA) were dissolved in few drops of 1N NaOH and brought up to 100 ml using distilled water and stored in refrigerator 20°C (Table 2).

Cytokinins

About 100 mg of cytokinin (BAP) were dissolved in few drops of 1N NaOH and brought up to 100 ml using distilled water and stored in refrigerator 20°C.

Experiment one: Effect of single and double disinfection regimes on the cleaning and nodal introduction of Blue mountain variety of *C. arabica*.

Single node vine cuttings of 4 months old coffee seedlings growing on a nursery bed in a screenhouse environment were cut (Fig 1), and taken to the laboratory for disinfection following the protocols outlined below for Single Disinfection (SD) and Double Disinfection (DD) protocols below;

Single Disinfecting Protocol

1. Coffee nodal cuttings are cleaned in running tap water.
2. In a Laminar flow hood, put into a glass jar, and two drops of tween 20 added into the jar.
3. 70% ethanol is poured into a jar for thirty seconds and then strained.
4. A mix of 20 ml of sodium hypochlorite and 80 ml of distilled water is poured in for 25 minutes and then strained.
5. Rinse thrice with sterilized distilled water.

Double Disinfecting Protocol

1. Coffee nodal cuttings are cleaned under running water.
2. In a Laminar flow hood, put in a glass jar where two drops of tween 20 are added.
3. For ten minutes, pour in a mix of 7 g/L of Mancozeb and 2 ml/L of Cypermethrin.
4. Take out from the mix and air dry in the flow hood for thirty minutes.
5. Put cuttings in the jar and rinse once with sterilized distilled water.
6. Pour in 70% ethanol for five minutes and then strain.
7. A mix of 50 ml of Sodium hypochlorite and 50 ml of distilled water is poured in for five minutes, then strained.
8. Rinse thrice with sterilized distilled water.

The introduction and disinfection of the nodal explants was repeated 5 times.

Figure 1. (a) Coffee seedlings in nylons (b) Nodal cuttings from coffee seedlings in screenhouse

Experiment two: Effect of media types on the multiplication of Blue mountain variety of Coffee Arabica.

Single node segments were obtained from seedlings at the Mai Shayi nursery screen house for this experiment. The nodes were introduced into media (4.43g Murashige and Skoog basal medium, 30g of sucrose, 4mg BA, 4mg NAA, 100mg Myo-inositol, 1g activated charcoal and 7g agar per litre, adjusted to a pH of 5.7±0.01 before autoclaving). To determine the effect of benzylaminopurine (BAP) and NAA concentration, the amounts per litre were varied +4mg. For each BAP and NAA concentrations, 40 single nodes were introduced into culture. The cultures were maintained at 25±2 ^{o}C under cool white fluorescent lamps with ~ 68 µmols -2.m-2 light and 16 hr photo period. Observations were taken on the number of shoots per node.

Five (5) different coffee media supplemented with varying PGR concentrations (Table 1) were prepared, dispensed into Weck-glass jars and Test tubes (50 ml per vessel), autoclaved at 121 ^{o}C and 15 Psi for 15 minutes and kept under the laminar flow hood. Single Node Cuttings (SNC) from the seeedlings were introduced into the culture media (3 SNCs per vessel) and kept under different day lengths; Long day (24 hr photoperiod) and short day (16 hr photoperiod) for 3 months.

Table 1. Culture medium regimes for coffee arabica in vitro

S/N	Treatments	Media combinations
1	M1	4.43 g/l MS + 30g/L sucrose + 4 mg/L BAP
2	M2	4.43 g/l MS + 30 g/l sucrose + 4 mg/L BAP +2 mg/L NAA
3	M3	4.43 g/l MS + 30 g/l sucrose + 4 mg/L NAA+ 4 mg/L BAP
4	M4	4.43 g/l MS + 30 g/l sucrose + 4 mg/L NAA + 8 mg/L BAP
5	M5	4.43 g/l MS + 30 g/l sucrose + 8 mg/L + NAA 8 mg/L BAP

NAA: Naphthaleneacetic acid, BAP: Benzylaminopurine, MS: Murashige and Skoog basal medium

Experiment 3: Effect of substrate types on the acclimatization of in vitro produced plantlets.

The 8 weeks old multiplied in vitro plantlets were used for the acclimatization studies. Plantlets were removed from the multiplication medium and washed with tap water to remove the remnants of culture medium, transplanted into seedling tray containing loamy soil + cocopeats (1: 1 ratio) and clay soil + cocopeat (1:1 ratio). The plantlets were covered with transparent polyethylene to ensure moderate humidity. Polythene cover were removed after two weeks to acclimatize plants to field condition.

Experimental design and layout

The experiment one was a 2 (disinfection protocol) x 5 (culture cycle) factorial, experiment two was a 5 (culture media) x 5 (cycle of introduction) factorial arranged in a completely randomized design and replicated 3 times, while the third experiment was a completely randomized design replicated 3 times. Data were collected on number of shoot, number of nodes, number of roots, clean plantlet, number of contamination, number of survived plants and number of new shoots. The data collected were analysed using Analysis of Variance (ANOVA) and differences in treatment means will be separated using Least Significance Differences (LSD)at 5% level of significance.

Molecular screening of the in vitro propagated seedlings of *C. arabica*

Sample collection / DNA extraction and screening

Six fresh leaf samples were collected from the in vitro produced plantlets at the 5th cycle of multiplication per media types in triplicates, and used for DNA extraction at the Biosciences center of the International Institute

of Tropical Agriculture, Ibadan. The DNA Extraction was carried out using the modified CTAB procedure (Doyle et al., 1987). The integrity and purity of the extracted DNA's were checked using 1% agarose gel electrophoresis and nanodrop machine. Polymerase chain reaction amplification was carried out using the matK chloroplast gene (F: 3' CGTACAGTACTTTTGTGTTTACGAG 5', R: 3' ACCCAGTCCATCTGGAAATCTTGGTTC 5') using the following condition; 1st denaturation at 94 °C for a period of 1 minute, 35 cycle denaturation for 30 seconds, annealing at 52 °C for 20 seconds, extension at 72 °C for 50 seconds, and final one cycle at 94 °C for 4 minutes according to Risa et al. (2024). To separate amplified PCR products, 0.8% agarose gel electrophoresis was used.

RESULTS AND DISCUSSION

Results

Effect explant disinfection protocol on contamination rate and *C. arabica* explant establishment in vitro

Result obtained showed that there were no significant differences between the single and double disinfection protocols on the percentage contamination of the introduced coffee nodal cuttings from 2nd to 6th week of culture, however, there were gradual increase on the percentage contamination from the 2nd to 6th week (Table 2). At 4th and 6th week of culture, the number of root formed in the nodal cultures treated with single disinfection (0.56±0.13) and (0.84±0.17) were significantly higher than the double disinfection with 0.00±0.13 and 0.00±0.17 at 4th and 6th week of culture respectively. There were gradual increase in the percentage contamination from the 2nd to 6th week of culture. At 2, 4, and 6 weeks of culture, the fifth batch of nodal introduction recorded the highest percentage contamination with 56.00±19.97, 58.00±20.45, and 66.00±22.93, respectively, and they were significantly higher than the rest batches of nodal introduction.

The number of roots formed at the 5th batches of nodal introduction (1.00±0.76) was not significantly higher than the 1st (0.50±0.76) and 2nd batches (040±0.76), but was significantly higher than the 3rd (0.00±0.76) and 4th (0.20±0.76) batches of nodal cultures. The number of nodes produced increased gradually from the 2nd week to the 6th week of culture (Table 3). At 4th week of culture, the number of nodes produced in the single node disinfected explants (3.72±0.26) was significantly higher than the double disinfected explants (2.20±0.26). Also, at the 6th week of culture, the number of leaves produced in the single disinfected explants (2.96±0.35) was significantly higher than the double disinfected explants (1.92±0.35).

The number of nodes and leaves produced increased gradually from 2nd to 6th week of culture with no significant differences amongst the batch of cultures on the number of nodes produced. At 2 weeks of culture, batch one and batch two cultures produced the highest number of nodes (2.90±0.41) which were significantly similar with other batches except batch five (1.50±0.41). At 4th and 6th weeks of culture, the highest number of leaves was produced with 3.00±0.62 and 3.00±0.56, respectively, and they were significantly similar with other cycles except cycle five with 1.10±0.62, and 1.10±0.56, respectively. The interaction between the disinfection protocol and cycle of culture introduction was significant on the number of nodes produced at the 4th week, and the number of leaves produced at 4th and 6th weeks of culture.

Table 2. Effect of explant disinfection protocol and cycle of introduction on contamination rate and root formation by *C. arabica* nodal explant in vitro

	Percentage contamination			Number of roots		
Treatments	Wk2	Wk4	Wk6	Wk2	Wk4	Wk6
double disinfection	14.40a	22.40a	37.60a	0.00a	0.00b	0.00b
single disinfection	23.20a	33.60a	42.40a	0.00a	0.56a	0.84a
LSD(0.05)	12.63	12.94	14.51	NA	0.37	0.48
SE	4.51	4.62	5.18	NA	0.13	0.17
Disinfectionxcycle	NS	NS	NS	NS	NS	NS
Batch 1	8.00b	18.00b	34.00b	0.00a	0.40a	0.50ab
Batch 2	6.00b	26.00b	26.00b	0.00a	0.40a	0.40ab
Batch 3	20.00b	26.00b	38.00b	0.00a	0.00a	0.00b
Batch 4	4.00b	12.00b	36.00b	0.00a	0.10a	0.20b
Batch 5	56.00a	58.00a	66.00a	0.00a	0.50a	1.00a
LSD(0.05)	19.97	20.45	22.93	NA	0.58	0.76
SE	7.13	7.30	8.19	NA	0.21	0.27

Means with the same alphabet down the groups are not significantly different from each other at 5% level of significance. LSD: Least significant differences, SE: Standard error, WK: week, NS: Not significant, *: Significant at 95% significant level

Table 3. Effect of explant disinfection protocol and cycle of introduction on nodal and leaf formation by *C. arabica* explant in vitro

	Number of nodes			Number of leaves		
Treatments	Wk2	Wk4	Wk6	Wk2	Wk4	Wk6
double disinfection	1.00a	2.20b	3.48a	2.48a	1.64a	1.92b
single disinfection	1.00a	3.72a	4.28a	2.56a	2.52a	2.96a
LSD(0.05)	0.00	0.73	1.44	0.74	1.09	0.99
SE	0.00	0.26	0.51	0.26	0.39	0.35
Disinfectionxcycle	NS	4.61*	NS	NS	1.56*	0.84*
Batch 1	1.00a	2.70a	4.10a	2.90a	3.00a	3.00a
Batch 2	1.00a	3.20a	4.10a	2.90a	2.20ab	2.70a
Batch 3	1.00a	3.20a	3.50a	2.50ab	1.90ab	2.20ab
Batch 4	1.00a	3.30a	4.10a	2.80a	2.20ab	3.20a
Batch 5	1.00a	2.40a	3.60a	1.50b	1.10b	1.10b
LSD(0.05)	0.00	1.15	2.28	1.16	1.74	1.56
SE	0.00	0.41	0.81	0.41	0.62	0.56

Means with the same alphabet down the groups are not significantly different from each other at 5% level of significance. LSD: Least significant differences, SE: Standard error, WK: week, NS: Not significant, *: Significant at 95% significant level

Figure 2. (a): Contaminated nodal explant (b): Clean regenerated explant via nodal cuttings

Effect of culture media and propagation cycle on *C. arabica* establishment of in vitro

The number of leaves produced by the cultured nodal explants increased gradually from 2 weeks to 8 weeks of culture in the different culture media and culture cycles (Table 4). At 8th week of culture, M4 produced the highest number of leaves (3.0±0.30) which was significantly higher than M2 (2.04±0.30) and M3 (1.56±0.30).

The highest number of leaves was produced in C2 (3.20±0.76) which was not significantly different from the rest cycles except C4 (2.20±0.76). At the 6th and 8th weeks of culture, the interaction between the culture media and the propagation cycles was significant.The number of nodes produced by the cultured nodal explants increased gradually from 2 weeks to 8 weeks of culture in the different culture media and culture cycles (Table 5). At 8th week of culture, M1 produced the highest number of nodes (4.92±0.34) which was significantly higher than the rest media except M2 (4.20±0.34).

At the 6th week of culture, the highest number of nodes was produced in C1 (2.60±0.28) which was not significantly different from the rest cycles except C3 (1.77±0.28). At the 4th week of culture, the interaction between the culture media and the propagation cycles were significant. The root formation by the cultured nodal explants increased gradually from 2 weeks to 8 weeks of culture in the different culture media and culture cycles (Table 6). At the 8th week of culture, M5 produced the highest number of roots (6.36±0.46) which was significantly higher than the rest of the media except M5 (5.80±0.46).There were no significant differences in the root formation amongst the propagation cycles and the interaction between culture media and the cycle of propagation.

Table 4. Effect of culture media and propagation cycle on the leaf production by *C. arabica* in vitro

	Number of leaves			
Treatments	Wk2	Wk4	Wk6	Wk8
M1	1.24ab	1.80ab	2.48a	2.48ab
M2	1.36a	1.60abc	2.32a	2.04bc
M3	1.00c	1.40c	2.20a	1.56c
M4	1.08bc	1.92a	2.52a	3.00a
M5	1.04c	1.44bc	2.24a	2.40ab
LSD(0.05)	0.17	0.38	0.52	0.84
SE	0.06	0.14	0.19	0.30
MediaXCycle	NS	0.84*	1.56*	4.94*
Cycle 1	1.20a	1.80ab	2.57a	3.03a
Cycle 2	1.10a	1.50bc	2.37ab	3.20a
Cycle 3	1.10a	1.50bc	2.30ab	2.97a
Cycle 4	1.07a	1.40c	2.00b	2.20b
Cycle 5	1.13a	1.87a	2.63a	2.80ab
LSD(0.05)	0.16	0.35	0.48	0.76
SE	0.06	0.13	0.17	0.27

Means with the same alphabet down the groups are not significantly different from each other at 5% level of significance. LSD: Least significant differences, SE: Standard error, M1: 30g/L sucrose + 4 mg/L BAP, M2: 30 g/l sucrose + 4 mg/L BAP +2 mg/L NAA, M3: 30 g/l sucrose + 4 mg/L NAA+ 4 mg/L BAP, M4: 30 g/l sucrose + 4mg/L IAA + 8 mg/L BAP, M5: 30 g/l sucrose + 8 mg/L +8 mg/L BAP. NS: Not significant

Table 5. Effect of culture media and propagation cycle on nodal production by *C. arabica* in vitro

	Number of nodes			
Treatments	Wk2	Wk4	Wk6	Wk8
M1	1.00b	3.92a	4.92a	4.92a
M2	1.00b	3.08b	4.20ab	4.20ab
M3	1.44a	2.88bc	3.68b	3.68b
M4	1.00b	2.40bcd	2.40c	2.45c
M5	1.00b	1.96d	1.96d	2.00c
LSD(0.05)	0.12	0.81	0.84	0.94
SE	0.04	0.29	0.3	0.34
MediaXCycle	NS	4.61*	NS	NS
Cycle 1	1.10a	3.23a	2.60a	2.97a
Cycle 2	1.07a	2.80a	2.00ab	2.73a
Cycle 3	1.07a	2.67ab	1.77b	2.57a
Cycle 4	1.10a	2.03b	2.07ab	2.40a
Cycle 5	1.03a	2.93a	2.40ab	3.00a
LSD(0.05)	0.11	0.74	0.77	0.86
SE	0.04	0.26	0.28	0.31

LSD: Least significant differences, SE: Standard error, M1: 30g/L sucrose + 4 mg/L BAP, M2: 30 g/l sucrose + 4 mg/L BAP +2 mg/L NAA, M3: 30 g/l sucrose + 4 mg/L NAA+ 4 mg/L BAP, M4: 30 g/l sucrose + 4mg/L IAA + 8 mg/L BAP, M5: 30 g/l sucrose + 8 mg/L +8 mg/L BAP. NS: Not significant

Table 6. Effect of culture media and propagation cycle on root development by *C. arabica* in vitro

	Number of roots			
Treatments	Wk2	Wk4	Wk6	Wk8
M1	0.00a	0.00c	0.00c	0.60d
M2	0.00a	1.92b	2.60b	3.24b
M3	0.00a	0.64c	1.56b	2.60bc
M4	0.00a	3.40a	4.96a	5.80a
M5	0.12a	2.00b	4.96a	6.36a
LSD(0.05)	0.14	0.87	1.38	1.29
SE	0.05	0.31	0.49	0.46
MediaXCycle	NS	NS	NS	NS
Cycle 1	0.00a	1.70a	2.90a	3.57a
Cycle 2	0.10a	1.97a	3.57a	3.60a
Cycle 3	0.00a	1.63a	3.17a	3.17a
Cycle 4	0.00a	1.53a	2.57a	3.03a
Cycle 5	0.00a	1.53a	3.10a	3.73a
LSD(0.05)	0.13	0.79	1.26	1.17
SE	0.05	0.28	0.45	0.42

Means with the same alphabet down the groups are not significantly different from each other at 5% level of significance. LSD: Least significant differences, SE: Standard error, M1: 30g/L sucrose + 4 mg/L BAP, M2: 30 g/l sucrose + 4 mg/L BAP +2 mg/L NAA, M3: 30 g/l sucrose + 4 mg/L NAA+ 4 mg/L BAP, M4: 30 g/l sucrose + 4mg/L IAA + 8 mg/L BAP, M5: 30 g/l sucrose + 8 mg/L +8 mg/L BAP. NS: Not significant

Figure 3. Clean introduced coffee cultures in the laboratory

Postflask acclimatization of in vitro propagated *C. arabica*

Results obtained on the postflask hardening of the in vitro propagated plantlets using two substrate mix showed that there were no significant differences between the substrates in the percentage survivals, number of new shoots, number of nodes produced at 4 and 6 weeks of acclimatization, and number of roots at 4 weeks old. However, at 8 weeks of acclimatization, the number of roots produced in a mixture of loam and cocopeat (1:1 by volume) was significantly higher than in the mixture of clay and cocopeat (1:1 by volume) (Table 7) (Fig 4).

Table 7. Effect of substrate types on the postflask acclimatization of in vitro propagated *C. arabica*

	Percentage survival		Number of new shoots		Number of nodes		Number of roots	
Substrate	PS4	PS8	NNS4	NNS8	NON4	NON8	NOR4	NOR8
loam+cocopeat	73.75a	48.75a	2.00a	3.75a	2.50a	2.50a	0.50a	2.00a
clay+cocopeat	52.50a	42.50a	0.50a	2.50a	2.00a	1.75a	0.00a	0.00b
LSD(0.05)	37.34	29.92	2.34	1.37	0.71	0.93	0.71	1.41
SE	13.34	10.69	0.836	0.49	0.25	0.33	0.25	0.50

Means with the same alphabet down the groups are not significantly different from each other at 5% level of significance. LSD: Least significant differences, SE: Standard error, PS: Percentage survival, NNS: Number of new shoots, NON: Number of nodes, NOR: Number of roots

Figure 4. Experimented with stem cutting multiplication of coffee with high mortality

Molecular characterization of regenerated plantlets

High quality DNAs were extracted from the in vitro plantlets (Fig 5), with all the plantlets showing visible bands and amplified with matK chloroplast gene at 300 base pair (Fig 6).

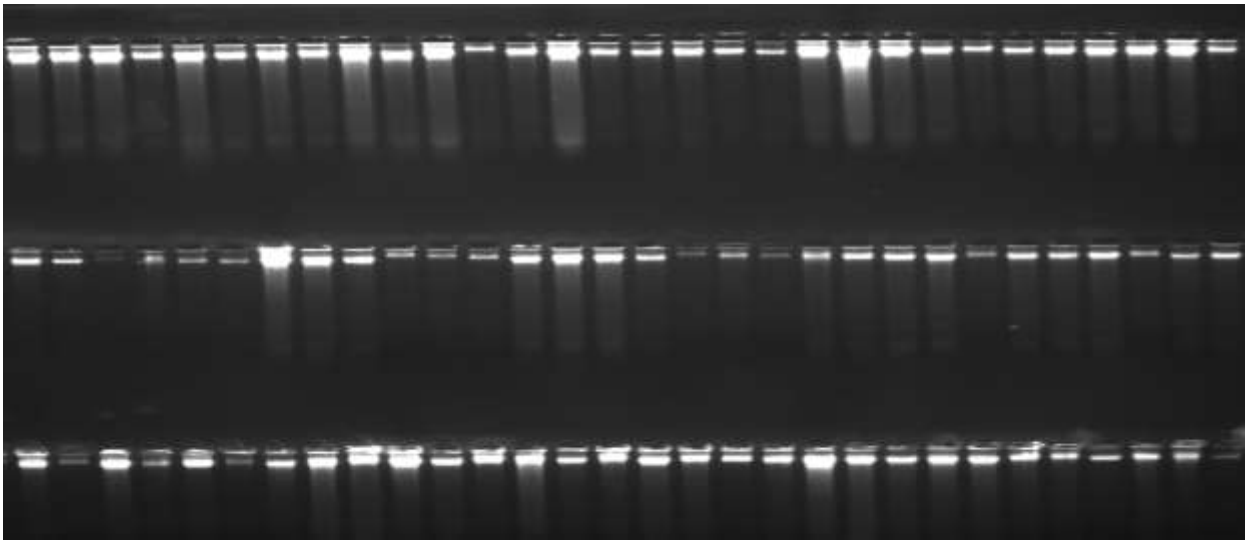

Figure 5. The extracted genomic DNA visualized at 1% agarose gel electrophoresis

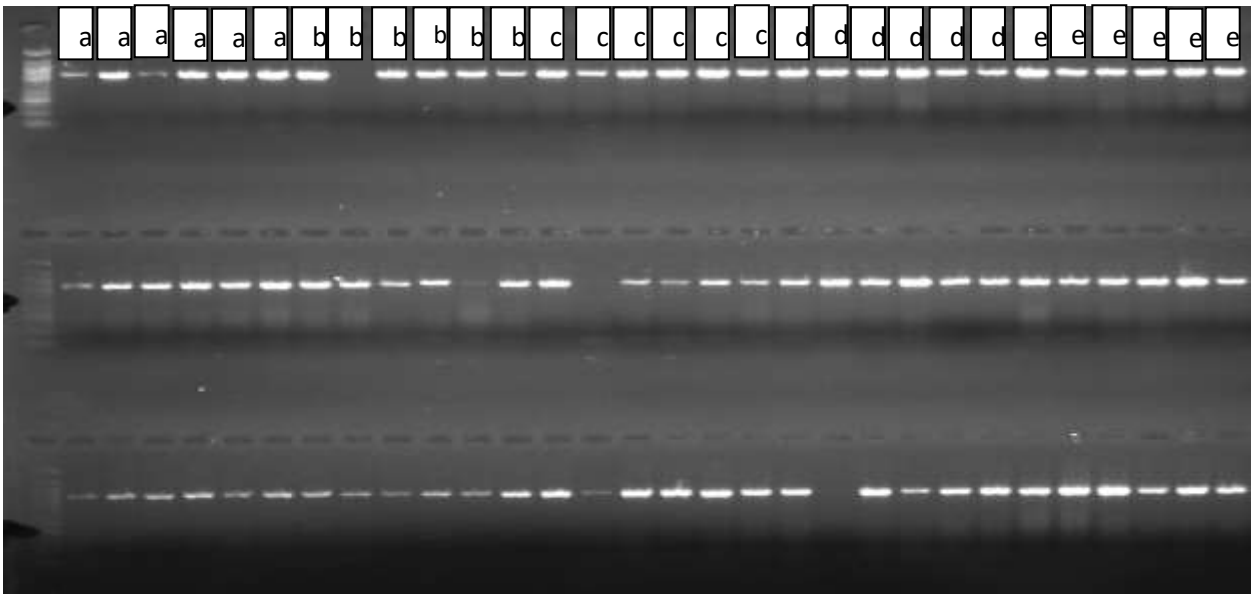

Figure 6. matK gene amplification result visualized on 0.8% agarose gel electrophoresis.
Keys: a (1-6): M1 plantlets, b (1-6): M2 plantlets, c (1-6): M3 plantlets, d (1-6): M4 plantlets, e (1-6): M5 plantlets.

Discussion

Plant tissue culture possesses the potential of rapidly multiplying plants including coffee within a short period of time and space (Tahakik, 2023). However, the phase of nodal introduction from greenhouse to the laboratory is characterized by microbial contamination which could lead to part or total loss of the explants (Abatenh et al., 2018). To address the contamination loss in tissue culture, different disinfection protocols have been used in the aseptic introduction of nodal explants in vitro, notably by the exposure of the explants to a combination of fungicides and insecticides (Balogun et al., 2017). In this study, the exposure of the nodal explants to a mixture of mancozeb and cypermethrin before sodium hypochloride was as effective in eliminating the microbial / fungal contaminants in the explants as the single disinfection protocol where the explants were exposed to only sodium hypochloride. This shows that the initial period of explants exposure to mancozeb and cypermethrin reduced the microbial / fungal contaminant loads before exposure to sodium hypochloride, however, the difference in result obtained between the two disinfection protocol is negligible as both were effective in reducing the microbial loads inherent in the introduced explants. This finding agrees with the report of Balogun et al. (2017) while working on the relative efficiency of yam disinfection methods that subjecting yam stem explants to a double disinfection protocol helps to reduce the microbial loads associated with the explants introduced from the field or green houses that are less sterile than the tissue culture environment. Sandle (2020) also explained further that due to the different sources of the microbial contaminants, broad spectrum of fungicide/bactericide is needed to reach the target organisms which presents an advantage for the use of double disinfection as against the single disinfection which could only target a limited spectra of microbes accompanying the coffee explants. Also, the findings of this study agrees with Florisa et al. (2020) who stated that the utilization of double disinfection protocol was more effective in elimination microbial contaminants in *Clinacanthus nutans*, although their constituent differs from those used in this study.

However, the explants are tender and fragile, which presents a case for the explants to be exposed to insecticides / fungicides for a considerably limited period of time to avoid damage to the active cellular tissues and alter their regeneration ability. This is evident in the delayed root, and shoot formation in the double disinfected explants, while the single disinfected nodal explants regenerated shoots and roots faster. This agrees with the report of Hashim et al. (2021) while working on *Clinacanthus nutans*. Also, the contamination load was heavier in the later batch of explant introduction than the earlier ones because the explants were cut from seedlings older in age which allows for heavier contamination loads due to rapid multiplication of microorganisms in the seedlings over time (Babu et al., 2022). The age of the seedlings / explants also plays a vital role in the totipotent and plasticity of the explants in vitro, as older the explants, the less totipotent it becomes (Ossai et al., 2023). This shows why the earlier cut explants responded faster to shoot formation up to the 4^{th} cycle and started depreciating at the 5^{th} cycle. Also, since the time of explant collection varies, the fluctuation in microclimatic condition can affect the survival rate of the explants as explained by Isah (2019) that nodal explants collected during winter have a higher survival rate than the ones collected during summer in vitro.

After the establishment period of in vitro introduced plantlets, the advantage of the use of tissue in propagating coffee comes in the number of times the plantlet is being subcultured to exponentially increase the number of plantlets in vitro, and ultimately justify the cost of inputs for the system. In this present study, the introduced explants were assessed up to the 5^{th} cycle of subculturing, with the rate of shoot production reducing gradually as the cycle increases. This finding agrees with other scientific findings that as the cycle of subculture increases, the rate of multiplication decreases (Pastelin et al., 2019). Although, reports that at the 5^{th} cycle of multiplication marks the end of the subculture cycle leading to acclimatization as there were no report of DNA methylation to the explants produced (Agbidinoukoun et al., 2017) following same protocol. However, DNA methylation could arise from the prolonged exposure of the tender explants to insecticides / fungicides during the disinfection period and the culture media constituents leading to somaclonal variation. However, the molecular screening of the coffee regenerants showed that all the regenerants are true-to-type irrespective of the culture media utilized in the multiplication, which also agrees with the findings of Agbidinoukoun et al. (2017) while working on yam in vitro and Pastelin et al. (2019) who worked on vanilla in vitro.

CONCLUSION

This study has shown that the exposure of coffee nodal explants to a double disinfection stages before its culture in vitro was more effective in the elimination of microbial contaminants than one stage explant exposure. However, single disinfection method established faster due to minimal cellular disruption than the double disinfection. Also, contamination was higher in older batches due to explant age and time allowed for microbial multiplication in the postflask. The media combinations of 30 g/l sucrose + 4 mg/L BAP +2 mg/L NAA was the most effective in multiplying the coffee in vitro. The in vitro propagated coffee seedlings were effectively acclimatized using a combination of clay and loamy soil (1:1 by volume).

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Original Article

Willingness of Hemp Farmers to Establish Producer Organizations: Evidence from Samsun, Türkiye

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ABSTRACT

Producer organizations play a significant role in agricultural value chains in terms of controlling the market, enhancing bargaining power, and ensuring economic sustainability. Industrial hemp is of strategic importance as a high-value-added fiber crop. However, in Türkiye, the hemp sector is largely dominated by private companies, and there is no producer organization established and operated by producers. The purpose of this study is to determine the willingness of hemp producers in Samsun Province, Türkiye's most important hemp-producing region, to establish a producer organization and to identify the factors influencing this willingness. The data for the study were obtained from face-to-face surveys conducted with 112 hemp producers selected using simple random sampling. The CART algorithm was used to identify the factors influencing the willingness to organize. The results show that the majority of farmers (89.3%) are willing to establish agricultural organizations. According to the results of the CART algorithm, none of the hemp producers who have had negative experiences with cooperatives in the past are willing to organize. Other important factors influencing the willingness to organize include having farming as one's primary occupation, the area under hemp cultivation, and the age of the producers. The findings indicate that institutional trust, rather than sociodemographic characteristics, is the primary determinant of decisions to establish producer organizations. This result indicated that rebuilding social trust following cooperative failures may be a lengthy process. To enable producers in the hemp sector to have a say in the market, increase their competitive and bargaining power, and achieve a sustainable structure, action must be taken to establish an organization by capitalizing on producers' strong willingness to organize.

Key words: Producer organization, CART algorithm, hemp, willingness to establish, Türkiye.

Kenevir Üreticilerinin Üretici Örgütü Kurma İstekliliği: Samsun İli Örneği

ÖZ

Üretici örgütleri, tarımsal değer zincirlerinde piyasa kontrolünün sağlanması, pazarlık gücünün artırılması ve ekonomik sürdürülebilirliğin desteklenmesi açısından önemli bir rol üstlenmektedir. Endüstriyel kenevir, yüksek katma değerli bir lif bitkisi olması nedeniyle stratejik bir öneme sahiptir. Buna karşın Türkiye'de kenevir sektörü büyük ölçüde özel firmaların hâkimiyetinde olup, üreticiler tarafından kurulan ve işletilen üretici örgütleri bulunmamaktadır. Bu çalışma, Türkiye'nin önemli kenevir üretim bölgelerinden biri olan Samsun ilinde kenevir üreticilerinin üretici örgütü kurma istekliliğini belirlemeyi ve bu istekliliği etkileyen faktörleri ortaya koymayı amaçlamaktadır. Araştırma verileri, basit tesadüfi örnekleme yöntemiyle seçilen 112 kenevir üreticisiyle yüz yüze gerçekleştirilen anketlerden elde edilmiştir. Üreticilerin örgütlenme istekliliğini etkileyen faktörlerin belirlenmesinde ise CART algoritmasından yararlanılmıştır. Araştırma bulguları, üreticilerin büyük çoğunluğunun (%89.3) üretici örgütü kurmaya istekli olduğunu göstermektedir. CART analizi sonuçlarına göre, geçmişte kooperatiflerle olumsuz deneyim yaşayan üreticilerin hiçbirinin örgütlenmeye istekli olmadığı belirlenmiştir.

Örgütlenme istekliliğini etkileyen diğer önemli faktörler ise üreticilerin temel mesleğinin çiftçilik olması, kenevir ekim alanı büyüklüğü ve yaş değişkenidir. Araştırma sonuçları, üretici örgütü oluşturma kararında sosyo-demografik özelliklerden ziyade kurumsal güvenin temel belirleyici olduğunu ortaya koymaktadır. Bulgular ayrıca, kooperatiflerin başarısızlıklarının ardından sosyal güvenin yeniden tesis edilmesinin zaman alacağını göstermektedir. Kenevir sektöründe üreticilerin piyasa içerisinde daha güçlü bir konuma sahip olabilmesi, rekabet ve pazarlık gücünü artırabilmesi ve sürdürülebilir bir yapının oluşturulabilmesi için üreticilerin yüksek örgütlenme istekliliğinin işlevsel örgütsel yapılara dönüştürülmesi önem taşımaktadır.

Anahtar kelimeler: Üretici örgütleri, CART algoritması, kenevir, kurma istekliliği, Türkiye.

INTRODUCTION

Hemp (Cannabis sativa L.) is an extraordinary plant that has economic and environmental benefits. Due to its environmental benefits and rapidly expanding market, hemp cultivation is given great importance in countries around the world, and hemp cultivation and production are rapidly increasing due to its advantages. It is also used as a raw material for making more than 50,000 different products from food, medicines, livestock feed, fuel, plastics to construction and textiles (Johnson, 2014; Tutek and Masek, 2022; EIHA, 2023).

Hemp is produced for two different purposes: seeds and fiber. According to 2025 data from the Food and Agriculture Organization (FAO), a total of 34,000 tons of hemp seeds and 85,000 tons of hemp fiber were produced worldwide in 2023 (FAO, 2025). Hemp seed production takes place in only eight countries worldwide: Canada, Australia, Chile, Russia, the United States, Ukraine, Türkiye and Iran. Being one of these eight countries makes Türkiye strategically important. Hemp fiber production, on the other hand, is carried out across a broader geographical area, with European Union (EU) countries leading the way after Korea and China. Türkiye is also among the countries that produce fiber. As with seeds, there is a significant upward trend in fiber production.

According to data from the European Industrial Hemp Association (EIHA), the area under hemp cultivation in the EU has increased significantly in recent years. An analysis of data from 2015 to 2022 shows that the area under hemp cultivation rose by 60% from 20,540 hectares to 33,020 hectares, while hemp production increased by 84% from 97,130 tons to 179,020 tons. France, which accounts for more than 60% of EU hemp production, is the leading producer, followed by Germany with 17% and the Netherlands with 5% (European Commission, 2024). Compared with 1993 figures, hemp cultivation areas in Europe have increased by 614% (EIHA, 2023). Within the EU, hemp producers benefit from direct payments provided under the Common Agricultural Policy (CAP). However, the tetrahydrocannabinol (THC) content of hemp varieties must be below 0.3%. Under certain conditions, the EU also provides Voluntary Coupled Support (VCS) to hemp growers. In addition, hemp producers benefit from rural development support provided under the second pillar of the CAP. These supports are designed to facilitate hemp-related investments, knowledge transfer, business creation, innovation, supply chain organization, organic farming, environmental protection, and responses to climate events (European Commission, 2024).

In 1961, hemp production in Türkiye amounted to 5,000 tons of hemp seed cultivated on 13,700 hectares and 10,700 tons of hemp fiber cultivated on 7,100 hectares. However, according to 2024 data, hemp seed production has decreased to 556 tons on 720 hectares, while hemp fiber production stands at 1,216 tons on 884 hectares (TURKStat, 2024). In other words, Türkiye's hemp cultivation areas have significantly declined over time. An examination of Türkiye's hemp policies reveals that there are no agricultural subsidies provided for hemp, and hemp was included in national development plans for the first time in the 11th Development Plan (2019–2023). It is also featured in the current 12th Development Plan (2024–2028), which states that industrial hemp production will be increased through the use of domestically developed varieties (Art. 491.5) (Official Gazette, 2024). Hemp production is permitted in 19 provinces in Türkiye. But Samsun province emerges as the leading province. Samsun has been the most important hemp producer in Türkiye from past to present. Between 2009 and 2018, the cultivation and production of hemp seed and fibre in Türkiye took place exclusively in Samsun province. Samsun accounted for 36% of Türkiye's hemp seed cultivation in 2021. For hemp fibre, Samsun made up 51% of cultivation in 2022. For this reason, Samsun Province was selected as the research area (TURKSTAT, 2024). Despite Türkiye's historical importance in hemp production, there are currently no agricultural organization established by hemp producers in Samsun, the leading province in hemp cultivation. This lack of producer organization has resulted in a market dominated by private sector actors, leaving farmers with limited influence over prices and supply chain decisions.

Ensuring sustainability in the agricultural sector, addressing producers' problems, improving their economic and social welfare, and shaping agricultural policies make producer organization indispensable (Kılıç

Topuz et al., 2022). Producer organizations in agriculture are regarded as the most important tool for agricultural development by most countries worldwide (Karami and Moghaddam, 2005), and being a modern society is associated with being organized. Agricultural organizations play a crucial role in achieving sustainable development in agriculture and provide farmers with numerous benefits, such as marketing their products at higher prices, reducing costs, increasing awareness and product quality through education, fostering cooperation with other stakeholders, facilitating easier market access, ensuring food security, and mitigating risks (Kilic Topuz, 2023). In the European Union, which includes the world's leading hemp-producing countries, it is observed that stakeholders across the supply chain have organized themselves starting from producers and established the European Industrial Hemp Association (EIHA) 20 years ago. EIHA is an organization representing more than 200,000 members across the entire industrial hemp value chain, from seed to shelf, including farmers, processors, and traders. It represents 25 EU member states and 12 non-EU countries. The association monitors EU hemp-related policies and the CAP, advocates for the hemp sector in EU policy decisions, and is able to influence policymaking (EIHA, 2023). In France, the largest hemp-producing country in the EU, the La Chanvrière cooperative was established in 1973 by hemp producers as a production, processing, and marketing cooperative. The cooperative, which accounts for 50% of France's hemp production and 30% of Europe's total hemp production, holds a significant market share, and through it, farmers learn and apply good agricultural practices to achieve the best yields (La Chanvrière, 2024). In addition, the Nordic Hemp Cooperative was founded in 2017 by the five largest hemp farmers in Estonia, and more than half of the country's hemp harvest is produced on over 6,000 hectares owned by cooperative members (Nordic Hemp, 2024).

In fact, in the EU, which includes some of the world's leading hemp producing countries, the hemp sector is organized along the supply chain beginning with producethis . Recent studies in the literature (Atalik and Kilic Topuz, 2025; Ayan and Kilic Topuz, 2025) emphasize that Türkiye needs a cooperative-based organisation in both hemp fibre and hemp seed production, as in the EU, and that this can carry Türkiye among the most important countries in the hemp sector in the coming years. However, there is no agricultural cooperative or similar organization established by hemp producers in Samsun province. For this reason, the private sector dominates the market at all stages of the supply chain, and producers are unable to intervene in the market (Ayan and Kilic Topuz, 2025). So, this problem is seen as the most important deficiency in the sector and it is of great importance for producers to unite by forming cooperatives in order to ensure the sustainability of hemp production.

Hemp is a product with very high potential in both domestic and international markets, so it is inevitable that producers form cooperatives to minimize the profits of intermediaries. Indeed, a study conducted in France, the EU's largest hemp producer and holder of 90% of the market, states that the hemp sector will disappear without being organized in the form of cooperatives (Bertucelli, 2013). Hellwinckel (2020) states that in the hemp sector, which he defines as the history and bright future of agriculture, small farmers can only market their products at a fair price and cover their production costs through cooperatives, and that national governments must take steps now to design a quota system operated by cooperatives. The objective of this study is to determine the willingness of hemp producers to establish a producer organization in Samsun, the most important cannabis producing province in Türkiye. In addition, the study identifies the factors influencing the willingness of hemp farmers to establish producer organization.

MATERIALS AND METHODS

Data collection methods

In Türkiye, hemp production is permitted in 19 provinces in accordance with the regulation numbered 29842 put into force by the Ministry of Agriculture and Forestry (MofAF) in 2016 (Fig. 1) (MoAF, 2025). However, Samsun province emerges as the leading province. Between 2009 and 2018, the cultivation and production of hemp seed and fibre in Türkiye took place exclusively in Samsun province. Samsun accounted for 36% of Türkiye's hemp seed cultivation in 2021. For hemp fibre, Samsun made up 51% of cultivation and 77.4% of hemp fiber production (TURKStat, 2024). For this reason, Samsun Province was selected as the research area.

According to the data obtained from Samsun Provincial Directorate of Agriculture and Forestry, in 2023, hemp cultivation was realized in Samsun province in an area of 2,760 decares, including hemp fiber in 2,025 decares and hemp seed in 735 decares (Anonymous, 2023). In this study, the main population consists of 172 hemp farms in Samsun province. The number of samples was determined based on the amount of hemp seed and fiber land (decares) cultivated by the hemp farms in the 2023 production period. The number of farms to be

included in the sample was calculated with the help of the following formula (1) according to the Simple Random Sampling Method (Yamane, 2010).

$$n = \frac{N(zC)^2}{Nd^2+(zC)^2} \quad (1)$$

In the formula,

N: Number of hemp farms in the main population (172),

z: The standard normal distribution value (1.65) corresponding to the desired degree of confidence (90%),

C: Coefficient of variation (Standard deviation/mean=14.75/13.5=1.09),

d: The margin of error accepted in the research (±%10),

n: Represents the number of samples required.

The margin of error accepted in the research is 10% and the sample volume is calculated as 112 at 90% confidence interval. In the research, a face-to-face survey was conducted with 112 hemp farms managers in Samsun province in January-February 2025.

$$n = \frac{172 * (1.65 * 1.09)^2}{172 * (0.10)^2 + (1.65 * 1.06)^2} = 112$$

The primary data of the research were obtained from face-to-face surveys with 112 identified hemp farmers. Face-to-face surveys were successfully completed with all selected participants; therefore, no non-response problem occurred in the study. No distinction was made between seed and fiber production in the selection of hemp farmers to be surveyed. In the research, secondary data were also obtained from published domestic and foreign literature on the subject, data, reports, etc. of domestic and foreign institutions and organizations.

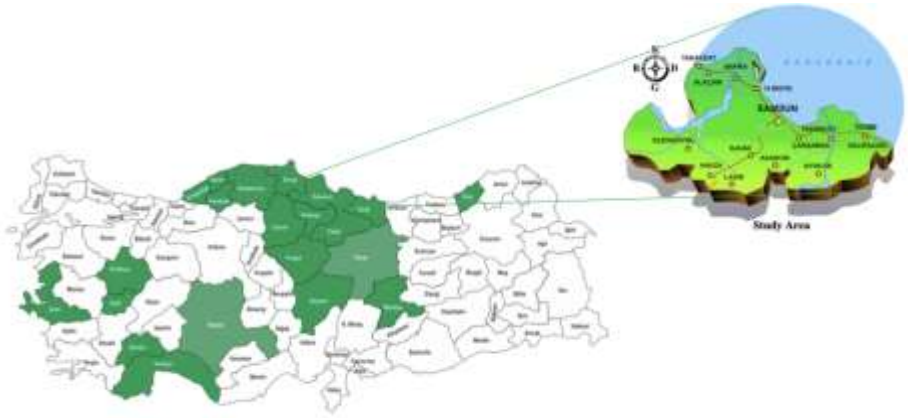

Figure 1. Map of provinces in Türkiye where hemp production is allowed (Source: Ministry of Agriculture and Forestry, 2025)

Data analysis methods

Classification (logistic regression, discriminant, cluster analysis, etc.) and regression models are frequently used in scientific studies to identify factors that statistically significantly affect the dependent variable. However, the assumptions that these models must satisfy limit the possibilities for statistical analysis in many areas. Classification and regression models emerge as a powerful alternative because they do not require any assumptions on the dataset being analyzed. In research, data mining decision tree algorithms are preferred due to reasons such as having fewer assumptions compared to other statistical methods, being visually easy to understand, and being applicable to large datasets (Pehlivan, 2006).

CHAID, Extended CHAID, and CART (Classification and Regression Tree) are regression tree methods based on data mining algorithms. They are preferred methods due to their advantages, such as not requiring any assumptions about the distribution of independent variables, and not being affected by multicollinearity, outliers, and missing observations (Mendeş and Akkartal, 2009). The CART algorithm has important advantages such as the ability to include both continuous and categorical data in the model simultaneously and not requiring any assumptions about the distribution of independent variables (Pehlivan, 2006; Mendeş and Akkartal, 2009; Karakaya et al., 2018). In this study, the CART algorithm (regression tree approach) was utilized to determine the

factors influencing the willingness of hemp farmers to establish a producer organization. The method was preferred because it enables the identification of the relative importance of explanatory variables and their interactions in the decision-making process. In addition, the easily interpretable tree structure helps to provide a clearer understanding of the factors influencing farmers' willingness to organise.

The CART data mining algorithm developed by Breiman et al. (1984) starts from the root node covering all individuals in the data set (learning sample) and continues iteratively until it reaches homogeneous nodes, creating only two child nodes from each node at each stage. CART is a non-parametric method that automatically incorporates important independent variables into the tree structure (Nisbet et al., 2009). When the dependent variable is categorical, the resulting trees are called classification trees, and when it is continuous, the resulting trees are called regression trees. In this study, the dependent variable is categorical data, as it involves hemp producers who are willing and unwilling to organize. The classification table used in the study is provided in Table 1. Analyses related to the CART algorithm were performed using the IBM SPSS (Statistical Package for Social Sciences) 25 software package.

Table 1. Classification table

Algorithm result	Actual situation		
	Unwilling	Willing	Total
Unwilling	A (GUW)	B (FUW)	A+B
Willing	C (FWP)	D (GWP)	C+D
Total	A+C	B+D	A+B+C+D

A: It provides the number of those who are not willing to organize and who are determined to be unwilling to organize according to the algorithm used, and they are referred to as Genuine Unwilling -GUW-.

D: It provides the number of those who are truly willing to organize and who are identified as willing to organize according to the algorithm used, and they are referred to as Genuine Willing Participants (GWP).

C: It provides the number of those who are truly reluctant to organize and those who are willing to organize according to the algorithm used, and they are referred to as False Willing Participants (FWP).

B: It provides the number of those who are truly willing to organize and those who are unwilling to organize according to the algorithm used, and they are referred to as False Unwilling -FUW.

In determining the most appropriate data mining algorithm for data on factors affecting willingness to establish producer organization, the method defined by Alpar (2012) was used to determine the validity of qualitative tests. To decide on the best algorithm in terms of prediction performance, correct classification (%), sensitivity, specificity, and the area under the ROC curve were calculated.

$$\text{Accurate classification rate (\%)} = \frac{A+D}{A+B+C+D} \quad (2)$$

$$\text{Sensitivity rate (\%)} = \frac{A}{A+C} \quad (3)$$

$$\text{Specificity rate (\%)} = \frac{D}{B+D} \quad (4)$$

The descriptive statistics of the dependent and independent variables used in the CART algorithm analysis were presented in Table 2. In the study, the dependent variable was based on the willingness to establish an agricultural organization (Willingness_Coop). The independent variables of the study were the age of hemp farmers (AGE), educational status (EDUCATION), primary occupation (M_OCCUPATION), hemp cultivation area (HEMP_AREA), bad cooperative experiences in the past (BAD_COOP_EXP) and satisfaction with hemp production (SATISFACTION).

The hypotheses formulated to determine the factors affecting hemp producers' willingness to establish producer organizations were as follows:

H_1: As the educational level of hemp farmers increases, so does their willingness to establish producer organization.

H_2: Those whose main occupation is farming are more willing to establish producer organizations.

H_3: Farmers who have had bad experiences with cooperatives in the past are reluctant to establish new agricultural cooperatives.

H_4: As satisfaction with hemp production increases, so does the willingness to establish producer organizations.

H_5: As farmers age, their willingness to establish producer organizations increases.

H_6: As the area under hemp cultivation increases, so does the willingness to establish producer organizations.

Table 2. Descriptive statistics of variables

Variables	Definition of variables	n	%	
Dependent variable				
Willingness_Coop	0. Not willing to establish a producer organization	12	10.7	
	1. Willing to establish a producer organization	100	89.3	
Independent Variables				
Categorical variables		Expected effect		Hypothesis
EDUCATION	1. Primary school and below	-		
	2. Middle and high school graduates	-/+		H_1
	3. University graduate	+		
M_OCCUPATION	0. Main occupation is farmer	+		H_2
	1. Main occupation is not farmer	-		
BAD_COOP_EXP	0. Those who have not had bad cooperative experiences in the past	-		H_3
	1. Those who have had bad cooperative experiences in the past	+		
SATISFACTION	0. Not satisfied with hemp production	-		H_4
	1. Satisfied with hemp production	+		
Continuous variables				
AGE	Age of hemp farmers (year)	+		H_5
HEMP_AREA	Hemp cultivation area (da)	+		H_6

RESULTS AND DISCUSSION

Descriptive statistics

The socio-demographic and farm characteristics of hemp farmers is presented Table 3. Shedding light on the demographic and behavioral characteristics of hemp farmers regarding their willingness to establish a producer organization. A striking finding is the high proportion of hemp farmers (89.3%) expressing willingness to establish a producer organization. This result indicated a generally positive attitude toward organization, among hemp farmers, which might be associated with the need to increase bargaining power, participate more actively in the hemp market, and improve access to production inputs. An analysis of the educational backgrounds of producers revealed that 82% had a high school education or lower, while 7.1% were college graduates. In a study conducted by Değer et al. (2020) in Muğla Province, it was found that 88% of tomato growers would be willing to join a cooperative if one were established for the purpose of marketing tomatoes. Similarly, in their study conducted in Iran, Mahmoodzadeh and Sabouri (2014) found that farmers showed a strong tendency to establish production cooperatives. While the findings in the literature are consistent with the present study, they also indicate that producers of different products are generally willing to engage in a high degree of organization in terms of marketing and bargaining power.

Interestingly, although hemp cultivation is a labor- and knowledge-intensive activity, 62.5% of the farmers reported that farming is not their main occupation. The study found that the vast majority of hemp producers (90.2%) had not had any negative experiences with cooperatives in the past. However, for the 9.8% of farmers who reported having had negative experiences with cooperatives in the past, this situation may act as a barrier to their willingness to form an organization. When examining the level of satisfaction among producers regarding hemp production, it was found to be moderate. Specifically, 40.2% of hemp producers expressed satisfaction with hemp production, while 59.8% stated they were dissatisfied. The study found that the average age of farmers was 52.9, indicating that the average age of the farming population involved in hemp production is high. Producers cultivate hemp on an average of 14.6 decares of land. Hemp production in the study area is

predominantly fibre-oriented, with 93.75% of farmers producing hemp fibre and only 11.60% producing hemp seed. The average cultivation area for hemp fibre production is 13.51 decares, while hemp seed production is carried out on a smaller area of 1.11 decares. Average yields were estimated at 761.66 kg/da for hemp fibre and 195.56 kg/da for hemp seed production.

Overall, these findings highlight both the potential and the limitations of cooperative-based development in hemp cultivation. While hemp producers show a high willingness to establish organizations, other structural and economic constraints such as the high average age of farmers, low educational levels, limited land availability, and dissatisfaction with hemp production must be taken into account during policy design and implementation.

Table 3. Socio-demographic and farm characteristics of hemp farmers

Categorical variables		n	%
Willingness_Coop	0. Not willing to establish a producer organization	12	10.7
	1. Willing to establish a producer organization	100	89.3
EDUCATION	1. Primary school and below	41	36.6
	2. Middle and high school graduates	62	55.4
	3. University graduate	8	7.1
M_STATUS	0. Single	12	10.8
	1. Married	100	89.2
SOC_SECURITY	0. Has no social security	3	2.7
	1. Has social security	109	97.3
M_OCCUPATION	0. Main occupation is farmer	42	37.5
	1. Main occupation is not farmer	70	62.5
BAD_COOP_EXP	0. Those who have not had bad cooperative experiences in the past	101	90.2
	1. Those who have had bad cooperative experiences in the past	11	9.8
SATISFACTION	0. Not satisfied with hemp production	67	59.8
	1. Satisfied with hemp production	45	40.2
MIGRATION	0. No migration from rural to urban	65	58.0
	1. There is migration from rural to urban	47	42.0
Continuous variables		Mean	Std.Dev.
AGE	Age of hemp farmers (year)	52.9	11.6
HOUSEHOLD	Number of household (person)	3.0	1.8
TOTAL_AREA	Total area (decar)	85.8	75.7
HEMP_AREA	Hemp cultivation area (decar)	14.6	12.3
HEMP_SEED_AREA	Hemp seed cultivation area (decar)	1.1	6.2
HEMP_FIBER_AREA	Hemp fiber cultivation area (decar)	13.5	12.8
PRICE_HSEED	Price of hemp seed ($/kg)	3.08	-
PRICE_HFIBER	Price of hemp fiber ($/kg)	0.26	-
EXP_HEMP	Experience of hemp growers (year)	12.9	15.6

Results of CART Algorithm

The CART algorithm correctly classified 100% of hemp producers who were not willing to establish producer organizations (sensitivity) and 99% of hemp producers who were willing to establish producer organizations (specificity). This algorithm correctly classified 99.1% of hemp producers who are not willing to establish producer organizations and those who are willing to establish producer organizations (Table 4).

The fact that the Re-substitution (0.009) and cross-validation (0.018) risk estimates for the CART classification algorithm created are close to each other indicates that there is no overfitting problem (Table 5). The area under the ROC curve was found to be 0.760 ($p<0.01$). Based on the findings, it was determined that the classification performance of the CART algorithm is quite good (Figure 2)

Table 4. Classification of the CART algorithm

	Predicted		
Observed	Now willing to establish a producer organization	Willing to establish a producer organization	Percent Correct
Now willing to establish a producer organization	12	0	100.0
Willing to establish a producer organization	1	99	99.0
Overall Percentage	11.6	88.4	99.1

Table 5. Re-substitution and cross-validation risk estimates of CART algorithm

Method	Estimate	Std. Error
Resubstitution	0.009	0.009
Cross-Validation	0.018	0.013

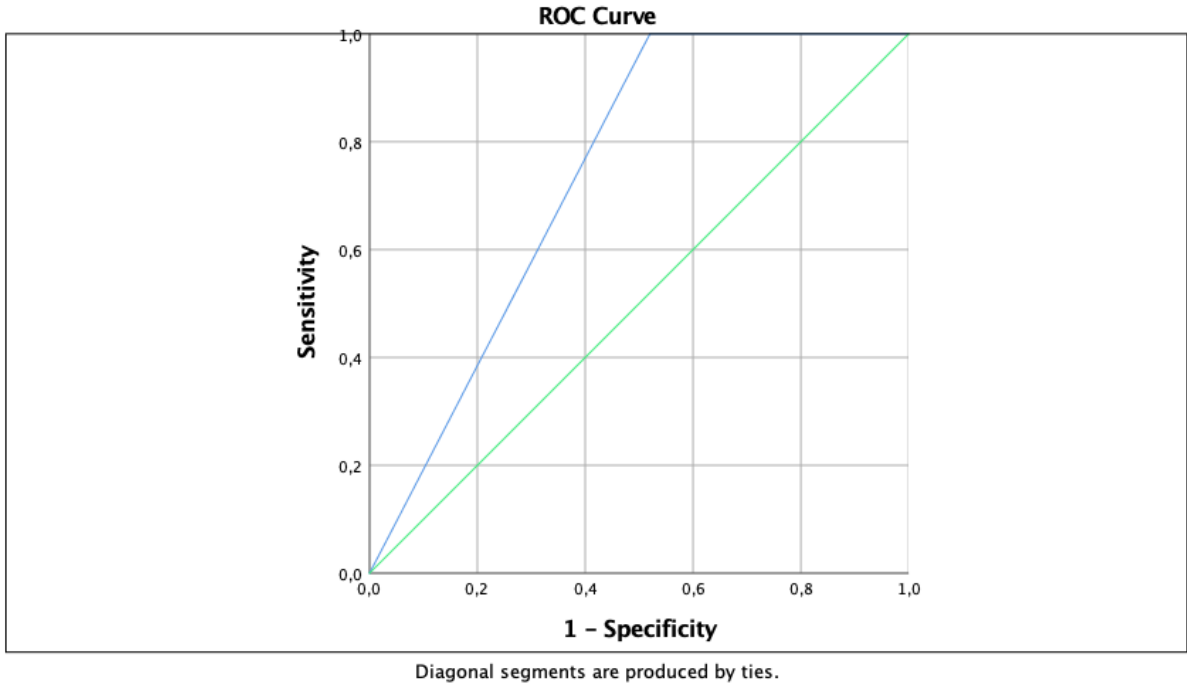

Figure 2. ROC curve of CART algorithm

Factors affecting the willingness of hemp farms managers to establish producer organizations

The CART algorithm results for the factors affecting hemp producers' willingness to establish producer organizations were presented in Figure 3. The model results identified the factors influencing hemp producers' willingness to establish a producer organization as follows: having had negative experiences with cooperatives in the past, whether their primary occupation is farming, the area of hemp cultivation, and the age of the producers. At the top of the classification tree was Node 0, referred to as the root node. This node provides the frequency distribution of all hemp producers who were willing and unwilling to establish a cooperative. While 89.3% of hemp producers were willing to establish producer organizations, 10.7% were unwilling. Node 0 was divided into two subgroups, Node 1 and Node 2, based on past negative experiences with cooperatives at the first tree depth. A study conducted by Everest (2021) in Türkiye's northwestern provinces revealed that 65.88% of farmers were willing to establish renewable energy cooperatives. This finding was consistent with the results of the current study and suggested that Turkish farmers across different agricultural sectors may show a tendency toward cooperative formation when economic and environmental benefits are perceived.

Node 1 represents individuals who have not had negative experiences with cooperatives in the past, while Node 2 represents those who have. Since Node 2 has achieved sufficient homogeneity, it has not split in subsequent levels of the tree. For this reason, this node is referred to as a terminal node. Based on this result, all hemp producers who have had negative experiences with cooperatives in the past (100%) are unwilling to join the organization. In particular, factors such as loss of trust and non-transparent management created reluctance

among producers who had previously experienced negative outcomes. These producers tended to develop a negative attitude, believing that the failure of a cooperative would likely recur, which caused them to overlook the potential economic and social benefits of collective organization. According to the CART algorithm results, the fact that all producers with past negative cooperative experiences were unwilling to organize indicated that this group was homogeneously affected by those experiences. Indeed, Birchall (2014) stated that rebuilding social trust after the failure of a cooperative took a long time. One of the major reasons why agricultural organizations in Türkiye failed to operate effectively was attributed to negative experiences in the past (Kılıç Topuz, 2017). Moreover, it was noted that reluctance stemming from past cooperative experiences was widespread among small-scale producers in Türkiye (Türk-Koop, 2019). Similarly, a study conducted by Kılıç Topuz et al. (2022) identified a negative relationship between farmers' past negative experiences with agricultural organizations and their participation in general assembly meetings of agricultural organizatons. The findings of Kılıç Topuz (2017) also emphasized that the key factor in agricultural organizations was people, with trust being a fundamental element. However, the study also found that negative organizational experiences in the past had a significant impact on trust. These findings indicated that reestablishing trust in agricultural organizations that had previously failed was highly challenging. Therefore, future cooperative initiatives needed to be supported not only by economic measures but also by efforts aimed at building trust.

Node 1 was divided into two nodes, Node 3 and Node 4, in terms of main occupation at the second tree depth. Node 3 represented hemp producers whose main occupation was farming. Node 4 represented hemp producers whose main occupation was not farming. According to the classification tree diagram, 97.2% of hemp producers whose main occupation was farming were willing to organize, while 2.8% were not. Since Node 4 had reached sufficient homogeneity, it was not divided in subsequent levels of the tree.

Node 3 was divided into two groups at the third tree depth: Nodes 5 and 6. Node 5 represented producers with a hemp cultivation area of 13.5 decares or less, while Node 6 represented producers with a hemp cultivation area of more than 13.5 decares. In Node 6, it was noted that all farmers with hemp cultivation areas exceeding 13.5 decares were willing to establish a producers' organization. A study conducted by Değer et al. (2020) in Muğla Province also found that small-scale producers were more inclined to join cooperatives.

Node 5 was divided into two subgroups, Node 7 and Node 8, at the fourth tree depth. Node 7 represented producers with a hemp cultivation area of 12.5 decares or less, while Node 8 represented producers with a hemp cultivation area of more than 12.5 decares. Node 7 was a terminal node and had not divided in subsequent tree depths because it achieved sufficient homogeneity. Node 7 showed that all producers with hemp cultivation areas of 12.5 decares or less were willing to establish producer organizations. In other words, it was evident that small-scale producers were more willing to form cooperatives, and that the focus should be on small-scale producers in this regard. Small-scale producers were unable to benefit sufficiently from economies of scale under market conditions.

At the fifth depth level of the tree, Node 8 was split into two branches: Node 9 and Node 10. Node 9 represented hemp producers aged 56.5 and below, while Node 10 represented those older than 56.5. Half of the hemp producers aged 56.5 and below were willing to establish producer organization, whereas the other half were not. In contrast, all producers over the age of 56.5 were willing to establish producer organization, indicating a positive relationship between willingness to organize and age.

The nodes with the highest level of willingness to establish producer organization (100.0%) were Node 10, Node 7, Node 6, and Node 4. These were followed by Node 1 (99.0%), Node 3 (97.2%), Node 5 (92.9%), Node 8 (75.0%), and Node 9 (50.0%), respectively. Hemp farmers who had experienced negative cooperative practices in the past had no willingness to establish producer organization (Node 2).

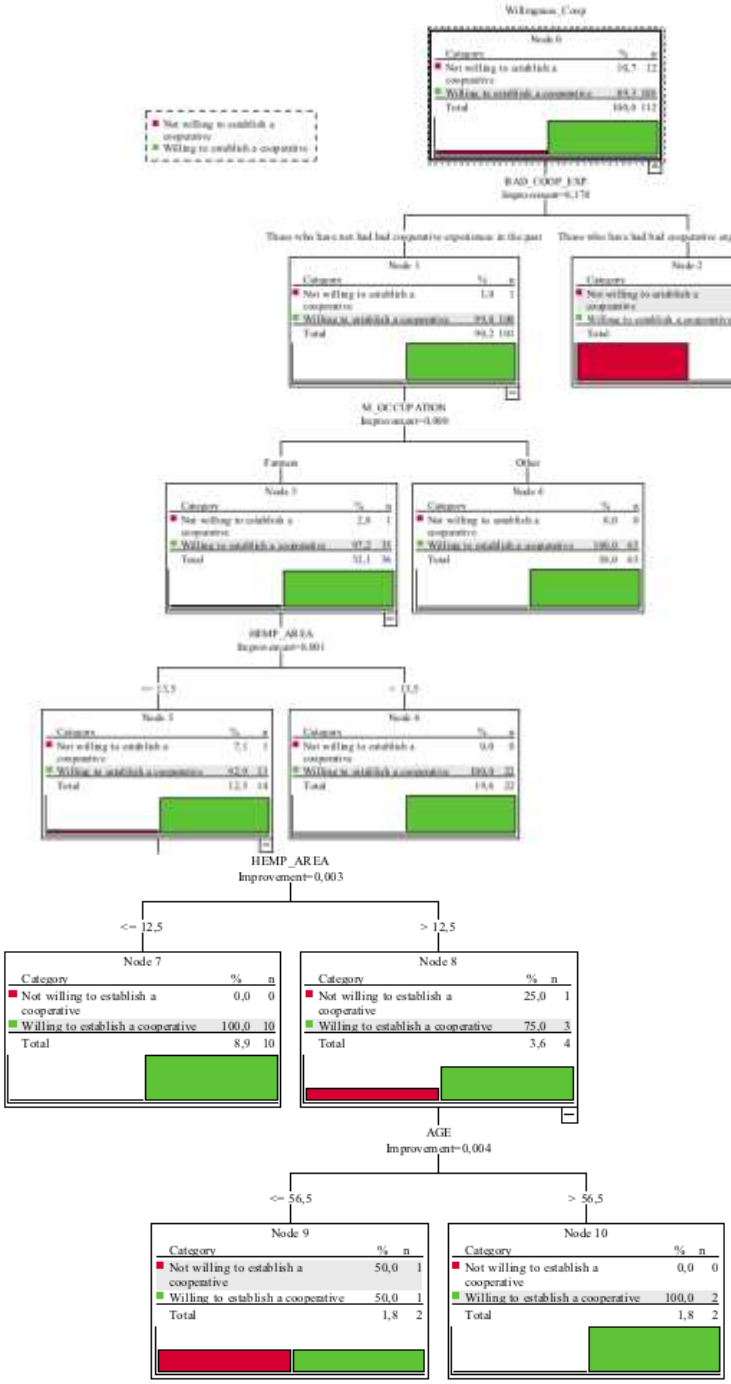

Figure 3. Decision tree diagram of the CART algorithm for factors influencing the willingness of hemp producers to establish producer organizations

As a result of the hypothesis tests conducted within the framework of the research model, hypotheses were evaluated using CART analysis. The analysis excluded any intervening variables and focused on the direct relationships between variables. According to the algorithm results, some hypotheses were supported while others were not, as shown in Table 6.

Table 6 reveals that the H_2 hypothesis is supported, which posits that farmers whose main occupation is farming are more willing to establish agricultural organizations. Similarly, H_3 is supported, indicating that farmers with negative past experiences with cooperatives are less inclined to establish new ones. H_5 is also supported, showing that as farmers age, their willingness to establish agricultural cooperatives increases. In addition, the H_6 hypothesis is also supported; this indicates that an increase in the area under hemp cultivation is associated with a greater willingness to form agricultural organizations.

On the other hand, Hypothesis H_1, which posits that an increase in the educational level of hemp producers enhances their willingness to establish producer organizations, is not supported. Similarly, Hypothesis H_4, which assumes that increased satisfaction with hemp production enhances the willingness to form organizations, is also not supported. These findings indicate that while demographic factors such as farming being the primary occupation, age, farm size, and past negative experiences with cooperatives have a statistically significant effect on hemp producers' willingness to establish agricultural organizations, they reveal that factors such as educational level and satisfaction with hemp production have no effect on the willingness to form agricultural organizations. The results of this study are consistent with the findings of a study conducted in Serbia by Brkljača et al. (2022). Brkljača et al. (2022) reported that all hemp producers (100%) believed that the industrial hemp producers' association facilitates stronger and more competitive production in rural areas. Furthermore, the study emphasizes that industrial hemp serves as both an economic opportunity and a marketing tool for rural areas, benefiting both consumers and producers. These findings underscore that institutional support, farmer organization, and consumer education are indispensable for fully realizing hemp's potential for rural development. Hellwinckel (2020) emphasized that without cooperative-run quota systems, hemp production risks following the trajectory of other industrial crops, where overproduction leads to falling prices, consolidation, and the marginalization of small farmers. Drawing lessons from the U.S. tobacco quota system, he argued that cooperatives can play a crucial role in managing supply, ensuring fair prices, and sustaining rural economies. These findings resonate with the present study, where farmers in Samsun expressed strong willingness to cooperate as a means of overcoming market disadvantages and gaining bargaining power. An effective cooperative structure in Türkiye could thus prevent similar risks of market concentration and contribute to both farmer welfare and rural development. Similar findings have been observed in Italy, where hemp cultivation has recently re-emerged as a multifunctional activity managed by young entrepreneurs. Giupponi et al. (2020) found that 83% of hemp farms were newly established within the past decade, often reclaiming abandoned marginal lands, and that 73% of producers diversified into multiple end-products, ranging from food to cosmetics and beverages. Farmers identified the absence of a clear legislative framework, insufficient mechanization, and the lack of a national production chain as major weaknesses, while highlighting the crop's strong potential for sustainable farming systems and rural development. These findings underline that, as in Türkiye, cooperative organization are essential to unlock hemp's multifunctional benefits and market competitiveness.

Table 6. Hypotheses and Supported/Un Supported

Hypothesis	Supported / Unsupported
H_1: As the educational level of hemp farmers increases, so does their willingness to establish producer organization.	Un-Supported
H_2: Those whose main occupation is farming are more willing to establish producer organizations.	Supported
H_3: Farmers who have had bad experiences with cooperatives in the past are reluctant to establish new agricultural cooperatives.	Supported
H_4: As satisfaction with hemp production increases, so does the willingness to establish producer organizations.	Un-Supported
H_5: As farmers age, their willingness to establish producer organizations increases.	Supported
H_6: As the area under hemp cultivation increases, so does the willingness to establish producer organizations.	Supported

CONCLUSION

This study examined the willingness of hemp producers in the Samsun province of Türkiye to establish an agricultural cooperative or union, as well as the factors influencing this willingness. The results indicate that the vast majority of producers (89.3%) are willing to organize under a cooperative or union model. It is demonstrated that there is strong potential for establishing cooperatives in Türkiye's leading hemp-producing province. However, producers' past negative experiences with cooperatives emerge as the most decisive factor reducing their willingness to form agricultural organizations, thereby highlighting the importance of institutional trust. The findings highlight that while hemp producers have a strong intention to form agricultural organizations through collaboration, rebuilding trust is essential for this to be realized. For this reason, any new cooperatives or unions that are established must adopt a transparent and honest management approach in order to build trust. Other key factors influencing the willingness to organize include having farming as one's primary occupation, the size of the hemp cultivation area, and the producers' age. Producers whose primary occupation is farming, who manage larger plots of land, and older producers demonstrate a stronger willingness to organize.

Although the potential of hemp is recognized in Türkiye's development plans, there are currently no policy tools that directly support the formation of cooperatives or producer organizations. Policy interventions should follow a sequential approach. First, efforts should focus on rebuilding institutional and social trust through transparent governance, since previous negative cooperative experiences emerged as the strongest barrier to organization. Second, educational and extension activities should be implemented to improve producers' knowledge regarding organizational structures, cooperative principles, and the potential economic benefits of collective organization. Third, legal and institutional support mechanisms, including cooperative incentives, should be incorporated into agricultural policies to facilitate the establishment and long-term sustainability of producer organizations.

Successful examples such as La Chanvrière (France) and Nordic Hemp (Estonia) demonstrate that cooperatives can achieve a strong market position and increase farmers' incomes. Turkey can also benefit from sharing knowledge and experience by collaborating with international organizations such as the European Industrial Hemp Association. Once these steps are taken, farmers' willingness to organize could lead to the establishment of stronger cooperative structures. This would not only increase farmers' incomes but also support competitiveness in the hemp sector and sustainable rural development.

This study has several limitations that should be considered when interpreting the findings. First, the study was conducted only in Samsun province, which may limit the generalizability of the results to other hemp-producing regions of Türkiye. Second, the analysis was based on cross-sectional survey data collected during a specific production period; therefore, changes in farmers' organizational attitudes over time could not be examined. Third, farmers' willingness to establish producer organizations reflects stated intentions rather than actual organizational behavior. Future studies may investigate alternative organizational models for hemp producers, compare organizational preferences across different regions, and examine how trust influences actual participation in producer organizations.

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Declaration of interests

The authors declare that they have no conflict of interest.

Author Contributions

Ömer ATALIK: Conceptualization; data curation; writing— original draft; writing.

Bakiye KILIÇ TOPUZ: Conceptualization; supervision; research design; data analysis; funding acquisition; investigation; methodology; project administration; software; writing— original draft; writing—review and editing.

Declaration of ethical code

This study was conducted in accordance with ethical principles and received approval from the Social and Human Sciences Research Ethics Committee of Ondokuz Mayıs University (Approval No. 2024-261, 29 March 2024). Participation in the survey was voluntary, and informed consent was obtained from all participants before data collection.

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Original Article

Determination of the Impact of Land Consolidation on Crop Production Through Satellite Images and NDVI Index

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ABSTRACT

The most important issue in terms of protecting the potential of soil and water resources is to determine the current situation and identifying the urgent measures that can be taken for sustainability. This study aims to determine the existing parcel status before (2017) and after (2019-2025) parcel change with the help of satellite images in and around Arifeoğlu Village of Yerköy District of Yozgat Province, where land consolidation studies were completed in 2018. Simultaneously, a survey study was conducted to examine the knowledge and skill levels of the farmers regarding the consolidation process and its results. In 2017, before consolidation, the area covered by stressed plants was higher than that covered by healthy plants. In 2019, consolidation led to an increase in the area covered by healthy plants and a decrease in the area covered by stressed ones. Compared with the previous period, the highest increase occurred in the stressed plant group in 2024 (25.423%) and in the healthy plant group in 2019 (103.592%). The stressed plant group, which indicates that there is no green plant activity, reached its lowest value in 2019 (33.616%) immediately after the consolidation.

Keywords: Land fragmentation, remote sensing, sustainable agriculture, topography, vegetation indices

Uydu Görüntüleri ve NDVI İndeksi Kullanılarak Arazi Toplulaştırmanın Bitkisel Üretim Üzerindeki Etkisinin Belirlenmesi

ÖZ

Toprak ve su kaynaklarının potansiyelini koruma açısından en önemli konu, mevcut durumu belirlemek ve sürdürülebilirlik için acilen alınabilecek önlemleri tespit etmektir. Bu çalışma, 2018 yılında arazi toplulaştırma çalışmaları tamamlanan Yozgat ili Yerköy ilçesi Arifeoğlu köyü ve çevresinde, parsel değişikliğinden önceki (2017) ve sonraki (2019-2025) mevcut parsel durumunu uydu görüntüleri yardımıyla belirlemeyi amaçlamaktadır. Eş zamanlı olarak, çiftçilerin toplulaştırma süreci ve sonuçlarına ilişkin bilgi ve beceri düzeylerini incelemek için bir anket çalışması yapılmıştır. 2017 yılında, toplulaştırmadan önce, stres altındaki bitkilerin kapladığı alan, sağlıklı bitkilerin kapladığı alandan daha fazlaydı. 2019 yılında ise toplulaştırma, sağlıklı bitkilerin kapladığı alanın artmasına ve stres altındaki bitkilerin kapladığı alanın azalmasına yol açmıştır. Önceki döneme kıyasla, en yüksek artış 2024 yılında stres altındaki bitki grubunda (%25.423) ve 2019 yılında sağlıklı bitki grubunda (%103.592) meydana geldi. Yeşil bitki aktivitesinin olmadığı anlamına gelen stres altındaki bitki grubu, toplulaştırmanın hemen ardından 2019 yılında en düşük değerine (%33.616) ulaşmıştır.

Anahtar kelimeler: Arazi parçalanması, bitki örtüsü indeksleri, sürdürülebilir tarım, topografya, uzaktan algılama

INTRODUCTION

Approximately 854 million people, or 14% of the global population, experience chronic malnutrition and hunger, with nearly 50% of this group linked to smallholder farming households and landless rural communities facing production and development inefficiencies (FAO, 2018; Jiang & Shao, 2011; Swaminathan, 2014; Yurui et

al., 2019). It is crucial to urgently address the sustainable management of limited resources and the scarcity of appropriate areas for human habitation.

Land is a finite resource whose loss and degradation are irreversible within a human lifetime. Effective management of agricultural practices concerning water, soil, forests, and wildlife is crucial for achieving sustainable rural development (Gatzweiler et al., 2002; FAO, 2025). Consolidation ensures the continuity of social and cultural life, and living conditions are improved. In addition, it can effectively guarantee the protection of agricultural land and food safety, as well as improve environmental protection and the management of arable land productivity. In addition, thanks to the reorganized rural areas, agricultural lands will be easier to cultivate, their use will be maximized, and the incomes of people engaged in agriculture will increase (Köken & Çay, 2019).

For all these reasons, to use the land properly, the temporal change in land use should be revealed, plans should be made with the results obtained, and a management approach should be adopted accordingly. In this context, geographic information systems (GIS) and remote sensing (RS) systems provide great convenience to researchers (Turan et al., 2021). Combining satellite images obtained with the help of RS with the analysis and interpretation power of GIS is preferred as an easy and reliable method to examine changes in land cover and land use. With the use of GIS technology, data can be stored in a digital environment, its updating is facilitated, and it is possible to develop a standard by creating models with existing data (Duran & Doğan, 2022; Fadhıl, 2022).

Numerous domestic and international studies on land consolidation and remote sensing have been conducted. Akkaya Aslan (2018), in her fragmentation analysis using Januszewski (JI) and Simmons indices (SI) in the land consolidation project of Pınarlar Village in Denizli-Tavas Province, determined that the percentage of farms with a value less than 0.40 before consolidation was 25.5% and 67.90%, respectively, while after consolidation these percentages were 1.08% and 21.20%, respectively. Başayiğit et al. (2016) analyzed the changes in parcel boundaries and land use between 1974 and 2014 in the Isparta Harmanören consolidation area. Their study revealed an increase in the number of parcels to 524, despite a reduction in average parcel size from 13684.10 m² to 6813.68 m², highlighting hidden fragmentation over approximately 40 years. In the Sulucakaçar neighborhood LC project in the Şanlıurfa Bozova district, RS and GIS techniques were used to assess land use changes before and after consolidation. Using Google Earth and Sentinel 2 images digitized with ArcGIS, land use maps were created and area calculations were done. The study found a decrease in rocky and wheat areas and an increase in cotton, corn, and barley areas post-consolidation (Özgültekin, 2019).

Many studies on consolidation include similar evaluations, due diligence, economic benefits, and before-and-after status reports. However, relatively few survey studies have been conducted with farmers, and even fewer have examined changes in product patterns. Therefore, it is believed that the original value of present study is also higher.

In this regard, the aim of this study is to determine the parcel product status before (2017) and the parcel product diversity change after (2019, 2025) the land consolidation works were completed in 2018 in Arifeoğlu Village and its surroundings in the Yerköy District of Yozgat Province, with the help of satellite images. In satellite images, images with dates between 01-15 April and low cloudiness ratios were preferred. Simultaneously, a survey study was conducted to examine the knowledge and skill levels of the farmers regarding the consolidation process and its results. The survey examines how LC practices affected the number of parcels, the sizes of the parcels, and the values that the producers assign to them. In addition, an effort was made to determine producers' perceptions and levels of satisfaction regarding land consolidation application.

MATERIALS AND METHODS

The consolidation project is a large study covering a total of six districts (Çiçekdağı, Merkez, Sorgun, Şefaatli, Yenifakılı, and Yerköy) and 43 villages. Initially, it was aimed to be completed in February 2015, but it was finally completed in September 2018 with the addition of time. The districts and villages where the project was carried out are listed in Table 1. Fig. 1 shows the land status after consolidation of the Arifeoğlu village and its surroundings.

The study area primarily features xerosols, specifically calcic xerosols, which possess a calcic horizon at 125 cm depth and lack an argillic B horizon above it. Additionally, luvic xerosols contain an argillic B horizon with a calcic or gypsum horizon below it. These soils dominate Central Asia's vast desert steppes and its outer desert regions, where agricultural activities are largely confined to river valleys due to limited water availability (FAO/UNESCO, 2025).

Sentinel-2 is a satellite designed to support Copernicus services, equipped with multi-spectral imaging technology for monitoring land, ocean, and the atmosphere. It delivers high-resolution optical images useful for land monitoring, emergency response, and security. The satellite features a multispectral imager with 12 spectral

bands, including visible, near-infrared, and shortwave infrared, covering latitudes from 56°S to 84°N. Applications include land cover mapping, land change detection, vegetation monitoring, and assessment of burned areas.

Table 1. Districts and villages where the consolidation project is located

	Project Districts					
No	Çiçekdağı	Merkez	Sorgun	Şefaatli	Yenifakılı	Yerköy
1	Köseli	Özlüce	Gedikhasanlı	Kızılyar	Eskiören	Yamuklar
2	Haydarlı	Sarınınören		Koç	Zafer	Karacaahmetli
3	Küçükteflek	Battal		İbrahimhacılı	Yazlak	Kumluca
4	Tatbekirli	Esenli		İnceşehir	Yenifakılı	Göçerli
5	Büyükteflek	Bayatören		Hasanpaşa	Altındağ	Arifeoğlu
6	Safalı	Gelingüllü		Paşaköy	Başağa	Kömüşören
7	Tepecik			Hallaçlı	Fehimli	Buruncuk
8				Saçlı	Cankurtaran	
9				Yenicami	Camikebir	
10				Armağan	Bektaşlı	
11					Yenicami	
12					Mehmet Akif	

Figure 1. Land parcel status after consolidation in the Arifeoğlu Village sub-project (2018)

Satellite images with dates between 2018-04-01 and 2018-04-15 and a low cloudiness ratio were preferred. Because the LC was completed on September 24, 2018, Sentinel-2 L2A satellite images from 2017 (pre-project) and between 2019 and beween 2020-2025 (project) were used. Resolution values range between 10 and 60 m. Each satellite image obtained consists of nine separate bands. The general features of the satellite images are presented in Table 2 (Sentinelhub, 2025).

Table 2. Properties of Satellite Images

Year	2017	2019	2020	2021	2022	2023	2024	2025
	2017/05/10	2019/04/30	2020/04/28	2021/04/28	2022/04/23	2023/04/18	2024/04/22	2025/05/24
Data Supply	2025/07/22	2025/07/22	2025/07/22	2025/07/22	2025/07/22	2025/07/22	2025/07/22	2025/07/22
Cloud Ratio	1.09%	11.73%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%
Resolution	10 - 60 m	10 - 60 m	10 - 60 m	10 - 60 m	10 - 60 m	10 - 60 m	10 - 60 m	10 - 60 m
Total Number of Bands	9	9	9	9	9	9	9	9

In the Arifeoğlu Village of the Yerköy District, the sample size of the study was determined to be 137 producers registered in the farmer registration system of the Provincial Directorate of Agriculture and Forestry. Various statistical methods were used in the analysis of the questionnaires with the JAMOVI 2.7.28 Package Program, an open source code analysis program.

A simple random sampling method for a finite universe was used to calculate the sample size. The formula used is as follow in Equation 1:

$$\boldsymbol{n = \frac{N.p.q.t^2}{d^2.(N-1)+t^2.p.q}} \quad \textbf{(}1\text{)}$$

Where;
N: Universe (Number of farmers registered in ÇKS-2025)
n: Sample
p: The frequency of the characteristic we are interested in within the universe,
q: The frequency of not seeing the feature we are interested in within the universe,
t = Standard value according to the confidence level (1.645 for 90% confidence interval) and
d = Represents the tolerable margin of error (0.10).

In this population, the sample size was determined as 46 at 10% error and 90% confidence limits, and the studies were completed by conducting surveys with 52 producers that could be reached. In addition, farmers' satisfaction levels were revealed using percentage frequency tables. The filling of the questionnaire forms was started on 2025-04-11 and completed on 2025-04-28. By reaching out to 52 producers whose land was consolidated in the region, we attempted to determine their opinions on the subject. The aim was to obtain the most accurate data in line with the answers provided by the producers.

The Wilcoxon Rank Test, a non-parametric comparison tool, was used to assess differences in data before and after LC, determining whether a significant difference exists between two data sets without assuming a specific data distribution.

In this study, ArcGIS 10.x software was used for image preprocessing and classification. The satellite image was subjected to geographic-geometric correction in ArcGIS software according to the Universal Transverse Mercator (UTM) projection coordinate and WGS84 North Zone 35 system, and the nearest neighbour, which had the least error, was used as the sampling method. After geometric correction, the boundaries of the study area were arranged to include the boundary of the study area.

There are many surface interpolation methods in GIS raster data analysis, such as the Thiessen polygon (nearest neighbour, NN), local average (fixed radius), inverse distance weighting (IDW), kriging, and spline. Each method has its own advantages and disadvantages, and it has not been proven that one method is the best method. In this study, the IDW method in the Interpolation subheading of the Geostatistical Analyst tab was used to create point density maps (Bolstad, 2005).

Digital elevation model (DEM) data with a resolution of 1 arc second (30 m) according to the WGS84 coordinate system were obtained from the ASTER DEM address. Slope and aspect maps of the land were created from the DEM map with the spatial analysis>surface auxiliary tool in ArcGIS 10.8 software. By overlapping these maps with the points where the analysis was performed, we attempted to determine the changes or effects depending on the altitude, slope, and aspect degree.

The base shape (.shp) maps determining the provincial borders to be used in the study were obtained from the General Directorate of Mapping. All data used in the study were converted to the WGS84-UTM-Zone-35 datum projection system and then used in the analyses. All produced raster and vector maps were saved in databases in the form of folders (HGM, 2025).

Land use and land cover data were obtained from the data produced within the scope of Sentinelhub (2025).

The large soil groups map was obtained by extracting the province of Yozgat from the world soil classification map created by (FAO/UNESCO, 2025).

NDVI analysis results are used in studies such as monitoring drought with the help of various bands of satellite images, estimating agricultural productivity, determining whether plants are sick, or determining the destruction of vegetation in fire zones. A healthy plant absorbs visible light and reflects a large portion of near-infrared light. In addition, an unhealthy plant reflects more visible rays and fewer near-infrared rays. The formula used for NDVI calculation is shown in Equation 2 (Rouse Jr et al., 1974; Karaca, 2025). The obtained NDVI values were arranged into 4 classes according to the class ranges shown in Table 3, as suggested by Auravant (2026).

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} = \frac{(B8-B4)}{(B8+B4)} \quad (2)$$

In the equation;

NIR: Near infrared band value (band=4 for Landsat 4-7, band=5 for Landsat 8-9)

RED: Red band value (band=3 for Landsat 4-7, (band=4 for Landsat 8-9)

Table 3. NDVI class ranges (Auravant, 2026)

Class Range	Description
-1-0	Dead Plants or Inanimate Objects
0-0.33	Diseased Plants
0.33-0.66	Moderately Healthy Plants
0.66-1	Very Healthy Plants

RESULTS AND DISCUSSION

Results

Surveys

The aspect of LC that satisfies the producers the most is the consolidation of fragmented lands, with a rate of 94%. The answer to the consolidation of fragmented lands is followed by a 75% rate of decrease in expenses, a 69% rate of separation from shareholders, a 60% rate of increase in land value, and a 50% rate of infrastructure services performed with LC. The Wilcoxon rank test showed that $P<0.05$, indicating a significant difference (decrease) in the number of parcels after LC compared to the number of parcels before LC.

While 55.8% of the participants in the survey believe that there was an increase in yield after the LC application, 30.8% were undecided on this issue. The percentage of those who do not agree that there was an increase in yield after LC is 13.5%. Additionally, 46% of the farmers stated that land consolidation works and procedures took a very long time. Overall, 76.90% of the producers are satisfied with the LC activities. Notably, reductions in the number of parcels at a rate of 71.39%, increases in land value at 57%, and the benefits of easier transportation and fuel savings are viewed as satisfactory by the producers.

DEM Maps

The DEM map of the study area is shown in Fig. 2, and the area it covers on the map and the percentage values are shown in Table 4. It has been determined that the area has an altitude varying between 716 m and 828 m. When Table 4 is examined, it is determined that a large part of the area, such as 63.10%, has values varying between 0-750 m. In terms of slope, approximately 60% of the area varies between 1-5°. Regions with a slope of 0-5 cover 92.07% of the total area.

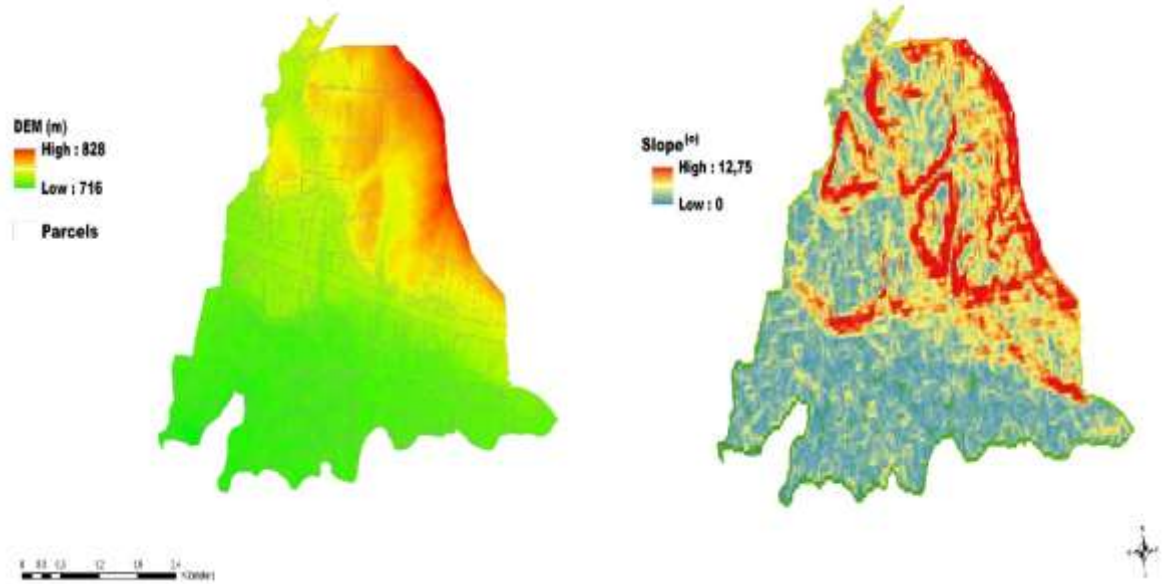

Figure 2. Study area DEM and slope maps

Table 4. Study area and percentages covered by DEM and slope map

DEM (m)			Slope (°)		
Range	Percent	Area (m^2)	Range	Percent	Area (m^2)
0-750 m	63.10	10253678.35	0-1	32.48	5277478.45
750-800 m	34.09	5540238.84	1-5	59.59	9684459.78
800-828 m	2.79	453714.68	5-10	7.70	1251967.04
			10-12.75	0.25	40154.73

Aspect Maps

The aspect map of the study area is shown in Fig. 3, and the area and percentage values covered by the aspect map are shown in Table 5. In terms of aspect, it has been determined that the south (23.33%) is in the first place and the southwest (24.14%) directions are in the second place in the project area. Southern directions cover 56.91% of the total area, while northern directions cover 20.25%. From this, it has been determined that a large part of the area consists of lands with a southern direction tendency.

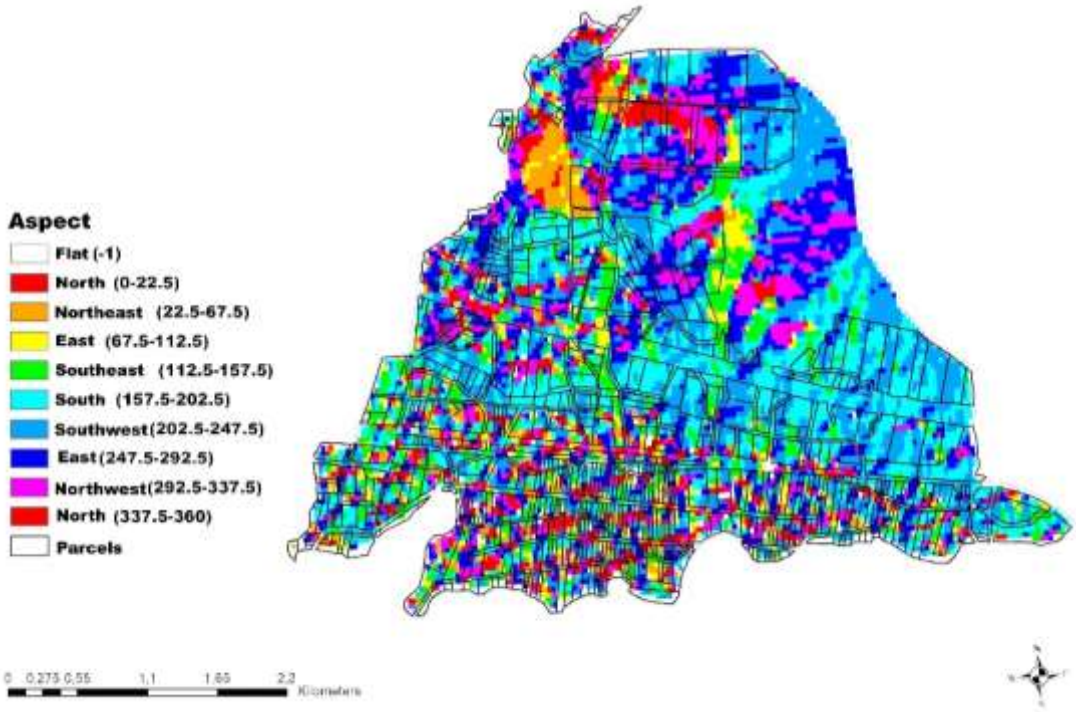

Figure 3. Aspect map of the study area

Table 5. Aspect map area and percentages

Description	Percentage	Area (m^2)
Flat (-1)	2.96	481503.23
North (0-22.5)	2.04	331033.47
Northeast (22.5-67.5)	5.25	852661.97
East (67.5-112.5)	4.88	792474.07
Southeast (112.5-157.5)	9.44	1534791.55
South (157.5-202.5)	23.33	3791837.94
Southwest (202.5-247.5)	24.14	3922245.06
West (247.5-292.5)	15.00	2437610.10
Northwest (292.5-337.5)	10.00	1625073.40
North (337.5-360)	2.96	481503.23

Land Cover Land Usage Maps

The land cover-land use map of the study area, obtained within the scope of the project, is shown in Fig. 4, and the area and percentage values covered by the map are shown in Table 6. According to the results of Table 6, it has been determined that the study area consists of mixed agricultural lands (53.25%) in the first place and non-irrigated arable lands (32.61%) in the second place. Agricultural areas with natural vegetation, plant change areas and sparse vegetation areas consist of places with less than 1% area (Sentinelhub, 2025).

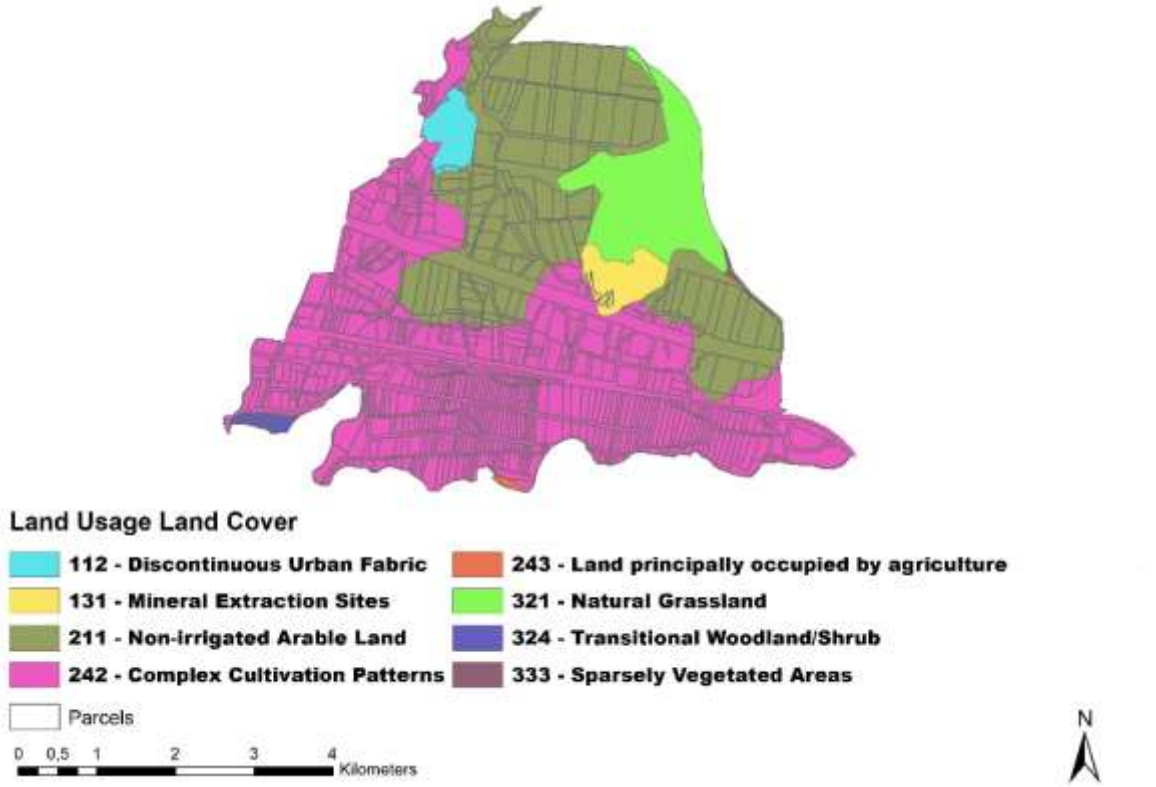

Figure 4. Land cover land use map of the study area

Table 6. Area and percentages of land cover in the land use map

No	Corine Code	Description	Area (m^2)	Area (ha)	Percent
1	112	Discontinuous urban fabric	303354.12	30.34	1.86
2	131	Mineral extraction sites	369626.82	36.96	2.26
3	211	Non-irrigated arable land	5328844.65	532.88	32.61
4	242	Mixed farming areas	8701143.38	870.11	53.25
5	243	Agricultural areas with natural vegetation	22519.01	2.25	0.14
6	321	Natural grassland	1496962.01	149.70	9.16
7	324	Areas of vegetation change	1699.33	0.17	0.01
8	333	Sparse vegetation areas	26584.69	2.66	0.16

NDVI Maps

Different NDVI results for each year derived from the Sentinel-2 L2A satellite using the NDVI formula in Equation 2 are shown in Table 7, and density maps are shown in Fig. 5. When the percentage values in Table 7 are carefully examined, it has been determined that the amount of stressed vegetation is approximately 3 times more than healthy vegetation in 2017, when consolidation has not yet started. In contrast, in 2019, in the post-consolidation period, the amount of stressed vegetation showed a decreasing trend of 33.616%. The value of healthy plants doubled and covered approximately 50% of the total area. This situation revealed that consolidation had a positive effect. However, due to the extreme drought seen in 2020-2021, the effect of consolidation began to disappear. 2021 was the year with the most extreme events, with 1024 extreme weather events recorded. In the same report, when looking at monthly temperature differences, it was stated that the temperatures of all months except March, September and October were above normal. As a result of this situation, it has been determined that the level of stressed vegetation is higher than the level of healthy vegetation every year, especially between 2020-2024. In contrast, starting from 2025, the level of healthy vegetation began to be determined more than the level of stressed vegetation, in contrast to previous years. Similarly, when looking at the rates of change compared with the previous year, it has been determined that the levels of stressed vegetation are gradually decreasing, while the levels of healthy vegetation are gradually increasing.

Table 7. Area percentages of density maps for 2017 and 2019-2025

Year	Range	Percentage	Area (m^2)	Area (ha)	Change (ha)
2017	Stressed plant	75.50	12337411.46	1233.74	-
	Healthy plant	24.50	4003530.87	400.35	-
2019	Stressed plant	50.12	8190080.29	819.01	-33.616
	Healthy plant	49.88	8150862.03	815.09	103.592
2020	Stressed plant	64.90	10605271.57	1060.53	29.489
	Healthy plant	35.10	5735670.76	573.57	-29.631
2021	Stressed plant	78.58	12840712.48	1284.07	21.079
	Healthy plant	21.42	3500229.85	350.02	-38.974
2022	Stressed plant	76.18	12448529.87	1244.85	-3.054
	Healthy plant	23.82	3892412.46	389.24	11.204
2023	Stressed plant	56.21	9185243.68	918.52	-26.214
	Healthy plant	43.79	7155698.65	715.57	83.837
2024	Stressed plant	70.50	11520364.34	1152.04	25.423
	Healthy plant	29.50	4820577.99	482.06	-32.633
2025	Stressed plant	47.17	7708022.50	770.80	-33.092
	Healthy plant	52.83	8632919.83	863.29	79.085

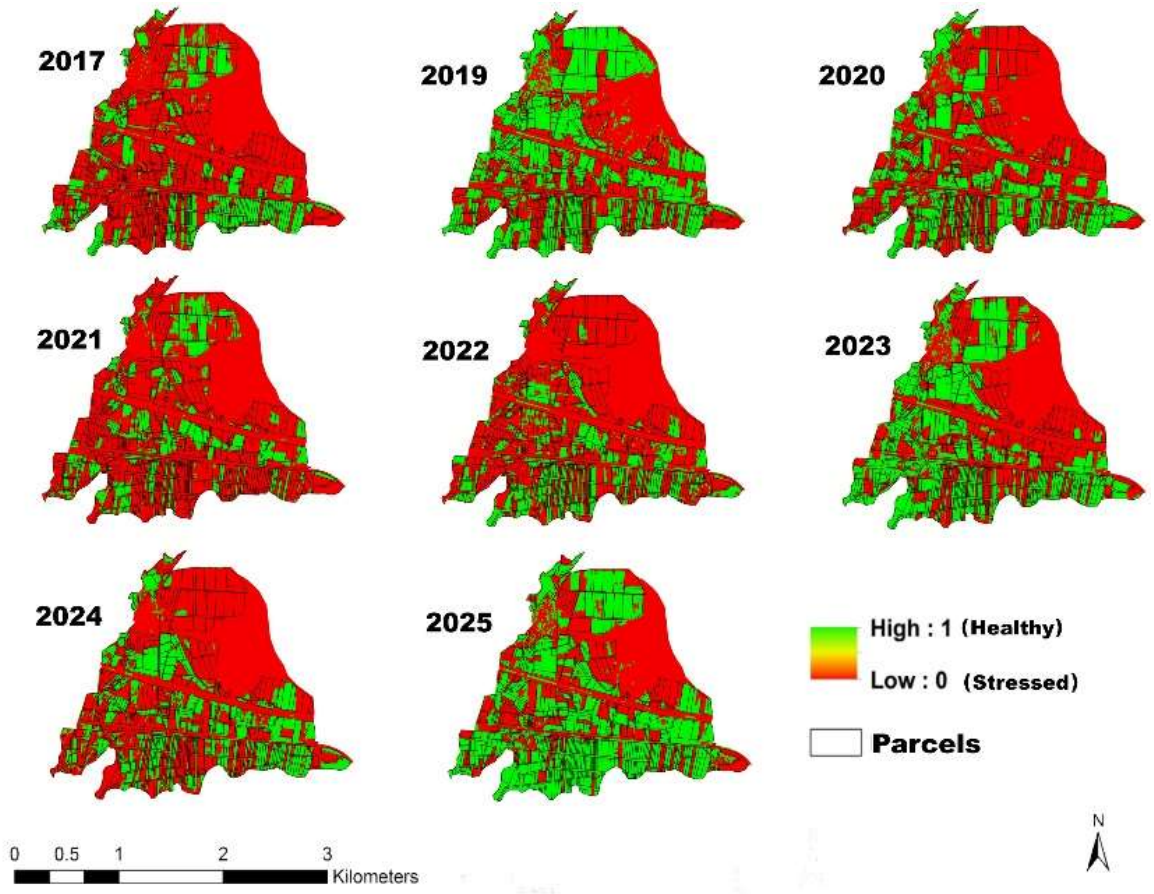

Figure 5. Density maps for 2017 and 2019-2025

Fig. 6 shows the change graph of the areas covered by healthy and stressed plants obtained as a result of NDVI analysis for different years. As can be seen in the figure, the amount of area covered by stressed plants in 2017 before consolidation is greater than that of healthy plants. In 2019, it was determined that there was an increase in the amount of area covered by healthy vegetation and a decrease in the amount of stressed vegetation, depending on consolidation. However, after this year, the positive effect of consolidation could not become very clear due to the extreme drought seen especially in 2020-2021.

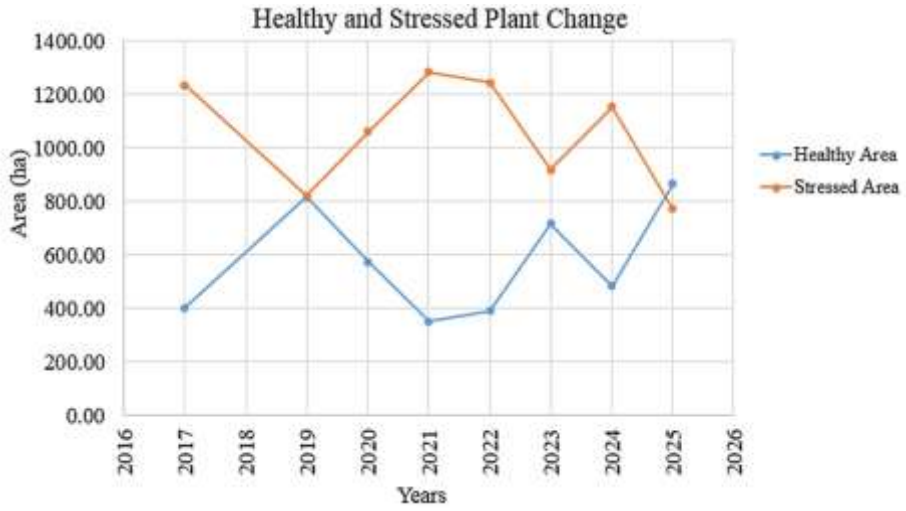

Figure 6. Spatial changes in healthy and stressed plants by year

Discussion

A common issue in agriculture within developing countries is land fragmentation, which negatively impacts agricultural profitability and population income levels. It results in reduced arable land and increased labor needed to manage small, irregular land parcels (Ertunç & Uyan, 2022; Janus et al., 2023).

In the studied area, 97.19% of the area falls within an elevation range of 0 to 800 m, which is linked to lower economic productivity in mountainous regions. Fragmented agricultural lands and topographical challenges elevate production costs and diminish net profitability, raising concerns among policymakers. Fragmentation incurs higher operating costs, as it extends travel time between parcels and limits machinery use. Evidence suggests that small, scattered plots lead to inefficiency and improper allocation of production inputs (Schultz, 1953; Kawasaki, 2010; Yucer et al., 2016; Deininger et al., 2017; Heider et al., 2018; Looga et al., 2018; Li & Li, 2019; Wang et al., 2020).

Farmer attitudes significantly influence the adoption of land consolidation projects in Turkey, with a survey indicating that 74.57% of agricultural stakeholders recognize land fragmentation as an issue, especially prevalent in the Marmara and Central Anatolia regions (Fig. 7). The majority of farmers (94%) expressed satisfaction with the consolidation of fragmented lands, followed by 75% satisfaction regarding cost reductions, 69% about separation from shareholders, 60% for increased land value, and 50% for improved infrastructure services. Overall, 76.9% of respondents were satisfied with LC activities, while only 5.8% were dissatisfied (Yucer et al., 2016).

Evidence from Japan and India indicates that the lack of LC leads to increased cultivation costs due to spatial fragmentation, highlighting the importance of LC projects in cost reduction for rice farming (Kawasaki, 2010; Deininger et al., 2017).

In Turkey, a significant issue is the concentration of agricultural enterprises, with 25.9% operating in the 20-49 decare size group. Most of the land is held by enterprises in the 200-499 decare group, comprising 24.5%. Additionally, 80.7% of agricultural enterprises are classified as small, with less than 100 decares, accounting for 29.1% of the total land held (TUİK, 2016).

The average number of parcels per farm in Turkey rose from 4.1 in 2001 to 5.9 in 2002, as per the 2001 General Agricultural Census. By 2011, the average parcel size reached 6.81 hectares. Despite this, the total average farm size decreased from 7.7 hectares in the 1950s to 6.1 hectares in the 2000s, before slightly increasing to 6.8 hectares in 2011 due to social agricultural policies. In 2020, the average agricultural farm size was reported as 5.9 hectares (Yucer et al., 2016; TUİK, 2020).

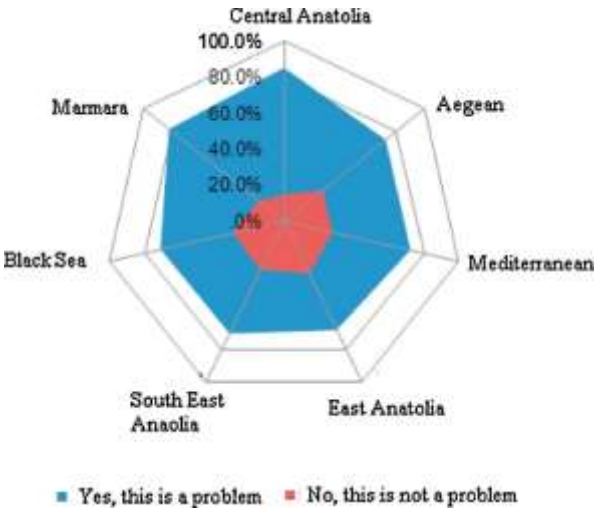

Figure 7. Fragmentation of agricultural lands is seen as a problem by stakeholders in different regions of Turkey (Yucer et al., 2016)

In 2020, the EU had 9.1 million agricultural holdings, with 63.8% being under 5 hectares (Fig. 8), playing a vital role in reducing rural poverty and supporting incomes. In contrast, 7.5% of farms, occupying 50 hectares or more, managed 68.2% of the agricultural area, while the average holding size was 17.4 hectares, with only 18% of farms reaching that size (Eurostat, 2022).

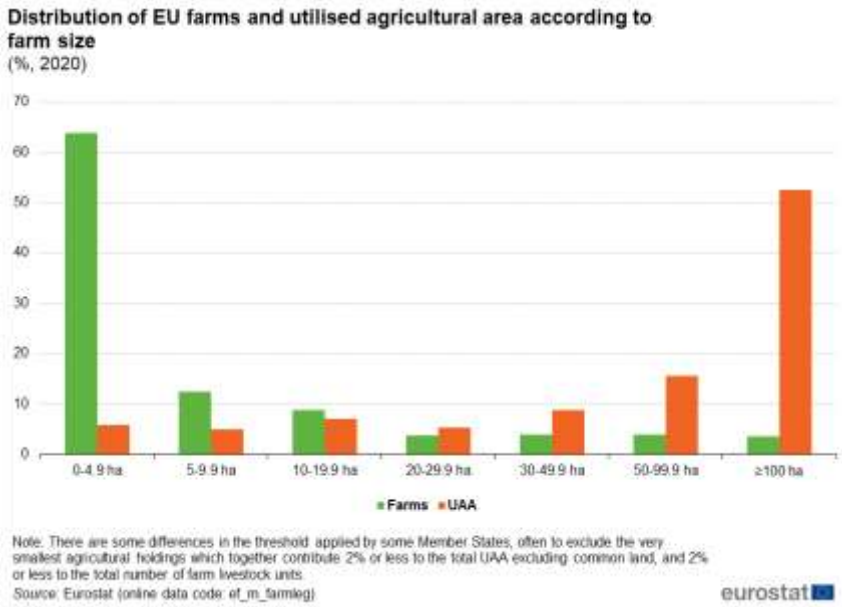

Figure 8. Distribution of EU farms and utilized agricultural area by farm size (%, 2020) (Eurostat, 2022)

As of 2024, the USA has 1.88 million farms, reflecting an 8% decrease from the 2.04 million reported in 2017. Additionally, farm land assets have declined to 876 million acres, a 3% fall from 900 million acres in 2017. The average land size per farm is 46.6 hectares (Fig. 9) (USDA, 2025).

In South China, the average land size is less than 0.64 hectares, notably smaller than the typical 1-4 hectares found in the EU and USA. Rapid urbanization and industrialization in the 21st century have caused a decline in the rural population and labor force, leading to abandoned houses and fields, which restrict effective land use (Sirami et al., 2019; Zou et al., 2024).

A study found that fragmentation in southwestern China's mountains is more severe than in other regions, with a Simpson index of 0.63. On average, 6.06 mu (1 mu = 666.67 m^2 or 1 mu = 1/15 ha) of cultivated land is divided into 6.16 parcels, requiring about 45 minutes for a round-trip from the farm to all parcels. They also stated that a one standard deviation increase in the number of parcels, the Simpson index, or the total minimum round trip time would lead to a 7.1%, 15.1%, and 12.2% increase in costs, respectively, when other conditions remain constant (Wang et al., 2020).

The overall consolidation rate for land consolidation projects in Turkey stands at 42.4%. Specific projects in Aşlama, Çarıklı, Çayırlı, and Karatlı villages within the Misli Plain of Niğde province showed varying rates of 54.18%, 23.08%, 35.72%, and 37.70%, respectively. These findings align with previous research indicating an average consolidation rate of 48% across 507 projects in 33 provinces of Turkey (Yağanoğlu et al., 2000; Başayiğit et al., 2016; Kuzu et al., 2018).

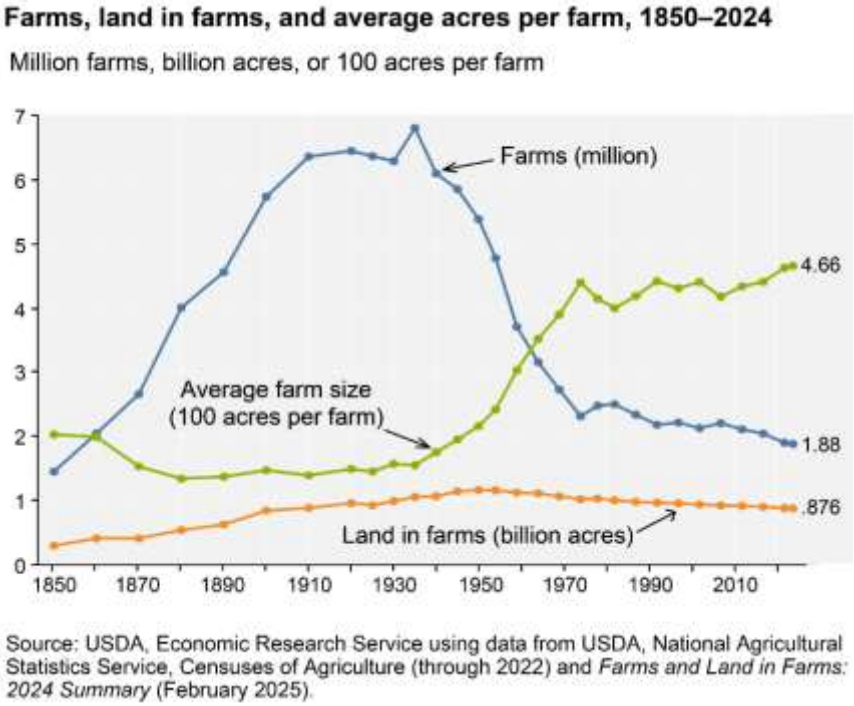

Figure 9. Farms, land in farms, and average area per farm, 1850-2024 (USDA, 2025)

In this study, it was found that the average number of parcels decreased from 11.71 to 3.35 after land consolidation (LC), reflecting a 71.39% reduction. Generally, consolidation projects in Turkey lead to a decrease in parcel numbers by over 50%, with some cases exceeding 80%. Other studies showed a 30.79% change in average parcel size in Beyazaltın Village and a 70.15% change in Yenipazar Plain. Additionally, one report indicated a reduction in parcels from 661 to 542, indicating an 18% consolidation rate, while another analyzed eight projects in Tavas Plain, with an average consolidation rate of 35.5% (Çay & Iscan, 2011; Uyan et al., 2013; Sönmezyıldız & Çakmak, 2013; Peker & Dağdelen, 2016; Tunalı & Dağdelen, 2018; Arslan & Değirmenci, 2026).

CONCLUSION

In the 2001-2024 period, there was an increase of approximately 33.64% in the population of Turkey, and the decrease in agricultural land per capita in the same period was 29.46%. Worldwide, the total agricultural area per capita, which was 0.64 ha in 2021, decreased to 0.45 ha in 2024. According to 2021 data, the cultivated agricultural area per capita in the world is 0.18 ha, and in the EU it is 0.22 ha (TUİK, 2025; DATABANK, 2025).

In this study, it was determined that the amount of stressed plants in 2017, when consolidation had not yet started, was approximately 3 times more than healthy plants. In contrast, in 2019, in the post-consolidation period, the amount of stressed plants showed a decrease trend of 33.616%. The healthy plant value doubled and covered approximately 50% of the total area. This situation revealed that consolidation had a positive effect.

As stated, 2021 was the year with the most extreme events, with 1024 extreme weather events recorded. In the same report, when looking at monthly temperature differences, it was stated that the temperatures of all months except March, September and October were above normal. In particular, May became the hottest month in the last 50 years, with a difference of 2.6°C, while January and July became the second-hottest months on record. In this context, during the period up to 2025, the area covered by stressed vegetation began to increase, similar to before consolidation (MGM, 2022).

In the light of all the results and information obtained, policies that can create services such as infrastructure integration and farmer education works need to be developed for a more efficient land consolidation. This is because land consolidation in rural areas aims not only to combine divided parcels, but also

to better manage all related areas such as agricultural, technical, social and cultural areas to improve land ownership standards (Mesci & Karlı, 2018; Pasakarnis & Maliene, 2010; Çay & Uyan, 2013).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Author Contributions

Ömer Faruk KARACA: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; writing-original draft; writing-review and editing.
Tuba ALBAYRAK: Investigation; writing-review and editing.

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Original Article

Contribution to the knowledge of the Cantharidae, Cleridae, Malachiidae and Melyridae (Coleoptera) fauna of Türkiye

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ABSTRACT

This study is based on specimens of the families Cantharidae, Cleridae, Malachiidae, and Melyridae (Coleoptera) collected from various localities in Türkiye. A total of 11 species belonging to four genera of Cantharidae, nine species belonging to one genus of Cleridae, five species belonging to two genera of Malachiidae and five species belonging to four genera of Melyridae were recorded. In addition, new locality records were reported for several species previously reported from Türkiye. The study also presents information on the vertical distribution, phenology, and geographical distribution of all species.

Key words: Cantharidae, Cleridae, Malachiidae, Melyridae, Türkiye.

Türkiye'nin Cantharidae, Cleridae, Malachiidae ve Melyridae (Coleoptera) Faunasına Katkılar

ÖZ

Bu çalışma, Türkiye'nin çeşitli bölgelerinden toplanan Cantharidae, Cleridae, Malachiidae ve Melyridae (Coleoptera) familyalarına ait örneklerden oluşmaktadır. Cantharidae familyasının dört cinsine ait toplam 11 tür, Cleridae familyasının bir cinsine ait dokuz tür, Malachiidae familyasının iki cinsine ait beş tür ve Melyridae familyasının dört cinsine ait beş tür kaydedilmiştir. Ayrıca, Türkiye'den daha önce bildirilen bazı türler için yeni lokalite kayıtları da verilmiştir. Ayrıca çalışmada tüm türlerin dikey dağılımı, fenolojisi ve coğrafi dağılımı hakkında bilgiler verilmiştir.

Anahtar kelimeler: Cantharidae, Cleridae, Malachiidae, Melyridae, Türkiye.

INTRODUCTION

Cantharidae, Malachiidae and Melyridae (Coleoptera) called soft-winged flower beetles. They are soft bodied and hairy. Both adults and larvae are usually predators. Adults are often found on vegetation, mainly in flowers, which they may also feed on pollen. The biology of Malachiidae remains insufficiently understood. Their larvae typically occur in soil, leaf litter, and beneath bark, where they behave as predators feeding on eggs, larvae, and soft-bodied adults. Adults are also frequently predatory, although they can additionally be encountered on vegetation, particularly flowers, where they may consume pollen. Cleridae are generally broad to elongate beetles, often exhibiting bright coloration, occasionally with a metallic sheen, and almost invariably bearing erect setae. Both larvae and adults are predominantly predatory and feed on other insects. Members of this family occur in a variety of habitats, including beneath bark, within the galleries of wood-boring insects, in bracket fungi, leaf litter, carrion, the nests of bees, wasps, and termites, as well as among stored products. Some adults are also found on flowers, where they may feed on pollen. Cantharidae are soft-bodied, generally

pubescent, and parallel-sided insects distinguished by the configuration of the metasternal–metepisternal suture. They are typically yellow, red, or black in coloration, although some species exhibit a metallic appearance. Most adults are predatory on other insects, whereas some may also consume nectar and pollen. Adults are commonly associated with flowers and plant foliage. The larvae inhabit soil, leaf litter, or decaying wood, where they are generally predaceous on other invertebrates, although some species may also feed on plant material (Booth et al., 1990).

Previous faunistic research on the beetle families Cantharidae, Cleridae, Malachiidae, and Melyridae in Türkiye has provided important baseline data. The Turkish Cantharidae fauna has been reported by Yıldırım et al. (2011), Tezcan and Onaral (2017), Bal and Özdikmen (2021), while Cleridae has been treated by Demir (2008), Bulak (2011), Bulak et al. (2012) and Bulak Korkmaz (2024). In addition, Malachiidae was studied by Yıldırım and Bulak (2012) and Melyridae was addressed by Liberti (2017, 2023) and these studies recorded various species from Türkiye.

In the present study, 11 species representing four genera of Cantharidae, nine species of a single genus of Cleridae, five species belonging to two genera of Malachiidae, and five species representing four genera of Melyridae were recorded from Türkiye.

MATERIALS AND METHODS

The examined material of Cantharidae, Cleridae, Malachiidae, and Melyridae (Coleoptera) was collected from various localities across Türkiye. The provinces from which the specimens were obtained are listed alphabetically below. All studied material is housed in the Atatürk University Biodiversity Science Museum (ABBM), Erzurum, Türkiye. Specimens were collected using several methods, predominantly by sweeping herbaceous vegetation in meadows and pastures, particularly around diverse flowering plants, as well as by means of light traps. The species identifications were made by the first author.

RESULTS AND DISCUSSION

In this study, a total of 30 species belonging to 11 genera of the families Cantharidae, Cleridae, Malachiidae, and Melyridae (Coleoptera) were recorded from different localities in Türkiye and are listed below.

Family Cantharidae

Genus: ***Boveycantharis*** Wittmer, 1969
Boveycantharis rufimana (Menetriez, 1832)
Material examined: Erzurum: İspir, Zeyrek, 2073 m, 22.VI.2011, 1 ex., Karayazı, Alemdağı, 16.VI.2012, 1 ex., Pazaryolu, Toprakkale, 1482 m, 19.VI.2014, 2 exs.
Distribution in Türkiye: Artvin, Rize, Tokat (Wittmer, 1969) ; Ardahan, Erzurum (Yıldırım et al., 2011); Rize, Tokat, Gümüşhane (Bal and Özdikmen, 2021).

Boveycantharis tokatensis (Pic, 1898)
Material examined: Erzurum: Tortum, Söğütlü, 1700 m, 9.VI.1997, 1 ex.
Distribution in Türkiye: Isparta (Silkin, 2008) ; Bayburt, Erzurum (Yıldırım et al., 2011); Bayburt, Bolu Abant, Erzurum, Isparta, Tokat Sultan Dağı, Uludağ (Bal and Özdikmen, 2021).

Genus: ***Cantharis*** Linnaeus, 1758
Cordicantharis cordicollis Küster, 1854
Material examined: Artvin: Şavşat, 1100 m, 22.V.1997, 7 exs.
Distribution in Türkiye: Türkiye (no locality cited) (Kazantsev, 2011) .

Cantharis lateralis Linnaeus, 1758
Material examined: Bilecik: 600 m, 15.VI.1995, 1 ex.; Erzurum: Aziziye, Eğerti, 1906 m, 22.VI.2011, 1 ex., Rizekent, 2100 m, 22.VI.2011, 1 ex., Toprakkale, 2327 m, 22.VI.2011, 1 ex., Yoncalık, 2044 m, 22.VI.2011, 1 ex., Çat, Yaylasuyu, 1918 m, 21.VI.2011, 2 exs.; Tunceli: Mazgirt, Kalaycı, 1200 m, 10.V.2011, 1 ex., 24.V.2011, 1 ex.
Distribution in Türkiye: Adana, Karaman, Kayseri, Mersin, Niğde, Sivas and Yozgat (Silkin, 2008); Bayburt, Erzurum (Yıldırım et al., 2011) ; Adana, Ankara, Antalya, Bayburt, Bolu, Erzurum, Karaman, Kayseri, Konya, Mersin, Niğde, Sivas, Yozgat (Bal and Özdikmen, 2021).
Remarks: New record for Bilecik and Tunceli.

Cantharis livida Linnaeus, 1758
Material examined: Erzurum: Karagöbek, 2048 m, 16.VII.2012, 1 ex., Aşkale, Çayköy, 1661 m, 19.VI.2012, 1 ex., 21.VI.2011, 1 ex., Kandilli, 1788 m, 21.VI.2011, 1 ex., Aziziye, Eğerti, 1906 m, 22.VI.2011, 2 exs., Çat, Çirişli, 2044 m, 18.VI.2012, 1 ex., Yukarıçat 1914 m, 21.VI.2011, 3 exs., İspir, Çayırözü, 2075 m, 19.VI.2014, 1 ex., Zeyrek, 2073 m, 22.VI.2011, 1 ex., Köprüköy, Eğirmez, 1641 m, 16.VI.2012, 1 ex., 13.VIII.2011, 1 ex., Narman, Demirdağ, 2121 m, 23.VI.2011, 3 exs., Kamışözü, 1877 m, 23.VI.2011, 1 ex., Tortum, Suyatağı, 1501 m, 27.V.2011, 2 exs.
Distribution in Türkiye: Aksaray, Diyarbakır, Isparta, İzmir, Konya, Nevşehir (Tuatay et al., 1972); Adana, Ankara, Antalya, Artvin, Erzincan, Erzurum, İzmit, Karaman, Kocaeli, Kayseri, Konya, Mersin, Niğde, Yozgat (Silkin, 2008); Amasya, Ardahan, Artvin, Bayburt, Bitlis, Çanakkale, Çorum, Diyarbakır, Erzincan, Erzurum, Hatay, Iğdır, Kars, Konya, Malatya, Rize, Tokat, Tunceli (Yıldırım et al., 2011); Adana, Aksaray, Amasya, Ankara, Antalya, Ardahan, Artvin, Çorum, Erzincan, Erzurum, Karaman, Kayseri, Kocaeli, Konya, Mersin, Niğde, Isparta, İzmit, Yozgat (Bal and Özdikmen, 2021).

Cantharis marginiventris funebris (Marseul, 1864)
Material examined: Denizli: Çal, Gömele, 839 m, 30.VI.1997, 1 ex.; Erzurum: Aziziye, Toprakkale, 2327 m, 22.VI.2011, 1 ex., İspir, Zeyrek, 2073 m, 22.VI.2011, 1 ex.
Distribution in Türkiye: Isparta (Demirözer and Karaca, 2014).
Remarks: New record for Denizli and Erzurum.

Cantharis melaspis Chevrolet, 1854
Material examined: Erzurum: University field, 1850 m, 20.VI.2012, 1 ex., Aşkale, Çayköy, 1661 m, 21.VI.2011, 1 ex., Olur, Olurdere, 1532 m, 23.VI.2011, 3 exs., Çat, Güzelyurt, 2044 m, 9.VIII.2011, 1 ex., Tuzla, 2300 m, 21.VI.2011, 2 exs, Yukarıçat, 1914 m, 18.VI.2012, 1 ex., İspir, 1200 m, 22.VI.2011, 1 ex., Çayırözü, 2075m, 19.VI.2014, 3 exs., Zeyrek, 2073 m, 22.VI.2011, 1 ex., Köprüköy, Eğirmez, 1641 m, 26.VI.2011, 1 ex., 13.VII.2011, 1 ex., Eyüpler, 1882 m, 16.VI.2012, 1 ex., Narman, Demirdağ, 2121 m, 23.VI.2011, 4 exs., Kamışözü, 1877 m, 23.VI.2011, 2 exs., Pazaryolu, 1472 m, 22.VI.2011, 1 ex., Kumaşkaya, 2085 m, 23.VI.2011, 3 exs., Tekman, Körsu, 2044 m, 26.VI.2011, 2 exs., Tortum, 1661 m, 23.VI.2011, 1 ex., Derekapı, 1630 m, 15.VI.2010, 1 ex., 13.VII.2011, 1 ex., Yukarısivri, 1902 m, 23.VI.2011, 3 exs., Uzundere, Çağlayan, 850 m, 27.V.2011, 9 ex.; Rize: Çamlıhemşin, Zilkale, 1500 m, 20.VI.2014, 1 ex., İkizdere, Tulumpınar, 1282 m, 19.VI.2014, 2 exs.; Trabzon: Araklı, Oylum, 922 m, 21.VI.2014, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 2.VI.2012, 3 exs., 3.VI.2012, 1 ex.
Distribution in Türkiye: Amasya, Malatya, Kahramanmaraş (Wittmer, 1969); Bayburt, Erzincan, Erzurum, Iğdır (Yıldırım et al., 2011).
Remarks: New record for Rize, Trabzon and Tunceli.

Genus: ***Metacantharis*** Bourgeois, 1886
Metacantharis taurigrada Bourgeois, 1900
Material examined: Bayburt: Demirözü, 1654 m, 17.VI.2010, 1 ex.; Erzurum: Dumlubaba, Güngörmez, 2168 m, 1.VII.2010, 1 ex., Pazaryolu, Kumaşkaya, 2085 m, 23.VI.2011, 1 ex., Toprakkale, 2327 m, 19.VI.2014, 2 exs.
Distribution in Türkiye: Adana, Hatay, Isparta and Mersin (Silkin, 2008); Tunceli (Yıldırım et al., 2011); Adana, Çankırı, Isparta, Hatay, Mersin (Bal and Özdikmen, 2021).
Remarks: New record for Bayburt and Erzurum.

Genus: ***Rhagonycha*** Eschscholtz, 1830
Rhagonycha aliena Dahlgren, 1972
Material examined: Erzurum: Pazaryolu, 1482 m, 15.VII.2012, 1 ex., 20.VII.2011, 1 ex., 24.VII.2011, 2 exs., Çiftepınar, 1758 m, 15.VII.2012, 1 ex., Uzundere, 1052 m, 21.VII.2012, 1 ex.; Giresun: Eynesil, Dizgine 11 m, 22.VI.2014, 4 exs., Espiye, 9 m, 24.VI.2014, 2 exs., Görele, Çavuşlu, 9 m, 22.VI.2014, 5 exs., Piraziz, 17 m, 23.VI.2014, 2 exs., Tirebolu, 18 m, 24.VI.2014, 3 exs., Balçıkbelen, 334 m, 22.VI.2014, 6 exs.; Ordu: Turnasuyu, 2 m, 23.VI.2014, 2 exs., Perşembe, Akçaova Köprüsü, 5 m, 23.VI.2014, 4 exs., Alınca, 88 m, 23.VI.2014, 2 exs., Çaytepe, 3 m, 23.VI.2014 1 ex.; Rize: Çamlıhemşin, 390 m, 20.VI.2014, 2 exs., İkizdere, Gürdere, 744 m, 19.VI.2014, 1 ex., Trabzon: Araklı, Küçükdere, 5 m, 21.VI.2014, 8 exs., Birlik, 415 m, 21.VI.2014, 2 exs., Oylum, 15 m, 21.VI.2014, 1 ex., Yomra, 327 m, 21.VI.2014, 2 exs.
Distribution in Türkiye: Bayburt, Bilecik, Erzincan, Erzurum, Hatay, Konya, Şanlıurfa (Yıldırım et al., 2011).
Remarks: New record for Giresun, Ordu, Rize and Trabzon.

Rhagonycha fulva (Scopoli, 1763)
Material examined: Ankara: Şereflikoçhisar, 947 m, 09.VII.1998, 1 ex., 11.VII.1998, 4 exs.; Giresun: 14 m, 07.VIII.1984, 2 exs.; Konya: Beyşehir, 1205 m, 05.VIII.1997, 1 ex.; Şanlıurfa: Merkez, 590 m, 12.VII.1990, 1 ex.
Distribution in Türkiye: Adana, Aksaray, Çorum, Gaziantep, Gümüşhane, Hatay, Niğde, Kahramanmaraş, Karaman, Kayseri, Kırklareli, Kocaeli, Niğde, Mersin, Osmaniye and Yozgat (Silkin, 2008); Erzurum (Yıldırım et al., 2011); Isparta (Demirözer and Karaca 2014).
Remarks: New record for Ankara, Giresun, Konya and Şanlıurfa.

Rhagonycha ruzickai Shivla, 2002
Material examined: Erzurum: Dumlubaba, Güngörmez, 2168 m, 01.VII.2010, 1 ex., Aziziye, Eğerti, 1906 m, 22.VI.2011, 1 ex., Toprakkale, 2327 m, 22.VI.2011, 1 ex., Çat, Aşağıçat, 1914 m, 21.VI.2011 3 exs., Yukarıçat, 1920 m, 21.VI.2011, 3 exs., Pazaryolu, Kumaşkaya, 2085 m, 23.VI.2011, 1 ex.; Kars: Sarıkamış, Akkurt, 1650 m, 22.VI.2010, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 10.V.2011, 1 ex., 24.V.2011, 2 exs.
Distribution in Türkiye: Şanlıurfa (Svihla, 2002); Erzurum (Yıldırım et al., 2011).
Remarks: New record for Kars and Tunceli.

Family Cleridae

Genus: ***Trichodes*** Herbst, 1792
Trichodes apiarius (Linnaeus, 1758)
Material examined: Erzurum: İspir, Yukarıözbağ, 1200 m, 20.VII.2011, 1 ex., Uzundere, Çamlıyamaç, 1350 m, 7.VIII.2011, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 2.VI.2012, 2 exs., 3.VI.2012, 3 exs., 15.VIII.2011, 1 ex., 19.VIII.2011, 1 ex., Pülümür, Akdik, 1500 m, 12.VI.2011, 1 ex., 18.VI.2011, 2 exs., 19.VI.2011, 1 ex.
Distribution in Türkiye: Yozgat (Demir, 2008); Bayburt, Erzurum (Bulak et al., 2012); Ankara (Bulak Korkmaz, 2024).
Remarks: New record for Tunceli.

Trichodes ephippiger Chevrolat, 1874
Material examined: Erzurum: Olur, Boğazören, 1168 m, 19.VII.2012, 1 ex., Coşkunlar, 999 m, 19.VII.2012, 1 ex., Demirtaş, 1888 m, 06.VII.2012, 1 ex., Taşlıköy, 885 m, 06.VII.2012, 1 ex., Yukarı karacasu, 1521 m, 19.VII.2011, 1 ex., Pasinler, 1877 m, 08.IX.2019, 1 ex., Pazaryolu, Kumaşkaya, 2085 m, 23.VI.2011, 2 exs, Şenkaya, Akşar, 1275 m, 10.VIII.2011, 1 ex., Çatalelma, 1583 m, 4.VII.2012, 1 ex., Sındıran, 1497 m, 10.VII.2011, 3 exs., Taht, 1283 m, 31.VII.2011, 2 exs., Tortum, 1661 m, 23.VI.2011, 1 ex., Derekapı, 1630 m, 13.VII.2011, 1 ex., Suyatağı Deresi, 1501 m, 27.V.2011, 1 ex., Şenyurt, 1265 m, 21.VII.2012, 1 ex.; Tunceli: Pülümür, Akdik, 1608 m, 13.VI.2011, 2 exs., 16.VI.2011, 2 exs., 20.VI.2011, 1 ex.
Distribution in Türkiye: Artvin, Bingöl, Diyarbakır, Erzurum (Bulak et al., 2012).
Remarks: New record for Tunceli.

Trichodes heydeni Escherich, 1892
Material examined: Tunceli: Mazgirt, Kalaycı, 1200 m, 12.VIII.2011, 2 exs., Ovacık, 1271 m, 28.VII.2012, 1 ex.
Distribution in Türkiye: Turkey (no locality cited) (Löbl and Smetana, 2007).

Trichodes insignis Fischer Von Waldheim, 1829
Material examined: Ardahan: Posof, 1583 m, 27.VII.2019, 1 ex.; Erzurum: Narman, 1610 m, 30.VI.2012, 1 ex.
Distribution in Türkiye: Bayburt, Iğdır, Tunceli (Bulak et al., 2012); Erzurum (Bulak Korkmaz, 2024).
Remarks: New record for Ardahan.

Trichodes longissimus (Abeille, 1881)
Material examined: Artvin: Yusufeli, Karakale, 1350 m, 23.VII.2003, 1 ex.; Erzurum: İspir, Kirazlı, 1206 m, 20.VII.2011, 2 exs.; Iğdır: Aralık, 820 m, 11.VI.2018; Konya: Güneysınır, Gürağaç, 1071 m, 04.VII.2000, 1 ex.
Distribution in Türkiye: Adana, Aksaray, Antalya, Artvin, Hatay, Isparta, Karaman, Kayseri, Konya, Mersin, Niğde, Osmaniye (Demir, 2008) ; Ankara, Artvin, Balıkesir, Burdur, Erzincan, Erzurum, Eskişehir, Kars, Konya, Mersin, Muş, Iğdır, İzmir (Bulak et al., 2012).

Trichodes oberthueri (Champenois, 1900)
Material examined: Tunceli: Mazgirt, Kalaycı, 1200 m, 1200 m, 19.VIII.2011, 1 ex.
Distribution in Türkiye: Diyarbakır (Bulak et al., 2012); Elazığ (Bulak Korkmaz, 2024).
Remarks: New record for Tunceli.

Trichodes reichei (Mulsant & Rey, 1863)
Material examined: Tunceli: Mazgirt, Kalaycı, 1200 m, 03.VI.2012, 1 ex.
Distribution in Türkiye: Diyarbakır, Mardin, Malatya, Şanlıurfa, Tunceli, (Liberti, 2023); Adana, Aksaray, Kayseri (Demir, 2008).

Trichodes quadriguttatus (Adams, 1817)
Material examined: Erzincan: 1200 m, 27.VI.2016, 1 ex., Tercan, 1394 m, 13.VI.2017, 1 ex.; Erzurum: Konaklı, Tekederesi, 2100 m, 22.VII.2011, 1 ex., University field, 1850 m, 20.VI.2012, 1 ex., Aşkale, Çayköy, 1661 m, 23.VII.2011, 2 exs., Küçükgeçit, 1709 m, 23.VII.2011, 1 ex., Aziziye, Ağören, 1788 m, 10.VI.2015, 1 ex., Çat, 1913 m, 23.VII.2011, 3 exs., Yukarıçat, 1914 m, 21.VI.2011, 1 ex., Tortum, 1661 m, 23.VI.2011, 1 ex.; Gümüşhane: 1150 m, 25.VI.2019, 1 ex.; Mersin: Tarsus, Boztepeköy, 1150 m, 6.VII.2015, 1 ex.; Niğde: Bor, 1100 m, 02.VIII.2018, 1 ex.
Distribution in Türkiye: Adana, Ankara, Antalya, Aksaray, Artvin, Çorum, Denizli, Erzincan, Isparta, Kahramanmaraş, Karaman, Kayseri, Kırşehir, Mersin, Nevşehir, Niğde, Yozgat (Demir, 2008); Antalya, Artvin, Bayburt, Diyarbakır, Erzincan, Erzurum, Iğdır, Rize (Bulak et al., 2012); Malatya (Háva, 2018).
Remarks: New record for Gümüşhane.

Trichodes sipylus (Linnaeus, 1758)
Material examined: Batman: Gercüş, 1000 m, 19.VI.2016, 1 ex.; Bingöl: Solhan, Başakköy, 1395 m, 26.VI.2000, 1 ex.; Erzurum: University field, 1850 m, 15.VII.2009, 1 ex., 15.VII.2011, 1 ex., Köprüköy, Eyüpler, 1882 m, 16.VI.2012, 1 ex., Olur, Yukarı karacasu, 1521 m, 19.VII.2012, 1 ex., Tortum, Derekapı, 1630 m, 13.VII.2011, 1 ex.; Kahramanmaraş: Elbistan, 1136 m, 05.VI.2017, 1 ex.; Mersin: Ayvagediği, 1200 m, 02.VIII.2013, 1 ex.; Tunceli: Mazgirt, Meşelik, 900 m, 20.VIII.2011, 2 exs.
Distribution in Türkiye: Adana, Ankara, Antalya, Isparta, Kayseri, Nevşehir, Niğde (Demir, 2008); Erzincan, Erzurum, Iğdır (Bulak et al., 2012).
Remarks: New record for Batman, Bingöl, Kahramanmaraş, Mersin and Tunceli.

Family Malachiidae

Genus: *Clanoptilus* Motschulsky, 1853
Clanoptilus dissimilis (Baudi, 1873)
Material examined: Erzurum: Dadaşköy, 1800 m, 04.VIII.2011, 1 ex., University Field, 1850 m, 20.VI.2012, 4 exs., Aşkale, 1661 m, 19.VI.2012, 1 ex., Tazegül, 1750 m, 19.VI. 2012, 1 ex., Kandilli, 1788 m, 21.VI.2011, 1 ex., Aziziye, Yoncalık, 2044 m, 22.VI.2011 2 ex., Eğerti, 1906 m, 22.VI.2011, 1 ex., Toprakkale, 2327 m, 22.VI.2011, 2 exs., 26.VI.2011, 1 ex., Çat, Aşağıçat, 1914 m, 21.VI.2011, 3 exs., Güzelyurt, 2044 m, 09.VIII.2011, 2 exs., Yukarıçat, 1914 m, 21.VI.2011, 1 ex., Yaylasuyu, 2300 m, 09.VIII.2011, 2 exs., 21.VI.2011, 1 ex., İspir, 1200 m, 22.VI.2011, 2 exs., Karayazı, Yukarı söylemez, 1896 m, 17.VI.2012, 1 ex., Köprüköy, Ataköy, 2000 m, 26.VI.2012, 1 ex., Eğirmez, 1641 m, 13.VIII.2011, 1 ex., Marifet, 1780 m, 16.VI.2012, 1 ex., 26.VI.2011, 2 exs., Eyüpler, 1882 m, 26.VI.2011, 3 exs., Narman, Çimenli, 2300 m, 10.VII.2011, 1 ex., Pasinler, Ovaköy, 1785 m, 30.VI.2011, 2 exs., Yiğit pınarı, 1805 m, 22.VII.2012, 1 ex., Ügümü, 1724 m, 17.VII.2011, 1 ex., Acı, 1820 m, 22.VII.2012., Pazaryolu, Kumaşkaya, 2085 m, 23.VI.2011, 1 ex., 1510 m, 22.VI.2011, 1 ex., 1445 m, 20.VII.2011, 1 ex., Oltu, Yarbaşı, 2092 m, 06.VII.2012, 1 ex., Demirtaş, 1882 m, 06.VII.2012, 2 exs., Orcuk, 1850 m, 06.VII.2012, 1 ex., Olur, Kaledibi, 1068 m, 23.VI.2011, 1 ex., Şenkaya, İçmesuyu, 1839 m, 14.VII.2012, 1 ex., Tekman, Çiçekdağı, 2044 m, 26.VI.2011, 2 exs., Tortum, 1661 m, 23.VI.2011, 1 ex., Taşbaşı, 2041 m, 09.VII.2011, 1 ex., Uzundere, Çağlayan, 850 m, 27.V.2011, 2 exs.
Distribution in Türkiye: Artvin, Bayburt, Erzurum, Iğdır, Tunceli (Yıldırım and Bulak, 2012).

Clanoptilus marginellus (Olivier, 1790)
Material examined: Erzincan: Refahiye, 1500 m, 20.VI.2009, 1 ex.; Erzurum: Olur, Olurdere, 1532 m, 23.VI.2011, 1 ex., Şenkaya, İçmesu, 1835 m, 14.VII.2012, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 24.V.2011, 1 ex.
Distribution in Türkiye: Artvin, Erzurum, Iğdır, Kars (Yıldırım and Bulak, 2012).
Remarks: New record for Tunceli.

Clanoptilus viridanus (Mulsant, 1852)
Material examined: Artvin: Ardanuç, Ferhatlı, 573 m, 15.VI.2010, 2 exs., Yusufeli, Demirkent, 1532 m, 15.VI.2010, 1 ex.; Erzurum: University field, 1850 m, 22.VII.2011, 1 ex., Aziziye, Kayapa, 1788 m, 03.VI.2010, 1 ex., Kümbet, 1850 m, 09.VIII.2011, 1 ex., Gelinkaya, 2044 m, 24.VI.2012, 1 ex., Özbek, 1820 m, 05.VIII.2011, 1 ex., Aşkale, Küçükgeçit, 1709 m, 23.VII.2011, 1 ex., Merdiven, 1950 m, 09.VIII.2011, 1 ex., Çayköy, 1661 m, 23.VII.2011, 1 ex., Çat, Çirişli, 2044 m, 23.VII.2011, 1 ex., Hınıs, 1720 m, 02.VII.2010, 1 ex., İspir, Kirazlı, 1206 m, 24.VII.2011, 1 ex., Narman, Kamışözü, 1877 m, 23.VI.2011, 1 ex., Oltu, Özdere, 2044 m, 16.VII.2012 1 ex., Yağmurcuk, 2300 m, 09.VIII.2011, 1 ex., Pasinler, Büyükdere, 1780 m, 12.VIII.2012 1 ex., Ovaköy, 1785 m, 12.VIII.2012, 1 ex., Acı, 1820 m, 22.VII.2012, 1 ex., Çöğender, 1735 m, 30.VII.2011, 2 exs., Şenkaya, Paşalı, 1276 m, 10.VII.2011, 1 ex., Deliktaş 13.VII.2011, 3 exs., Tekman, Körsu, 2044 m, 26.VI.2011, 1 ex., Tortum, Taşbaşı, 2041 m, 09.VII.2011, 1 ex., Derekapı, 1630 m, 13.VII.2011 1 ex., Uzundere, Çağlayan, 850 m, 27.V.2011, 1012 m, 2 exs., Çamlıyamaç, 1350 m, 07.VIII.2011, 1 ex.
Distribution in Türkiye: Artvin, Bayburt, Erzurum, Iğdır, Kars (Yıldırım and Bulak, 2012).

Genus: *Malachius* Fabricius, 1775
Malachius aeneus (Linnaeus, 1758)
Material examined: Erzurum: Aziziye, Gelinkaya, 2044 m, 24.VI.2012, 4 exs., Toprakkale, 2327 m, 22.VI.2012, 1 ex., Eğerti, 1906 m, 22.VI.2011, 2 exs., Çat, Aşağıçat, 1914 m, 21.VI.2011 2 exs., Güzelyurt, 2044 m, 09.VIII.2011, 1 ex., Tuzla, 2300 m, 21.VI.2011, 1 ex., Yukarıçat, 1914 m, 21.VI.2011, 4 exs., 18.VI.2012, 1 ex., Köprüköy, Eğirmez, 1641 m, 13.VIII.2011, 1 ex., 16.VI.2012, 1 ex.,Tekman, Çiçekdağı, 2044 m, 26.VI.2011, 1 ex., Hacıömer, 2044 m, 16.VI.2012, 1 ex., Uzundere, Çağlayan, 850 m, 27.V.2011, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 02.VI.2012, 1 ex.
Distribution in Türkiye: Artvin, Erzurum, Iğdır (Yıldırım and Bulak, 2012).
Remarks: New record for Tunceli.

Malachius semiaeneus Abeille de Perrin, 1891
Material examined: Artvin: Ardanuç, Ferhatlı, 573 m, 15.VI.2010, 1 ex.; Erzincan: Mercan, 1364 m, 10.VI.2010, 1 ex.; Erzurum: Çat, Güzelyurt, 2044 m, 09.VIII.2011, 1 ex., Yukarıçat, 1914 m, 21.VI.2011, 1 ex., İspir, 1200 m, 22.VI.2011, 3 exs., Kan, 1172 m, 22.VI.2011, 2 exs., Maden Köprübaşı, 1256 m, 22.VI.2011, 1 ex., Köprüköy, Eğirmez, 1641 m, 16.VI.2012, 1 ex., Narman, Demirdağ, 2121 m, 23.VI.2011, 6 exs., Yukarısivri, 1902 m, 23.VI.2011, 2 exs., Oltu, Çamlıbel, 1775 m, 13.VII.2011, 1 ex., İğdeli, 1660 m, 30.VI.2012, 1 ex., Olur, Yukarıkaracasu, 1521 m, 19.VI.2012, 1 ex., Pazaryolu, Kumaşkaya, 2085 m, 23.VI.2011, 5 exs., Şenkaya, İçmesuyu, 1839 m, 14.VII.2012, 1 ex., Tortum, 1653 m, 23.VI.2011, 2 exs., Suyatağıderesi, 1501 m, 27.V.2011, 3 exs., Taşbaşı, 2041 m, 09.VII.2011, 1 ex., Uzundere, Çağlayan, 850 m, 27.V.2010, 3 exs., 27.V.2011, 6 exs.; Kars: Kağızman, 1410 m, 22.VI.2010, 1 ex.; Tunceli: Mazgirt, Kalaycı, 1200 m, 28.IV.2010, 1 ex.
Distribution in Türkiye: Artvin, Bayburt, Diyarbakır, Erzincan, Erzurum, Iğdır, Kars, Tunceli (Yıldırım and Bulak, 2012).

Family Melyridae

Genus: *Enicopus* Stephens, 1830
Enicopus ater (Fabricius, 1787)
Material examined: Amasya: 453 m, 14.VII.1983, 3 exs.; Artvin: Yusufeli, Morkaya, 700 m, 15.VI.2010, 4 exs., Pamukçular, 700 m, 16.VI.2010, 2 exs., Sebzeciler, 500 m, 16.VI.2010, 1 ex., Şavşat, 400 m, 16.VI.2010, 1 ex.; Erzincan: Geyikli, 1160 m, 11.VI.2010, 1 ex., Refahiye, 1500 m, 20.VI.2009, 1 ex.; Erzurum: 1850 m, 02.VI.1983, 2 ex., 09.VI.1983, 1 ex., 12.VI.1988, 2 exs., 14.VI.1971, 1 ex., 15.VI.1965, 1 ex., 20.VI.1966, 1 ex., 05.VII.1973, 2 exs.,13.VII.1979, 1 ex., 18.VII.1979, 8 exs., 12.VIII.1979, 1 ex., Abdurrahmangazi,1900 m, 22.VII.2012, 1 ex., Dadaşkent, 1806 m, 14.VI.2010, 3 exs., Karagöbek Mountains, 2200 m, 05.VII.1989, 3 exs., Palandöken, 2300 m, 18.VII.1979, 3 exs., Söğütlü, 1788 m, 25.VI.2010, 1 ex., University field, 1850 m, 17.VI.1971, 4 exs., 24.VI.2009, 6 exs., 25.VI.2009, 7 exs., 14.VII.1997, 30 exs., 05.VIII.2010, 2 exs., Çat, Çukurçayır, 2183 m, 18.VII.2012, 1 ex., Aziziye, 1800 m, 14.VI.2010, 7 exs., Beypınarı, 1850 m, 15.VII.2009, 7 exs., Çiftlik, 1850 m, 15.VII.2009, 7 exs., Aşkale, 1650 m, 08.VII.2009, 71 exs., 22.VI.2011 1 ex., Horasan, 1588 m, 23.VI.2009, 6 exs., 02.VII.2010, 6 exs., 20.VII.2009, 4 exs., Köprübaşı, 994 m, 21.VI.2010, 1 ex., Narman, 1640 m, 24.VII.2009, 2 exs., Toygarlı, 2123 m, 10.VI.2011 1 ex., Araköy, 1472 m, 23.VI.2011, 2 exs., Karayazı, Alemdağı, 2022 m, 16.VII.2011, 7 exs., Kırgındere, 2215 m, 02.VII.2010, 6 exs., Yukarısöylemez, 1896 m, 02.VII.2010, 1 ex., Oltu, 1455 m, 25.VI.1971, 1 ex., Çamlıbel, 1700 m, 13.VI.2011, 1 ex., Pasinler, 1660 m, 10.VI.1983, 1 ex., Tutlu, 1240 m, 23.VI.2011, 1 ex., Sansar deresi, 1817 m, 17.VII.2011 1 ex., Tortum, Derekapı, 1630 m, 1400 m, 15.VI.2010, 1 ex., 13.VI.2011 1 ex., Uzundere,

Çağlayan, 850 m, 27.V.2010, 5 exs., 27.V.2011, 1 ex., Tekman, Körsu, 2044 m, 26.VI.2011, 1 ex.; Iğdır: 825 m, 20.VI.2009, 1 ex., 20.VI.2010, 4 exs., Suveren, 1000 m, 23.VI.2010, 1ex., Tuzluca, 900 m, 18.VI.2009, 3 exs., Menderes, 1100 m, 23.VI.2010, 1 ex.; Giresun: Eynesil, Dizgine, 11 m, 22.VI.2014, 1 ex., Kars: Sarıkamış, Karakurt, 1500 m, 22.VI..2010, 9 exs., Akkurt, 1525 m, 22.VI.2010, 3 exs.
Distribution in Türkiye: Türkiye (no locality cited) (Liberti and Constantin, 2009).

Genus: ***Dasytes*** Paykull, 1799
Dasytes xanthocnemus Kolenati, 1846
Material examined: Kars: Sarıkamış, 1900 m, 13.VIII.2009, 3 exs.
Distribution in Türkiye: Türkiye (no locality cited) (Plonski and Ghahari, 2018).

Genus: ***Dasytidius*** Schilsky, 1896
Dasytidius funebris Marseul, 1864
Material examined: Erzurum: Aziziye, Eğerti, 1750 m, 15.VII.1997, 1 ex.
Distribution in Türkiye: Afyon, Antalya, Aydın, Balıkesir, Çanakkale, Denizli (Liberti, 2023).
Remarks: New record for Erzurum.

Genus: ***Danacea*** Laporte de Castelnau, 1836
Danacea zolotarewi Pic, 1910
Material examined: Bayburt: Kopdağı, 2370 m, 13.VII.1997, 5 exs.; Erzincan: Kemaliye, Sandıklı, 1397 m, 20.VI.1982, 1 ex.; Erzurum: Güzelyayla, 2100 m, 11.VII.1997, 3 exs., Palandöken, 2500 m, 23.VII.1997, 2 exs., Aşkale, Tepebaşı, 1900 m, 15.VII.1997, 2 exs., Aziziye, Serçeme, 1750 m, 02.VI.1997, 1 ex., İspir, Madenköprübaşı, 1400 m, 03.VII.1997, 1 ex., Tortum, Yumaklı, 2250 m, 14.VII.1997, 25 exs.
Distribution in Türkiye: Türkiye (no locality cited) (Liberti, 2017).

Danacea olivacea Baudi a Selve, 1873
Material examined: Erzurum: Oltu, Subatık, 1580 m, 25.VI.1996, 1 ex., Pazaryolu, Akbulut, 1350 m, 03.VII.1997, 1 ex., Tortum, 1611 m, 02.VI.1978, 1 ex.
Distribution in Türkiye: Giresun, Gümüşhane (Liberti, 2017).
Remarks: New record for Erzurum.

According to Table 1, the examined Cantharidae taxa showed variation in their altitudinal distribution ranges. Among them, *R. aliena* exhibited the widest altitudinal distribution, being collected from seven different ranges, followed by *C. melaspis*, which was recorded from six ranges. In contrast, only two species, *B. tokatensis* and *C. cordicollis*, were restricted to a single altitudinal range, namely 1501-1750 m and 1001-1250 m, respectively. Within the family Cleridae, *T. ephippiger* showed the broadest altitudinal distribution, occurring in six different altitude ranges, whereas *T. sipylus* was recorded from five ranges. By contrast, *T. insignis* was restricted to 1501-1750 m, whereas *T. oberthueri* and *T. reichei* were both recorded from 1001-1250 m. Most species were recorded from the 1001-1250 m altitude range. Within the family Malachiidae, the recorded taxa showed a comparatively broad altitudinal distribution. *M. semiaeneus* and *C. viridanus* were the most widely distributed species, each occurring in seven different altitude ranges, followed by *C. dissimilis*, which was recorded from six ranges. *C. marginellus* and *M. aeneus* were each found in four altitudinal ranges. No species within this family was restricted to a single altitude range. Overall, the recorded malachiid taxa were distributed across a wide altitudinal range. Within the family Melyridae, the species with the widest altitudinal distribution was *E. ater*, whereas *D. xanthocnemus* and *D. funebris* showed the narrowest distribution, each being recorded from a single altitude range. Moreover, all species except one were found within the 1501-1750 m altitude range. The seasonal activities of insects significant importance. The specimens in the study were evaluated from this perspective as well. The seasonal activity of the recorded taxa was also evaluated based on the collection data. The species were generally collected from April to August, among these months, June and July were the most prominent in terms of species occurrence. Some species were present over a wider seasonal period, whereas others were recorded only in a limited number of months. These findings indicate that the main activity period of the examined taxa extends from late spring to mid-summer.

Table 1. The distribution of collected species in Türkiye

Data of collected species: VD: Vertical distribution, SD: Seasonal dynamics, GR: Geographical regions, DT: Distributions in Türkiye.

Names of Taxa	VD	SD	GR	DT
Cantharidae				
Boveycantharis rufimana (Menetriez, 1832)	E, H	J	EAR	Erzurum
Boveycantharis tokatensis (Pic, 1898)	F	J	EAR	Erzurum
Cordicantharis cordicollis Küster, 1854	D	M	BSR	Artvin
Cantharis lateralis Linnaeus, 1758	B, E, G, H	M, J	MR, EAR	*Bilecik, Erzurum, *Tunceli
Cantharis livida Linnaeus, 1758	F, G, H	M, J, Jl, Ag	EAR	Erzurum
Cantharis marginiventris funebris (Marseul, 1864)	C, H	J	AR, EAR	*Denizli, *Erzurum
Cantharis melaspis Chevrolet, 1854	C, D, E,F, G, H	J, Jl, Ag	BSR, EAR	Erzurum, *Rize, *Trabzon, *Tunceli
Metacantharis taurigrada Bourgeois, 1900	F, H	J, Jl	BSR, EAR	*Bayburt, *Erzurum
Rhagonycha aliena Dahlgren, 1972	A, B C, D, E, F, G	J, Jl	BSR, EAR	Erzurum, *Giresun, *Ordu,*Rize, *Trabzon
Rhagonycha fulva (Scopoli, 1763)	A, B, C, D	Jl, Ag	BSR CAR, SAR,	*Ankara, *Giresun, *Konya, *Şanlıurfa
Rhagonycha ruzickai Shivla, 2002	D, F, G, H	M, J, Jl,	EAR	Erzurum, *Kars, *Tunceli
Cleridae				
Trichodes apiarius (Linnaeus, 1758)	D, E	J, Jl, Ag	EAR	Erzurum, *Tunceli
Trichodes ephippiger Chevrolat, 1874	C, D E, F, G, H	M, J, Jl, Ag, Sp	EAR	Erzurum, *Tunceli
Trichodes heydeni Escherich, 1892	D, E	Jl, Ag	EAR	Tunceli
Trichodes insignis Fischer Von Waldheim, 1829	F	J, Jl	EAR	*Ardahan, Erzurum
Trichodes longissimus (Abeille, 1881)	C, D, E	J, Jl	BSR, CAR, EAR	Artvin, Erzurum, Iğdır, Konya
Trichodes oberthueri (Champenois, 1900)	D	Ag	EAR	*Tunceli
Trichodes reichei (Mulsant & Rey, 1863)	D	J	EAR	Tunceli
Trichodes quadriguttatus (Adams, 1817)	D, F, G, H	J, Jl, Ag	BSR,CAR, EAR,MDR	Erzincan, Erzurum, *Gümüşhane, Mersin, Niğde
Trichodes sipylus (Linnaeus, 1758)	C, D, E, F, G	J, Jl, Ag	EAR, MDR, SAR,	*Batman, *Bingöl, Erzurum, *Kahramanmaraş, *Mersin, *Tunceli
Malachiidae				
Clanoptilus dissimilis (Baudi, 1873)	C, D, E, F, G, H	M, J, Jl, Ag	EAR	Erzurum
Clanoptilus marginellus (Olivier, 1790)	D, E, F, G	M, J, Jl	EAR	Erzincan, Erzurum, *Tunceli
Clanoptilus viridanus (Mulsant, 1852)	B, C, D, E, F, G, H	M, J, Jl, Ag	BSR, EAR	Artvin, Erzurum
Malachius aeneus (Linnaeus, 1758)	C, F, G, H	M, J, Ag	EAR	Erzurum, *Tunceli
Malachius semiaeneus Abeille de Perrin, 1891	B, C, D, E, F, G, H,	Ap, M, J, Jl, Ag	BSR, EAR	Artvin, Erzincan, Erzurum, Kars, Tunceli

Names of Taxa	VD	SD	GR	DT
Cantharidae				
Melyridae				
Enicopus ater (Fabricius, 1787)	A, B, C, D, E, F, G, H	M, J, Jl, Ag	BSR, EAR	Amasya, Artvin, Erzincan, Erzurum, Iğdır, Giresun, Kars
Dasytes xanthocnemus Kolenati, 1846	G	Ag	EAR	Kars
Dasytidius funebris Marseul, 1864	F	Jl	EAR	*Erzurum
Danacea zolotarewi Pic, 1910	E, F, G, H	J, Jl	BSR, EAR	Bayburt, Erzincan, Erzurum
Danacea olivacea Baudi a Selve, 1873	E, F	J	EAR	*Erzurum

VD (metre): A: 0-500 m, B: 501-750 m, C: 751-1000 m, D: 1001-1250 m, E: 1251- 1500 m, F: 1501-1750 m, G: 1751-2000 m, H: 2001-2500 m. Ap: April, M: May, J: June, Jl: July, Ag: August, Sp: September. AR: Aegean Region, BSR: Black Sea Region, CAR: Central Anatolian Region, EAR: Eastern Anatolia Region, MR: Marmara Region, MDR: Mediterranean Region, SAR: Southeastern Anatolia Region; * New locality record in Türkiye.

CONCLUSION

A total of 19 new locality records were determined for 11 species belonging to four genera of Cantharidae. In Cleridae, 10 new locality records were determined for six of the nine species belonging to a single genus. In Malachiidae, two new locality records were determined for two of the five species belonging to two genera, and in Melyridae, two new locality records were determined for two of the five species belonging to four genera. Overall, 33 new locality records were added in the present study.

In summary, the discovery and documentation of new faunistic data on Cantharidae, Cleridae, Malachiidae, and Melyridae will contribute significantly to future faunistic and taxonomic studies and provide a valuable basis for researchers dealing with these families.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Original Article

Modeling the Impact of Sustainable Packaging and Food Safety Perceptions on Consumer Purchasing Behavior Using an AI-Based Fuzzy Logic Approach: The Burdur Example

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ABSTRACT

This study examines the impact of perceptions of sustainable packaging and food safety on consumers' purchasing behavior and models these interactions using an AI-based fuzzy logic approach. The research was conducted based on data obtained from consumers living in Burdur province through an online survey. The survey assessed participants' demographic characteristics, packaging expectations, and the importance they placed on environmentally friendly packaging elements. The data obtained provided a foundation for understanding the multidimensional and complex nature of consumer behavior. The main objective of the research is to develop a system that can predict consumers' purchasing intentions by modeling their subjective and uncertain perceptions regarding sustainable packaging and food safety within a mathematical framework. Today, sustainable packaging is gaining increasing importance in terms of reducing environmental impacts, conserving natural resources, and raising consumer awareness. Features such as packaging being environmentally friendly, produced from recyclable materials, and not harming nature are among the important factors influencing consumers' purchasing decisions. However, measuring and modeling these perceptions is a complex process due to consumers' varying levels of knowledge, attitudes, and values. The fuzzy logic model developed within this scope allows for the mathematical expression of uncertainties and subjective evaluations in consumers' perceptions. In the model, demographic characteristics, packaging expectations, and the importance given to environmentally friendly packaging elements are used as basic inputs, while purchase intention is considered as the output variable. As a result, the study reveals the impact of perceptions of sustainable packaging and food safety on consumer purchasing behavior and demonstrates that the artificial intelligence-based fuzzy logic approach is an effective method for modeling consumer behavior. The research makes significant contributions to both the academic literature and sustainable packaging practices.

Key words: Consumer Behavior,Sustainable Packaging,Food Safety,Fuzzy Logic,Purchase Intention, Burdur.

Sürdürülebilir Ambalaj ve Gıda Güvenliği Algılarının Tüketici Satın Alma Davranışı Üzerindeki Etkisinin Yapay Zeka Tabanlı Bulanık Mantık Yaklaşımı ile Modellenmesi : Burdur İli Örneği

ÖZ

Bu çalışmada, sürdürülebilir ambalajlama ve gıda güvenliği algılarının tüketicilerin satın alma davranışları üzerindeki etkisi incelenmiş ve bu etkileşimler yapay zekâ tabanlı bulanık mantık yaklaşımıyla modellenmiştir. Araştırma, Burdur ilinde yaşayan tüketicilerden çevrimiçi anket yöntemiyle elde edilen veriler temelinde gerçekleştirilmiştir. Anket kapsamında katılımcıların demografik özellikleri, ambalajlama beklentileri ve çevre dostu ambalajlama unsurlarına verdikleri önem değerlendirilmiştir. Elde edilen veriler, tüketici davranışlarının çok boyutlu ve karmaşık yapısının anlaşılmasına yönelik temel oluşturmuştur.Araştırmanın temel amacı, tüketicilerin sürdürülebilir ambalajlama ve gıda güvenliğine ilişkin sübjektif ve belirsizlik içeren algılarını matematiksel bir çerçevede modelleyerek satın alma niyetlerini tahmin edebilen bir sistem geliştirmektir.

Günümüzde sürdürülebilir ambalajlama; çevresel etkilerin azaltılması, doğal kaynakların korunması ve tüketici bilincinin artması açısından giderek önem kazanmaktadır. Ambalajın çevre dostu olması, geri dönüştürülebilir malzemelerden üretilmesi ve doğaya zarar vermemesi gibi özellikler, tüketicilerin satın alma kararlarını etkileyen önemli unsurlar arasında yer almaktadır. Bununla birlikte, tüketicilerin farklı bilgi düzeyleri, tutumları ve değer yargıları nedeniyle bu algıların ölçülmesi ve modellenmesi karmaşık bir süreçtir.Bu kapsamda geliştirilen bulanık mantık modeli, tüketicilerin algılarındaki belirsizlik ve sübjektif değerlendirmeleri matematiksel olarak ifade etmeye olanak sağlamaktadır. Modelde demografik özellikler, ambalaj beklentileri ve çevre dostu ambalajlama unsurlarına verilen önem temel girdiler olarak kullanılırken, satın alma niyeti çıktı değişkeni olarak ele alınmıştır. Sonuç olarak çalışma, sürdürülebilir ambalajlama ve gıda güvenliği algılarının tüketici satın alma davranışları üzerindeki etkisini ortaya koymakta ve yapay zekâ tabanlı bulanık mantık yaklaşımının tüketici davranışlarının modellenmesinde etkili bir yöntem olduğunu göstermektedir. Araştırma, hem akademik literatüre hem de sürdürülebilir ambalajlama uygulamalarına yönelik önemli katkılar sunmaktadır.

Anahtar kelimeler: Tüketici Davranışı,Sürdürülebilir Ambalaj,Gıda Güvenliği,Bulanık Mantık,Satın Alma Niyeti, Burdur

INTRODUCTION

In today's food and machinery industries, packaging and preservation processes have become one of the most important factors. As global competition increases, the importance of packaging has further grown due to rising consumer welfare, a focus on health, customer satisfaction, and the need to protect consumer rights. The packaging and sustainable packaging sectors play a significant role in purchasing behavior due to reasons such as ease of transport and use, product protection, providing consumers with necessary information about the product, and attracting consumer interest. The fundamental function of packaging material is to help transport food efficiently and safely throughout the distribution chain from producer to consumer. Numerous studies over the past thirty years have highlighted how beverage and food packaging informs consumers at the point of sale and during consumption, and how the perception of safe packaging materials is shaped throughout the process. It has been shown that even relatively small changes in design elements such as shape, color, orientation, and location in packaging design can significantly influence consumer evaluations and purchasing intentions, positively or negatively (Brody et al., 2008; Simmonds et al., 2018). Differences in consumer perceptions increase the importance of the language and labels used in product marketing. Furthermore, the importance of trust as a factor within green consumer behavior is supported by the study conducted by Alamsyah and Aryanto (2021). This study indicates that consumers' perceived quality and ecological labels increase green trust, which positively influences purchase intention (Alamsyah & Aryanto, 2021). Advances in packaging and sustainable packaging technology have created new trends and opportunities in packaging modeling and design. Transparency has been introduced to packaging across a wide range of products, and new product modeling systems have been developed to improve expected quality. This study examines the impact of sustainable packaging perception on consumer purchasing behavior through an online survey conducted in Burdur province. The relationships and connections between consumers' demographic characteristics, packaging expectations, and the importance they place on environmentally friendly packaging features were analyzed. Additionally, the findings from these analyses were used to create a Fuzzy Logic model. This model aims to predict purchase intention by modeling consumers' subjective and uncertain perceptions within a mathematical framework (Almalki et al., 2021).

MATERIALS AND METHODS

A Conceptual Framework

The concept of sustainability has gained increasing prominence in response to environmental, social, and economic challenges, including global warming and food security concerns. This paradigm shift extends beyond business enterprises to encompass governmental policies and consumer behavior patterns. The concepts of green marketing and green consumerism have become increasingly prevalent in marketing literature, reflecting growing demand for consumption patterns that minimize negative environmental impacts (Agyeman, 2014; Çavuşoğlu, 2021).

Although consumers generally express positive attitudes toward sustainable products and brands, research indicates that these attitudes do not consistently translate into purchasing behaviors, suggesting that sustainability perception varies significantly according to demographic and psychological factors (Özsaçmacı & Özdemir, 2021). Studies examining the effects of environmentally friendly packaging on consumer attitudes and purchase intentions consistently emphasize the critical role of packaging in shaping purchasing decisions (Bingöl, 2023).

When examining Turkish consumers' reactions to packaging from design, sustainability, and environmental perspectives, previous research has identified a notable gap between awareness of sustainable packaging and actual adoption as a purchasing behavior. This study investigates the factors and elements influencing consumer purchase intentions regarding sustainable packaging (Köse, 2024). Preliminary findings indicate that 54% of consumers have preferred sustainable packaging products in the past six months, reflecting evolving perceptions across different countries and informing global reports on consumer purchasing behavior.

Research Design and Sample

This research was conducted with individuals residing in Burdur province, located in the Mediterranean Region of Turkey. The sample size was determined as 392 participants according to the Krejcie and Morgan (1970) formula, employing a 95% confidence interval, 5% margin of error, and 50% population proportion assumption (Yazıcıoğlu & Erdoğan, 2004; Çaylak et al., 2019).

The measurement instrument consisted of a 22-item, five-point Likert-type scale designed to examine Burdur residents' expectations and concerns regarding food packaging. The scale comprises six sub-dimensions: advertising features, visual features, practical packaging, food safety impact, epidemic disease transmission concerns, and environmentally friendly packaging features. Responses were scored from "strongly disagree" (1) to "strongly agree" (5).

Statistical Analysis

Factor analysis was employed to determine the construct validity of the scale, while Cronbach's alpha coefficient was calculated to assess internal consistency reliability. Data analysis was conducted using SPSS statistical software. Descriptive statistics (frequency, percentage, mean ± standard deviation) were computed for all variables. Normality of numerical variables was assessed using the Shapiro-Wilk test and examination of skewness-kurtosis values.

Group differences in scale scores and sub-dimension scores according to socio-demographic characteristics were analyzed using one-way analysis of variance (ANOVA) and independent samples t-tests. Pearson product-moment correlation analysis was employed to examine relationships between the scale and its sub-dimensions. Statistical significance was set at $p < 0.05$ for all analyses.

Fuzzy Logic Model Development

In addition to traditional statistical analyses, a fuzzy logic approach was designed to model consumers' purchase intention. Fuzzy logic provides an appropriate framework for processing uncertain and imprecise information by mimicking human cognitive processes (Kosko, 1986). The model architecture consists of three input variable classes and one output variable class.

Fuzzy logic provides a rigorous mathematical framework for processing uncertain and imprecise information by mimicking human cognitive processes (Kosko, 1986). The theoretical foundation of fuzzy logic rests on the concept of fuzzy sets, where elements can have partial membership in multiple sets simultaneously, characterized by membership functions $\mu(x)$ that map elements to the interval [0,1].

In contrast to classical set theory where an element either belongs to a set (membership = 1) or does not belong (membership = 0), fuzzy set theory allows for gradual membership transitions. This characteristic makes fuzzy logic particularly suitable for modeling human perceptions, which are inherently imprecise and context-dependent (Zadeh, 1965).

The application of fuzzy logic to consumer behavior modeling is grounded in the recognition that consumer perceptions of packaging attributes exist on continua rather than as discrete categories. For example, a consumer's perception of a packaging being "environmentally friendly" is not binary but exists along a spectrum from "not at all environmentally friendly" to "very environmentally friendly" with many gradations in between.

Input Variables

Sustainable Packaging Perception: Captures consumer perceptions regarding packaging characteristics such as recyclability, use of natural materials, and environmental impact.

Food Safety and Inspection Perception: Measures consumer confidence in the packaging's ability to ensure food safety and hygiene.

1. Sustainable Packaging Perception (x_1): Captures consumer perceptions regarding packaging characteristics such as recyclability, use of natural materials, and environmental impact. The variable is defined over the domain $X_1 = [1,5]$, corresponding to the Likert scale responses.

2. Food Safety and Inspection Perception (x_2): Measures consumer confidence in the packaging's ability to ensure food safety and hygiene. Domain: $X_2 = [1,5]$.

3. Purchase Intention (y): Represents the consumer's likelihood or willingness to purchase a particular packaged product, expressed as a percentage. Domain: Y = [0,100].

Usability and Practicality Perception

Assesses consumer perceptions of practical packaging features, including ease of opening, closing, carrying, and handling. Domain: X_3 = [1,5].

Output Variable

Purchase Intention: Represents the consumer's likelihood or willingness to purchase a particular packaged product, expressed as a percentage.

Fuzzy sets and membership functions were defined for each variable. Fuzzy rules establishing relationships between input and output variables were developed based on expert knowledge and empirical findings from the literature. The model incorporated 27 rules governing the relationships between input combinations and predicted purchase intention.

RESULTS AND DISCUSSION

The findings regarding the socio-demographic characteristics and food packaging expectations of the 392 participants in the study are presented below. This study examined the effects of changes occurring or expected in the food sector on consumers through direct and indirect questions. In this context, socio-demographic parameters that were thought to have an impact on consumer awareness were asked in the survey, and the information obtained is summarized in Table 1.

The average age of the participants was found to be 37.3 ±11.5. 35.7% of the participants were between 34-44 years old, 19.9% between 25-34 years old, 19.4% between 45-54 years old, 18.4% under 25 years old, and 6.6% over 54 years old. 58.4% of the participants were female and 41.6% were male. Regarding educational attainment, 53.1% held a bachelor's degree, 21.7% an associate's degree, 14% a high school diploma, 10.5% a master's degree, 5.4% a doctorate, and 4.1% primary or secondary school diplomas. In terms of income levels, 62.2% of the participants had incomes between 17,001 and 25,000 TL, and 19.1% had incomes of 50,000 TL and above (Table 1).

The socio-demographic structure of Burdur province was compared with data from the Mediterranean Region, according to a report published by the Turkish Statistical Institute (TÜİK, 2024). This comparison was crucial for understanding the extent to which the sample represents the general population and for guiding the modeling. The analysis model for Burdur province revealed that the proportion of female participants (58.40%) is higher than the national average (49.98%). This indicates that the survey reached a larger number of women. In terms of education level, the modeling and sampling showed that the proportion of university graduates (69.0%) is significantly higher than the average (approximately 25-30%) according to TÜİK data. This indicates that the sample consists of individuals with a high level of education, and the impact of this on packaging perceptions should be considered. Looking at the age group factor, Burdur province shows a more dense distribution, especially in the 34-44 age range (35.70%), compared to regional and national averages.

According to TÜİK (Turkish Statistical Institute) data, approximately 20% of Turkey's population is in the 35-44 age group. This difference indicates that the sample focuses more on specific age groups. This comparison reveals that the socio-demographic structure of Burdur province shows some differences from the national average. In particular, the greater representation of women and highly educated individuals in the analysis, sample, and modeling is a point that should be considered in terms of the generalizability of the findings. However, these differences are presented in tabular form by taking the mean scores and standard deviations of the sub-dimensions of the scale examining the expectations and attention points of the people of Burdur regarding food packaging (Table 2). The graphs created in light of this data are shown below (Figure 1).

Table 1. Distribution of consumers by average age, age group, gender, education and training status, and income level (n: 392)

Variable	Subgroup	X̄ ± SS	n	%	Min	Max
Average Age		37.3 ± 11.5			14	69
Age Groups	Under 25 years old		72	18.4		
	25–34		78	19.9		
	34–44		140	35.7		
	45–54		76	19.4		
	55 years and older		26	6.6		
Gender	Male		163	41.6		
	Female		229	58.4		
Educational Level	Primary and Secondary Education		16	4.1		
	High School		51	14.0		
	Associate Degree		55	21.7		
	Bachelor's Degree		208	53.1		
	Master's Degree		41	10.5		
	Doctorate		21	5.4		
Income Level (Monthly, TL)	Minimum wage and below		73	18.6		
	17.001 – 25.000 TL		98	25.0		
	25.001 – 35.000 TL		146	37.2		
	35.001 – 50.000 TL		29	7.4		
	50,000 TL and above		46	11.7		

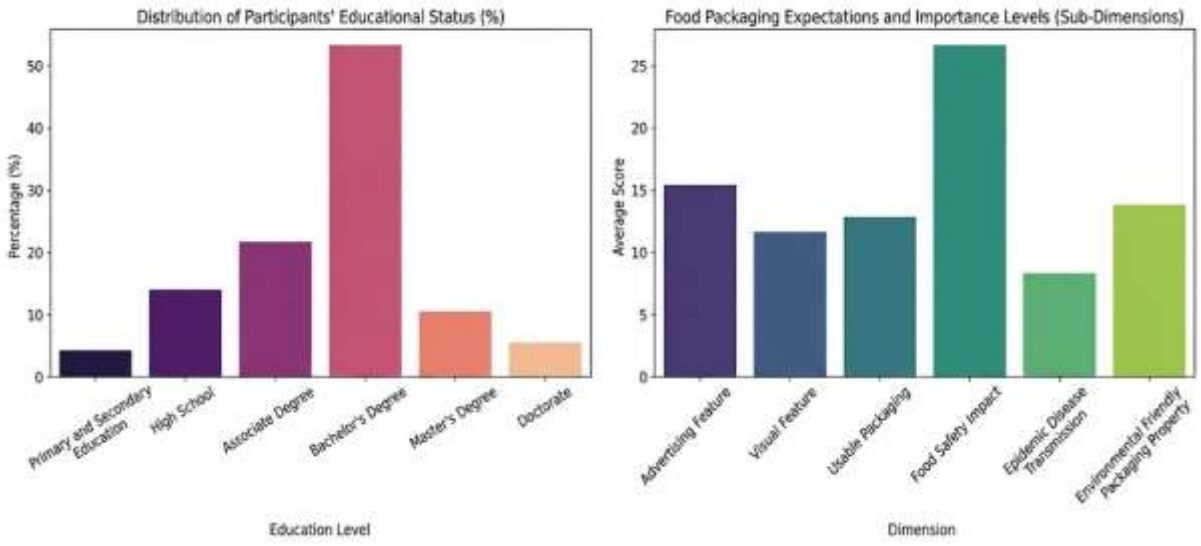


Figure 1. Distribution of Participants' Educational Backgrounds and Their Expectations and Importance Levels Regarding Food Packaging.

Table 2. presents the mean scores and standard deviations for each sub-dimension of the packaging expectations scale, expressed as proportional values.

Scale Factors	n	X̄ ± SS	Min-Max	Item Numbers	α
Advertising Feature	392	15.4 ± 3.2	4-20	1-11-14-21	0.731
Visual Feature	392	11.6 ± 2.6	3-15	2-15-19	0.708
Practical Packaging	392	12.9 ± 2.6	3-15	3-16-17-20	0.843
Food Safety Impact	392	26.7 ± 4.7	6-30	4-5-6-12-13-18	0.923
Epidemic Disease Transmission	392	8.3 ± 1.8	2-10	7-8	0.659
Environmentally Friendly Packaging Feature	392	13.8 ± 2.5	3-15	9-10-22	0.931
Total Scale	392	88.5 ± 15.2	21-105	All	0.956

Table 2 presents the mean scores and standard deviations for each sub-dimension of the packaging expectations scale, expressed as proportional values. Table 2: Scale sub-dimension scores and Cronbach's alpha coefficients (n = 392). X̄ = arithmetic mean; SD = standard deviation; α = Cronbach's alpha.

"Food Safety Impact" yielded the highest average value (26.7 ± 4.7), while "Epidemic Disease Transmission" recorded the lowest value (8.3 ± 1.8); this modeling observation shows that the perception of food safety is among the most important priorities and impacts on the consumer in packaging structure and in the development of a sustainable packaging model.Analysis by gender revealed that men scored higher on visual features, while women scored higher on the epidemic disease transmission feature, with a statistically significant difference ($P<0.05$). Analysis by education level showed statistically significant differences between education level and the entire scale and its sub-dimensions ($P<0.05$). In the advertising feature and food safety impact sub-dimensions, high school graduates scored higher than primary and secondary school, associate degree, bachelor's degree, master's degree, and doctorate graduates. Regarding the environmentally friendly packaging feature, those with postgraduate education scored higher than the others.

The fuzzy logic model was applied to predict purchase intention under varying input scenarios. Table 3 presents the model outputs for four representative scenarios.

Table 3. Fuzzy logic model predictions for purchase intention under different input scenarios

Scenario	**Environmental Perception**	**Food Safety Perception**	**Usability Perception**	**Predicted Purchase Intention**
Ideal Sustainable	4.5	4.8	4.2	80.24%
Traditional but Safe	1.2	4.5	4.0	44.26%
Eco-friendly but Unsafe	4.0	2.0	3.5	37.58%
Average Packaging	3.0	3.0	3.0	50.00%

The model outputs demonstrate consistent logical relationships within the defined rule structure. Scenario 1, representing packaging with high performance across all three dimensions, yielded the highest purchase intention (80.24%). Scenario 2, representing traditional packaging with strong food safety but weak environmental credentials, produced moderate purchase intention (44.26%). Notably, Scenario 3, representing environmentally friendly but unsafe packaging, yielded the lowest purchase intention (37.58%), indicating that food safety concerns outweigh environmental benefits when safety is compromised. Scenario 4, representing average performance across all dimensions, produced exactly 50% purchase intention, serving as a baseline reference point.

Surface plot analysis of the interaction between environmental perception and food safety perception (holding usability constant at 3.5) revealed that purchase intention increases non-linearly with food safety perception, exhibiting a steep increase once the safety threshold exceeds approximately 4.0 on the 5-point scale. In contrast, environmental perception demonstrates a more gradual, linear relationship with purchase intention across its entire range. (Figure 2).

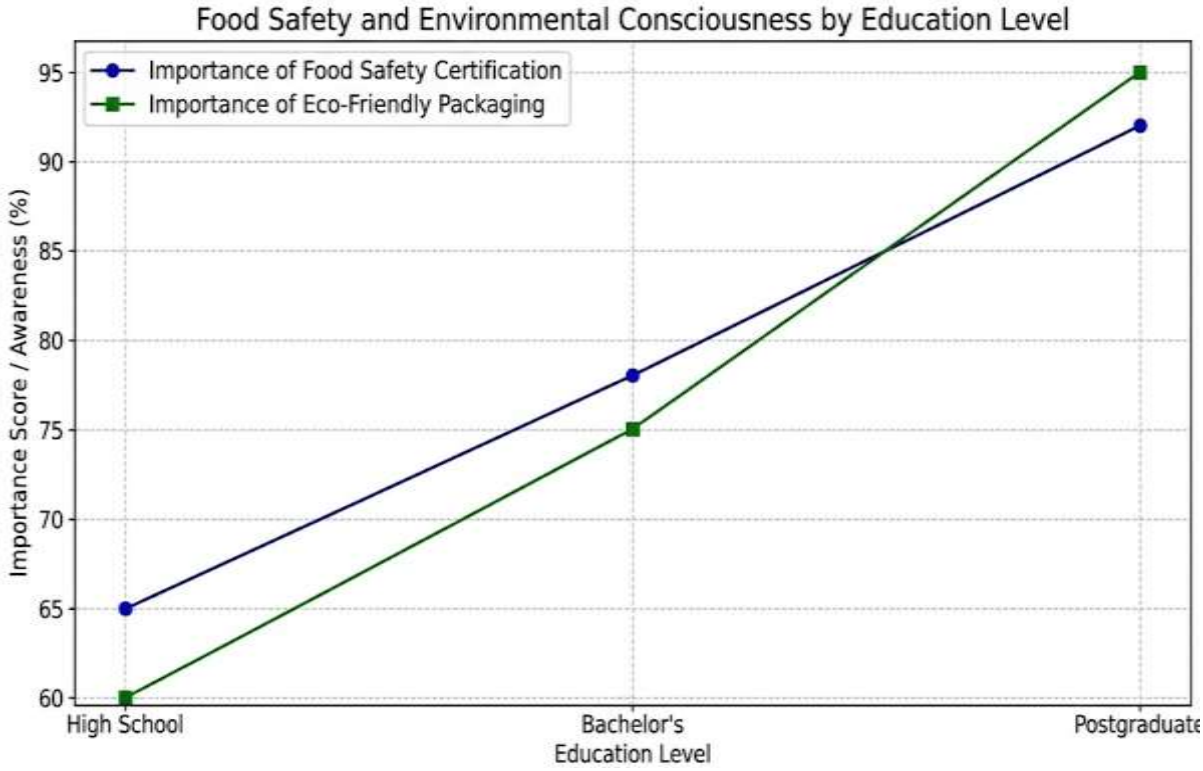


Figure 2. Correlations between sub-dimensions and food safety and environmental awareness according to education level

The relationships between the scale and its sub-dimensions were examined using Pearson product-moment correlation analysis. According to the findings, a high degree of correlation was determined between the scale and the transmission of infectious diseases, and a very high and significant correlation was found with the other sub-dimensions. A significant and moderate correlation was found with visual features, packaging usability, food safety effect, transmission of infectious diseases, and environmentally friendly packaging features. The advertising feature was found to have a very high correlation with the other sub-dimensions (Table 2).

In light of the findings obtained from the survey data, a Fuzzy Logic approach was designed to model consumers' purchase intention. Fuzzy logic aims to mimic human thought processes by providing a suitable framework for processing uncertain and imprecise information. The model consists of three input variables and one output variable The model structure consists of three input variable classes and one output variable class. The input class reflects consumers' perceptions of packaging, while the output class indicates their purchase intentions. Fuzzy sets and membership functions are defined for each variable (Figure 3).

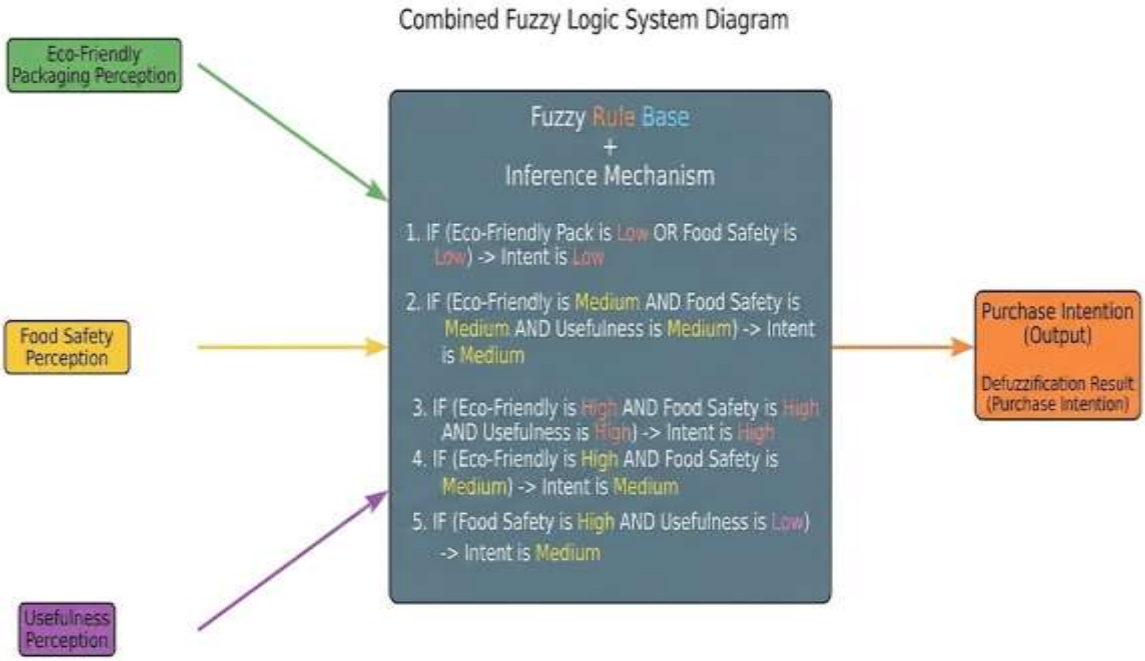


Figure 3. Figure of a Combined Fuzzy Logic System.

Input Variables and Membership Functions

Sustainable Packaging Perception: Establishing a methodology for understanding consumers' perceptions of packaging characteristics such as recyclability, use of natural materials, and environmental impact.

Food Safety and Food Inspection Perception: A methodology for understanding how well the packaging ensures the safety and hygiene of the food.

Usability and Sustainability Perception: Consumers' perception of the practical features of packaging, such as ease of opening, closing, carrying, and use.

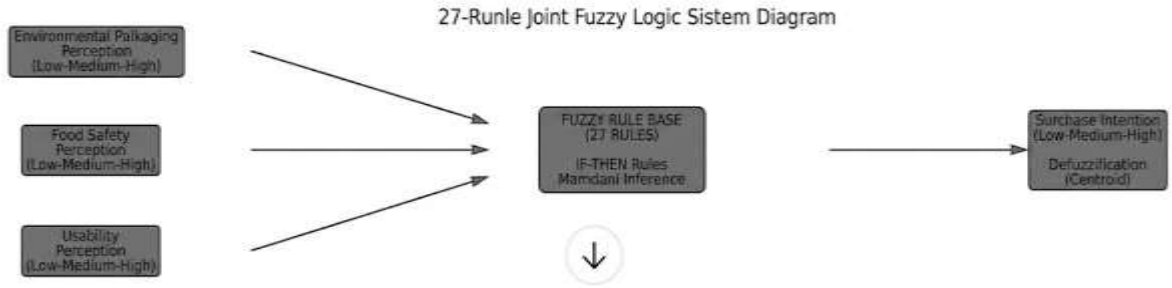
Output Variables and Membership Functions

Purchase Intention: Indicates the consumer's likelihood or willingness to purchase a particular packaged product.

In the visualization of membership rates, the distribution of each variable within fuzzy sets is clearly shown. These graphs are a fundamental tool for understanding how the model interprets the input and output variables:

Fuzzy rules define the relationships between input and output variables. These rules were created in light of expert knowledge and the findings in the article. Example rules are given below (Figure 2).

1. IF (Eco-Friendly Packaging Perception is Low) OR (Food Safety Perception is Low), Purchase Intention is Low.
2. IF (Eco-Friendly Packaging Perception is Medium) AND (Food Safety Perception is Medium) AND (Usefulness Perception is Medium), Purchase Intention is Medium.
3. IF (Eco-Friendly Packaging Perception is High) AND (Food Safety Perception is High) AND (Usefulness Perception is High), Purchase Intention is High.
4. IF (Eco-Friendly Packaging Perception is High) AND (Food Safety Perception is Medium), Purchase Intention is Medium.
5. IF (Food Safety Perception is High) AND (Usefulness Perception is Low), Purchase Intention is Medium.



Fuzzy Logic System Prediction Scenarios and Results

Scenario ID	Environmental Perception	Food Safety (0-5)	Usability (0-5)	Purchase Intention (%)
Scenario 1 (Ideal Sustainable Packaging)	4.5	4.8	4.2	✓ 80.24% ✓ [cite: x]
Scenario 2 (Traditional but Safe Packaging)	1.2	4.5	4.0	✓ 44.26% ✓ [cite: x]
Scenario 3 (Environmentally Friendly but Unsafe Packaging)	4.0	2.0	3.5	✓ 37.58% ✓ [cite: x]
Scenario 4 (Average Packaging)	3.0	3.0	3.0	✓ 50.00% ✓ [cite: x]

Figure 4. Figure of a 27-rule Unified Fuzzy Logic System

This shows that the fuzzy logic model realistically reflects the consumer decision-making process. Specifically, when the results are examined, it is seen that purchase intention is significantly influenced not only by perceptions of environmental sustainability, but also by perceptions of food safety and usability.

Scenario 1: Ideal Sustainable Packaging (80.24%)

In this scenario, environmental perception (4.5), food safety perception (4.8), and usability perception (4.2) are at high levels. Due to the high values of all input variables, the model generated a high purchase intention (80.24%). This result shows that consumers tend to prefer sustainable, safe, and convenient packaging. The highest value for food safety perception is a significant factor supporting purchase intention. This indicates that sustainability features are important to consumers, but these features translate into stronger purchasing behavior when presented together with safety and ease of use.

Scenario 2: Traditional but Safe Packaging (44.26%)

In this scenario, although environmental perception is quite low (1,2), food safety (4,5) and usability (4,0) are at high levels. As a result, purchase intention is calculated at 44.26%. It is noteworthy that purchase intention does not decrease completely despite the low performance in terms of environmental sustainability. This result shows that even if consumers prefer environmentally friendly features, they see food safety and practical usability as more fundamental requirements. In other words, safe packaging may be more acceptable to the consumer than less environmentally ideal packaging.

Scenario 3: Environmentally Friendly but Unsafe Packaging (37.58%)

This scenario reveals one of the most important findings of the model. Although environmental perception is high (4,0), food safety perception is low (2,0). Usability perception is at a medium-high level (3,5). As a result, purchase intention is calculated at only 37.58%. This value is lower than the 44.26% obtained in Scenario 2. This indicates that consumers are significantly less likely to purchase a product with environmentally friendly features if they believe it is unsafe.

This finding is the most critical result of the research. Because while sustainability is important for consumers, food safety is seen as a fundamental expectation. When safety requirements are not met, environmental advantages cannot compensate for the purchase decision. Therefore, the model confirms that food safety is a more dominant decision variable than environmental sustainability.

Scenario 4: Average Packaging (50.00%)

In this scenario, when all variables are at a moderate level, the purchase intention is calculated as exactly 50%. This result shows that the model works in a balanced and symmetrical way. When no feature stands out significantly, the consumer's propensity to purchase is also at a moderate level. This is important in demonstrating that the membership functions and the rule base are structured consistently.

Overall Assessment

When the four scenarios are considered together, the order of importance of factors influencing purchase intention can be interpreted as follows:

Perception of food safety (strongest influence)
Availability and practicality
Perception of environmental sustainability

The comparison between Scenario 2 and Scenario 3 clearly demonstrates this result. Packaging perceived as safe but with low environmental perception (44.26%) generated a higher purchase intention than packaging perceived as unsafe but with high environmental perception (37.58%). This shows that consumers primarily want the product to meet their health and safety expectations, and sustainability features are only included in the decision-making process after these basic expectations are met.

From a fuzzy logic model perspective, the results show that the defined membership functions and rule base represent consumer behavior in a logical and realistic way. The model successfully reflects the uncertainty and rated evaluations in human perceptions, predicting purchase intention under different consumer profiles. Therefore, the developed system has the potential to be used as a decision support tool for sustainable packaging design, product development processes, and marketing strategies (Öztırak & Senem, 2024).

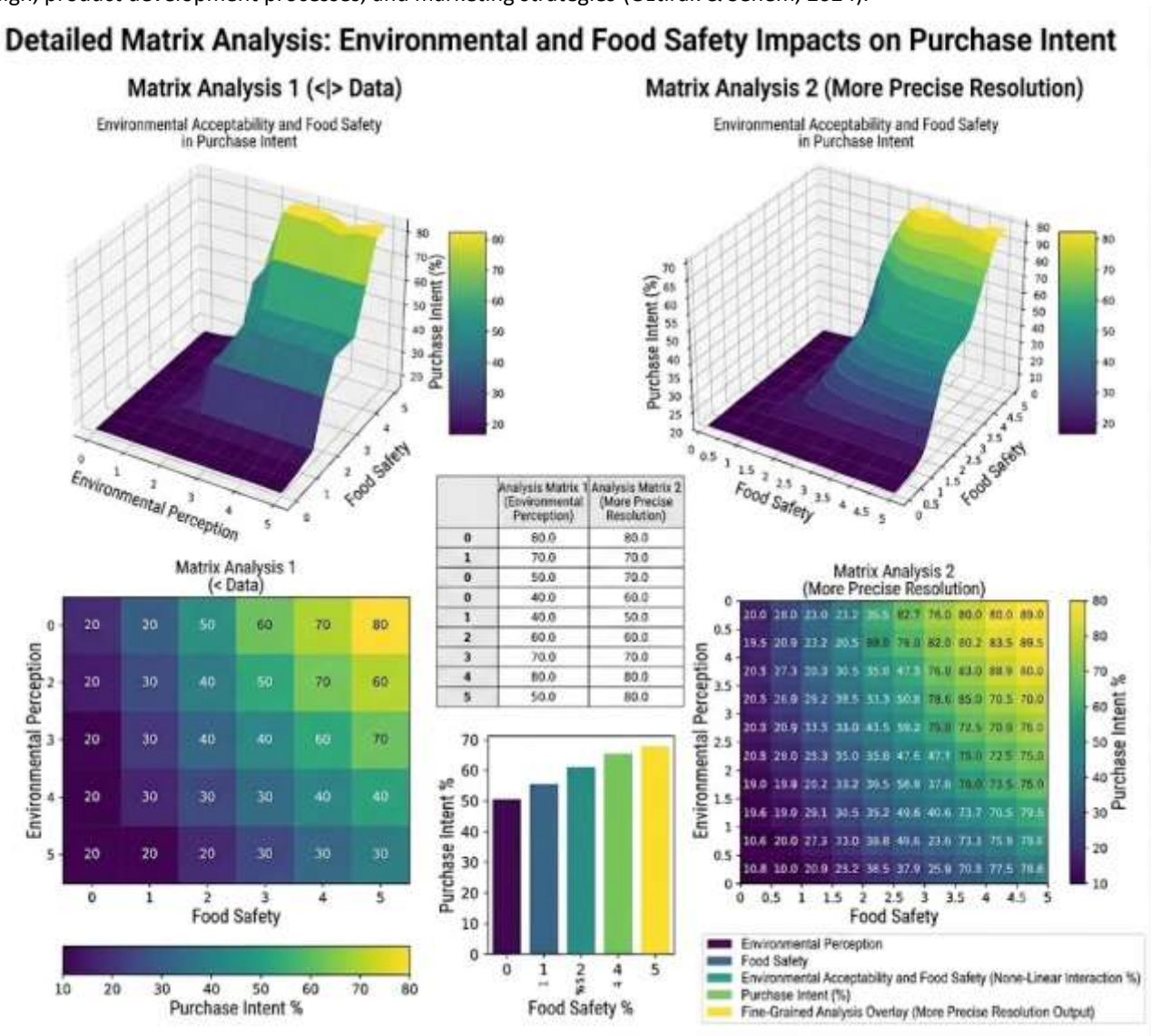


Figure 5. The Effect of Environmental Perception and Food Safety on Purchase Intention.

A surface plot was created to better understand the interaction between perceptions of environmentally friendly packaging and food safety on purchase intention. This plot shows how the other two input variables affect purchase intention, while keeping the perception of usefulness constant. The surface plot shows that, especially when food safety perception exceeds a certain threshold, purchase intention increases rapidly. While environmental perception also increases purchase intention, it does not exhibit as sharp an upward trend as food safety (Hussien et al., 2025).

CONCLUSION

This study examined the impact of consumers' perceptions of sustainable packaging on their purchasing behavior in Burdur province and developed a fuzzy logic–based decision model to evaluate these relationships. The findings revealed that food safety remains the primary factor influencing consumers' packaging preferences, while sustainable packaging attributes such as environmental friendliness, recyclability, and the use of natural materials are becoming increasingly important in shaping purchasing decisions. Furthermore, socio-demographic characteristics, particularly education and income levels, were found to significantly influence consumers' expectations, awareness, and attitudes toward sustainable packaging.

To better understand these complex relationships, a Mamdani-type fuzzy inference system was developed. By incorporating subjective consumer perceptions into a quantitative framework, the model successfully captured the uncertainty and ambiguity inherent in human decision-making processes. The results demonstrated that perceptions of food safety exert a stronger influence on purchase intention than environmental concerns, indicating that consumers prioritize basic safety and hygiene requirements before considering sustainability-related attributes. This finding highlights the hierarchical nature of consumer decision-making in the context of packaged food products.

Compared with conventional statistical approaches, the fuzzy logic model provided several advantages. First, it enabled the representation of imprecise and subjective consumer evaluations through linguistic variables and membership functions. Second, its rule-based structure enhanced transparency and interpretability, allowing researchers and practitioners to understand how different combinations of consumer perceptions affect purchase intentions. Third, the model proved capable of handling incomplete or uncertain information, making it suitable for real-world applications where consumer judgments are often ambiguous and context dependent.

Based on the findings, several practical implications can be proposed for industry stakeholders and policymakers. Increasing consumer awareness through educational campaigns and public information programs can strengthen understanding of the environmental and health benefits associated with sustainable packaging. Educational initiatives should particularly target consumers with lower education and income levels, as these groups demonstrated comparatively lower awareness of sustainability-related packaging attributes. In addition, packaging manufacturers should invest in innovative designs that combine environmental sustainability, food safety, functionality, and visual appeal, since all of these factors contribute to purchase intention. Marketing strategies should also consider regional differences in consumer perceptions and preferences, allowing companies to develop more effective and localized communication approaches. Furthermore, transparent labeling practices that clearly communicate recyclability, environmental impact, and material composition can enhance consumer trust and positively influence purchasing decisions.

Overall, this research contributes to the growing body of literature on sustainable packaging by integrating consumer behavior analysis with artificial intelligence–based fuzzy logic modeling. The study demonstrates that data-driven and intelligent decision-support systems can provide valuable insights into consumer preferences while supporting the development of more sustainable packaging strategies. Increasing public awareness through education, transparent communication, and evidence-based policymaking will be essential for promoting sustainable consumption patterns and strengthening the acceptance of environmentally responsible packaging solutions.

Future research may expand the proposed model by incorporating additional variables such as price sensitivity, brand loyalty, environmental consciousness, and product quality perceptions. Moreover, integrating fuzzy logic with advanced machine learning techniques, such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS), may further improve predictive performance and provide deeper insights into consumer decision-making processes. Such developments would contribute to the creation of more robust and adaptive models capable of supporting sustainable production, marketing, and policy decisions in the packaging industry.

Declaration of interests

The authors declare that they have no conflict of interest.

Author Contributions

***İbrahim Ulaş YÜZGEÇ*:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; writing— original draft; writing—review and editing.

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Original Article

Influence of Wind Speed and Aggregate Size on Soil Loss from Heavy Metal-Contaminated Soils: A Wind Tunnel Study

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ABSTRACT

Wind erosion is a fundamental process that facilitates soil degradation and redistribution of contaminants from polluted sites. Wind-tunnel experiments were conducted under controlled conditions to assess the effects of wind speed (8, 10, and 12 m s^{-1}) and aggregate size (0.5, 1.0, and 2.0 mm) on soil loss from heavy-metal-contaminated soils collected from a contaminated site in İncesu district of Kayseri, Türkiye. Experimental results indicated that aggregate size and wind speed had significant effects on soil loss ($p \leq 0.01$). The greatest soil loss (30.85 kg m^{-2}) was encountered in 0.5 mm aggregates at a wind speed of 12 m s^{-1} and the lowest (5.15 kg m^{-2}) in 2.0 mm aggregates at a wind speed of 8 m s^{-1}. Soil loss values decreased with increasing aggregate sizes, but increased with increasing wind velocities. Soil samples of different aggregate sizes were also subjected to heavy metal analyses. It was observed that finer aggregates had higher Zn, Cd, and Pb concentrations. Present findings revealed that aggregate size is a key parameter for wind erosion susceptibility of contaminated soils. It was also concluded that aggregate size could significantly affect redistribution of heavy metals through wind-driven soil loss. Management strategies and practices are recommended to promote aggregate formation and maintain surface stability of contaminated sites. Such practices are also recommended to reduce soil loss and contaminant dispersal in polluted sites.

Key words: Aggregate size, heavy metal contamination, soil loss, wind erosion, wind speed.

Ağır Metal ile kirlenmiş topraklarda rüzgâr hızı ve agregat boyutunun toprak kaybı üzerindeki etkisi: Rüzgâr tüneli çalışması

ÖZ

Rüzgâr erozyonu, yalnızca toprak bozunmasına yol açan önemli bir çevresel süreç değil, aynı zamanda kirlenmiş alanlardan kirleticilerin yeniden dağılımına da neden olan bir mekanizmadır. Bu çalışma, kontrollü rüzgâr tüneli koşullarında agregat büyüklüğü ve rüzgâr hızının ağır metal ile kirlenmiş topraklardaki toprak kaybı üzerindeki etkilerini değerlendirmeyi amaçlamıştır. İncesu (Kayseri, Türkiye) bölgesindeki kirlenmiş bir sahadan alınan yüzey toprak örnekleri üç farklı agregat büyüklüğü sınıfına (0,5, 1,0 ve 2,0 mm) ayrılmış ve 8, 10 ve 12 m s^{-1} rüzgâr hızlarına maruz bırakılmıştır. Her uygulama sonrasında meydana gelen toprak kaybı ölçülmüş ve istatistiksel olarak değerlendirilmiştir. Sonuçlar hem agregat büyüklüğünün hem de rüzgâr hızının toprak kaybını önemli derecede etkilediğini göstermiştir ($p \leq 0,01$). En yüksek toprak kaybı (30,85 kg m^{-2}), 12 m s^{-1} rüzgâr hızında 0,5 mm agregat fraksiyonunda belirlenirken, en düşük değer (5,15 kg m^{-2}) 8 m s^{-1} rüzgâr hızında 2,0 mm agregat fraksiyonunda ölçülmüştür. Agregat büyüklüğü arttıkça toprak kaybı azalırken, rüzgâr hızındaki artış tüm agregat sınıflarında toprak taşınımını önemli ölçüde artırmıştır. Denemede kullanılan toprağa ait ağır metal analizleri, daha ince agregat fraksiyonlarının daha yüksek Zn, Cd ve Pb konsantrasyonları içerdiğini ortaya koymuştur. Bu bulgular, agregat büyüklüğünün kirlenmiş toprakların rüzgâr erozyonuna karşı duyarlılığını belirleyen temel bir faktör olduğunu ve ağır metallerin rüzgârla taşınan sedimentler aracılığıyla yeniden dağılım potansiyelini etkileyebileceğini göstermektedir. Bu nedenle, agregat oluşumunu teşvik eden ve yüzey stabilitesini koruyan

yönetim uygulamaları, kirlenmiş alanlarda hem toprak kaybının hem de kirleticilerin yayılımının azaltılmasına katkı sağlayabilir.

Anahtar kelimeler: Agregat büyüklüğü, ağır metal kirliliği, Toprak kaybı, rüzgâr erozyonu, rüzgâr hızı

INTRODUCTION

Wind erosion results in various environmental problems, such as soil degradation, loss of soil and nutrients, desertification, deterioration of air quality, especially in arid and semi-arid regions of the world. Loose, dry, fine particles on the soil surface are moved by wind-induced shear stress, lifted from the surface, dragged, and transported over long distances (Shao and Lu, 2000; Shao, 2008). It poses a serious threat to land use and sustainable development by causing soil loss, nutrient depletion, and decreases in agricultural productivity. Additionally, wind erosion also significantly influence ecosystem services (Guo et al., 2014). Through land degradation and environmental deterioration, wind erosion has various socioeconomic affects including food crises and poverty.

On-going global warming and climate change have already altered worldwide temperatures, wind speeds and precipitation patterns and energy. All these altered parameters significantly influence soil erosion dynamics (Zhao et al., 2021).

Previous studies revealed that wind erosion facilitated the movement of soil aggregates and carried soil pollutants (microplastics and heavy metals) over long distances, thus uncontaminated sites quite far from the original source of pollutants are affected (Erpul et al., 2025). It was indicated that wind-borne particles were able to carry chemicals and toxic substances, displaced them from their original source to new areas and ultimately resulted in regional, even global, pollution (Rezaei et al., 2019).

Heavy metals basically accumulate in soils around industrial facilities, mining and metal plating industries, and waste disposal sites. Such an accumulation of heavy metals may end up with significant environmental problems (Alloway, 2012). Since heavy metals attached to soil particles can be moved by the wind, they pose a serious pollution threat to the atmosphere and surrounding soils. Resultant contamination then significantly effects nearby communities and ecosystems (Brotons et al., 2009). A previous study on wind erosion processes indicated that wind erosion facilitated movement and transport of soil particles containing heavy metals, then resulted in deterioration of air quality. Such adverse effects of wind erosion are prevalent especially in arid and semi-arid zones of the world (Zhao et al., 2021). Among the heavy metals, cadmium, zinc and lead are the most prevailing ones encountered around almost all industrial facilities and they all have a quite low toxicity threshold. Transport of heavy metal-contaminated soils through wind erosion carries heavy metals to new areas, then plants, microorganisms and air exposed to transported heavy metals pose serious public health risks (Goossens, 2004; Davidson et al., 2005; Thompson, 2018).

Heavy metals are heterogeneously distributed among the soil aggregates and largely accumulate around fine particles (Zhang et al. 2021) since they have greater specific surface areas, higher adsorption capacities, and facilitate metal binding. A previous study on heavy metal concentration of urban roadside soils indicated that that vehicle-induced heavy metals generally concentrated around the finest particle fractions (<45 µm). Copper (Cu), zinc (Zn) and lead (Pb) were encountered at higher concentrations around the fine particles. Such higher concentrations are attributed to higher surface area and adsorption capacity of fine particles (Wang et al., 2006). Therefore, fine particles play a critical role in transport and accumulation of heavy metals.

Previous research on atmospheric transport of heavy metal-containing soils have mostly focused on transport of metals through desert dust, wind-borne metal emissions of mining sites, and resuspension of contaminated particles in new sites (Csavina et al., 2011; Rodríguez et al., 2011; Gao et al., 2017). Such research are commonly conducted in wind tunnels since they offer various advantages over field measurements, especially in designating threshold friction speed, quantifying transported mass flow, identifying particle size-metal content relationships, and testing the effect of surface conditions (Shao et al., 1993; Larney et al., 1999; Zamani and Mahmoodabadi, 2013; Webb et al., 2014). Increasing wind speeds significantly enhance the transport of windblown particles, including metal-laden fine fractions, over long distances (Meng et al., 2019).

Studies that experimentally evaluate the transport of heavy metal-contaminated soils under controlled wind tunnel conditions at different wind speeds are limited. Determining the transport behavior of Zn-, Cd-, and Pb-contaminated soils in a wind tunnel under varying wind speeds is important for accurately assessing the risk of heavy metal spread and for developing erosion control strategies. This study aims to contribute to existing studies by examining the transport amounts of surface soils contaminated with Zn, Cd, and Pb, separated into aggregate sizes of 0.5, 1.00, and 2.00 mm, at different wind speeds.

MATERIALS AND METHODS

Soil Material

The soil material contaminated with heavy metals used in this study was collected from a heavy metal-contaminated area in the İncesu district of Kayseri province at a depth of 0-20 cm using a random sampling method (38.7143144°N, 35.2625447°E). Some physical and chemical properties of the collected soil samples were determined at the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, and are given in Table 1. The organic matter content of the soils was determined according to the Smith-Weldon method (Nelson and Sommers, 1982, 1996). Soil texture was analyzed using the Bouyoucos hydrometer method (Bouyoucos, 1928). Soil reaction (pH) was measured with a pH meter with a glass electrode in a 1:2.5 soil-water suspension (McLean, 1982). The lime ($CaCO_3$) content of the soils was determined volumetrically using the Scheibler calcimeter method (Nelson, 1982). Available phosphorus content was determined spectrophotometrically in filtrates extracted with sodium bicarbonate (Olsen and Sommers, 1982). The soil texture is quite high in sand (78.80%), and with low proportions of clay (11.84%) and silt (9.36%), the soil is classified as "sandy-loam texture". The soil pH is 8.22, indicating a slightly alkaline character. According to the EC value (0.39 dS m^{-1}), it is classified as a non-saline soil. The lime content (3.68%) is considered low. The organic matter content (1.25%) is quite low. Available phosphorus (P_2O_5) is very low at 3.21 kg da^{-1}.

Table 1. Some physical and chemical properties of the research soil

Soil Properties	Values
Sand (%)	78.80
Clay (%)	11.84
Silt (%)	9.36
pH	8.22
EC (dS m^{-1})	0.39
Lime (% $CaCO_3$)	3.68
Organic Matter (%)	1.25
P_2O_5 (kg da^{-1})	3.21

Table 2 presents a comparison of the total Zn, Cd, and Pb concentrations determined at different aggregate sizes of the research soil with critical and legal limit values. The results showed that heavy metal concentrations were significantly above the critical and legal limit values at all aggregate sizes examined. Total Zn concentration ranged from 9418.01 to 11850.92 mg kg^{-1}, with the highest value determined at 0.5 mm aggregate size (11850.92 mg kg^{-1}) and the lowest value at 2.0 mm aggregate size (9418.01 mg kg^{-1}). All Zn values were approximately 31-40 times above the limit value range (300 mg kg^{-1}). Cd concentration ranged from 17.29 to 66.41 mg kg^{-1}; The highest values were detected in 0.5 mm aggregates, and the lowest values in 2.0 mm aggregates. The determined Cd levels were significantly above the limit value (3 mg kg^{-1}). Pb concentration ranged from 268.14 to 593.13 mg kg^{-1}. The highest Pb value was determined in 1.0 mm aggregate size (593.13 mg kg^{-1}), and the lowest value was determined in 0.5 mm aggregate size (268.14 mg kg^{-1}). Pb concentration exceeded the limit value (300 mg kg^{-1}) in 1.0 and 2.0 mm aggregates, while in 0.5 mm aggregates it was below the limit value but within the critical range. The experimental soil was found to be highly contaminated, particularly with Zn and Cd, and Pb concentrations exceeded critical and legal limits at certain aggregate sizes. Zn and Cd concentrations increased as aggregate size decreased, while the highest Pb accumulation occurred at 1.0 mm aggregate size.

Table 2. Comparison of total Cd, Pb, and Zn concentrations determined in the research soil with limit values (pH>6) (TKKY, 2005)

Aggregate size (mm)	Zn (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})
0.5	11850.92	66.41	268.14
1.0	11390.23	28.26	593.13
2.0	9418.01	17.29	408.11
Limit value*	300.00	3.00	300.00

Wind Tunnel Studies

The wind tunnel, located within the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, whose characteristics are described in detail by Kaplan et al. (2026), was used in this study. The tunnel was specifically designed and developed to investigate wind erosion processes and sediment transport in detail. Thanks to its structure, which is more than 5 m long, its experimental platforms located 0.9 m above the ground, and its modular design, the wind tunnel offers a flexible test area where different setups can be easily placed. The rectangular opening measuring 0.8 × 0.9 m in the entrance section, along with the 1% base slope, complies with the standards recommended for wind tunnel applications. Covering one surface of the tunnel with a transparent material allows for direct observation of both flow and sediment movement (Figure 1).

Figure 1. Wind tunnel test section and contraction cone views.

A high-capacity axial fan with a power of 7.5 kW, a speed of 950 rpm, air flow rate of 60,000 m³ per hour and stable flow conditions in the range of 20-200 Pa was used to realistically model the erosion processes. A digital control panel was used to adjust fan speed precisely (±0.05 m s^{-1}). Such a precise control of fan speed increased the repeatability of the experiments.

Soil samples were separated into aggregate size fractions through sieving. Tests were run in three replicates with 5 kg of each particle size fraction placed in test trays (0.4 x 0.4 = 0.16 m²). Each run at reference wind speeds of 8, 10, and 12 m s^{-1} (able to represent the typical erosive winds in semi-arid regions of Central Anatolia) lasted 10 minutes. Initial and final weights were used to quantify soil loss of each case. The results are presented in kg m^{-2} units to ensure comparability with different studies and to express soil loss on an area basis.

Statistical Analyses

The findings obtained from the research were subjected to analysis of variance using the JUMP SAS (2009) software package. Whether the difference between the means was significant was determined using the Tukey test.

RESULTS AND DISCUSSION

Soil transport values for different wind speeds and aggregate sizes are given in Table 3. Examination of Table 3 reveals that aggregate size and wind speed have a statistically significant effect on soil loss ($p \leq 0.01$). The highest soil losses were observed at an aggregate size of 0.5 mm and a wind speed of 12 m s^{-1} (30.85 kg m^{-2}), followed by applications of 10 m s^{-1} (30.57 kg m^{-2}) and 8 m s^{-1} (29.25 kg m^{-2}) at the same aggregate size. The lowest soil losses were detected at an aggregate size of 2 mm and a wind speed of 8 m s^{-1} (5.15 kg m^{-2}). When the average aggregate sizes were evaluated, the highest value was 0.5 mm (30.22 kg m^{-2}), and the lowest was 2 mm (19.74 kg m^{-2}). Decreasing soil loss values were seen with increasing aggregate sizes, but soil loss values

increased with increasing wind speeds. In terms of wind speeds, the greatest soil loss was seen at 12 m s^{-1} (29.99 kg m^{-2}) and the lowest at 8 m s^{-1} (20.43 kg m^{-2}).

Table 3. Soil loss (kg m^{-2}) values determined at different aggregate sizes and wind speeds.

Aggregate size (mm)	Wind Speeds			Means (kg m^{-2})
	8 m s^{-1}	10 m s^{-1}	12 m s^{-1}	
0.5 mm	29.25^{cd}	30.57^{ab}	30.85^{a}	30.22^{A}
1 mm	26.89^{e}	29.86^{bcd}	30.04^{abc}	28.93^{B}
2 mm	5.15^{g}	24.97^{f}	29.09^{d}	19.74^{C}
Means (kg m^{-2})	20.43^{C}	28.47^{B}	29.99^{A}	

A 3-D surface graph was generated to present the combined effects of variables (aggregate size and wind speed) on soil transport (Figure 2). As can be seen from the figure, soil loss values increased with increasing wind speeds and decreased with increasing aggregate sizes. The greatest soil loss value was seen at the smallest aggregate sizes (0.5 mm) and the greatest wind speed (12 m s^{-1}) and soil loss values significantly decreased toward to the greatest aggregate size (2 mm). Reductions in soil loss values at greater aggregate sizes were partially offset by increasing wind speeds, but soil loss values converged to each other at high wind velocities. The curvature on surface graph reveals a non-linear relationship between the variables. In other words, the curvature indicated the combined effect of variable on response values. Protective role of aggregate size against wind erosion clearly was remarkable.

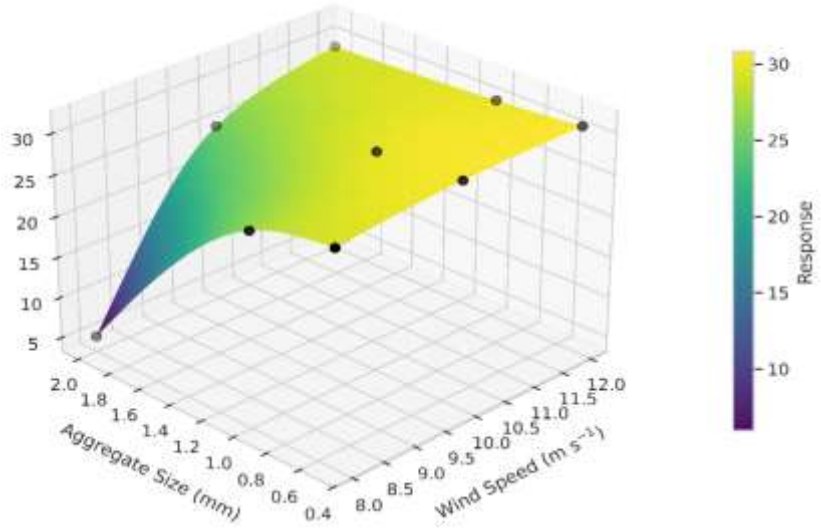

Figure 2. Soil loss graph as a function of wind speed and aggregate size.

Discussion

Present findings clearly demonstrated that both aggregate size and wind speed had significant effects on soil loss values. Soil loss values significantly decreased with increasing aggregate sizes, but increased significantly with increasing wind speeds. The greatest soil loss value was seen at the smallest aggregate size (0.5 mm) and the greatest wind speed (12 m s^{-1}); the lowest soil loss value was seen at the greatest aggregate size (2 mm) and the lowest wind speed (8 m s^{-1}). Such values clearly indicated that aggregate size was a key factor designating the soil loss in wind erosion cases. Aggregate size distribution of the surface soil directly influences the resistance of soil surface to wind erosion. Erosive winds can easily transport fine and loose aggregates. Supporting the present findings, Presley and Tatarko (2009) indicated that increasing fine fractions and disruption of aggregate integrity remarkably increased soil transport.

Present findings on soil loss comply with the results of previous studies indicating the key role of soil aggregate size distribution in wind erosion cases and reporting that larger aggregate sizes reduced wind-induced soil losses through improved soil surface stability (Dai et al. 2025; Kaplan et al. 2024). In present experiments,

the smallest soil loss value was obtained from the greatest aggregate size (2 mm), indicating that coarser aggregates exhibited higher resistance to erosive winds.

Influence of aggregate size on erosion resistance of soil surface is largely associated with physical soil properties. A strong negative correlation between mean weighted aggregate diameter and erosion susceptibility factor (K) indicates that soil becomes more resistant to erosion as aggregate size increases (Zamani and Mahmoodabadi 2013). Mapa and Gunasena (1995) indicated that coarser aggregates are related to higher organic carbon contents and lower bulk densities, which creates a more stable soil structure and reduces the risk of erosion. In this sense, lower soil loss value of coarser aggregates in present study confirms the decisive role of aggregate size in controlling wind erosion.

Increased wing kinetic energy at high wind speeds facilitate soil erosion. Anderson (1986) indicated that kinetic energy flow of particles striking the surface was closely associated with wind shear speed. It was also indicated that relatively small increases in wind speed could result in disproportionately large increases in particle detachment and transport. Armbrust and Bilbro (1997) and Ferro (1998) reported accelerated particle detachment and transport, thus increased erosion severity at high wind speeds. In present experiments, increasing soil loss values from 20.43 kg m^{-2} at 8 m s^{-1} to 29.99 kg m^{-2} at 12 m s^{-1} clearly supports this mechanism. Soil loss, particularly in 2 mm aggregates, was determined to be 5.15 kg m^{-2} at a wind speed of 8 m s^{-1} and 29.09 kg m^{-2} at 12 m s^{-1} and such a case clearly indicates that high wind speeds could disrupt the stability of even coarser aggregates. Larger aggregates show lower soil loss than small aggregates even at the highest wind speeds indicates that the protective effect of aggregate size continues.

Another important aspect of the study is that it reveals the potential of wind erosion to increase environmental risks in heavy metal-contaminated soils. Wind erosion transports fine soil particles detached from the surface, contributing to the spread of heavy metals attached to them over wide areas. The formation of microaggregates is primarily controlled by inorganic colloids and organic colloidal substances derived from the decomposition of soil organic matter (Basaran et al., 2008). Heavy metals, including those investigated in the present study, are largely retained by these colloidal fractions because of their extensive negatively charged surface area and high adsorption capacity. In contrast, macroaggregate formation is mainly governed by sand particles and partially decomposed organic matter. Therefore, appropriate management of soil organic matter in contaminated areas can promote macroaggregate formation, thereby increasing soil structural stability and reducing the potential for heavy metal dispersion through wind erosion. Consequently, improving aggregate stability may not only mitigate soil loss but also help prevent the spread of heavy metal contamination, reducing risks to surrounding ecosystems. Paramonova et al. (2025) reported that wind erosion plays a significant role in redistributing heavy metals by transporting soil particles over long distances. Nyiramigisha et al. (2021) and Rajput et al. (2025) stated that heavy metal transported by erosion carry pollution outside of mining sites and contaminated areas, posing risks to both ecological systems and human health. Therefore, in our study, the finding that small aggregates and high wind speeds lead to greater soil loss can be considered a significant environmental threat to heavy metal transport and dispersal. Kılıç et al. (2026) reported that Festuca arundinacea varieties grown in conjunction with Haematococcus pluvialis application increased the heavy metal removal efficiency and improved soil quality in soils contaminated with Cd, Pb, and Zn. These results indicate the importance of biological and sustainable approaches to managing heavy metal pollution. The results show that applications aimed at increasing aggregate size in heavy metal-contaminated areas can not only reduce soil erosion but also help limit heavy metal transport.

CONCLUSION

This study has shown that aggregate size and wind speed significantly affect the behavior of heavy metal-contaminated soils against wind erosion. Soil loss decreased as aggregate size increased, while higher wind speeds significantly increased soil loss. The lowest soil loss was observed in the 2 mm aggregate treatment at a wind speed of 8 m s^{-1}. On the other hand, the greatest soil loss was seen at the smallest aggregate size (0.5 mm) and the greatest wind speed (12 m s^{-1}). Such findings revealed that coarser aggregates provide greater resistance to wind erosion, while finer ones are significantly more vulnerable to disintegration and transport. Present findings also indicated that increasing wind speeds could partially offset the protective effect of aggregate size, leading to increased soil losses even in coarser aggregates. Therefore, soil structural properties and erosive wind conditions should together be taken into consideration while assessing erosion risks in contaminated environments. From an environmental point of view, mobilization of soil particles contaminated with heavy metals through wind can lead to the redistribution of heavy metals beyond their source of origin. It was concluded based on present findings that aggregate size can affect not only wind erosion susceptibility but also the transport potential of heavy metal-contaminated particles. Therefore, fine aggregates/fractions that are easily transported by wind plays a key role in assessing the risk of heavy metal transport. Further studies are

recommended to examine the transport dynamics of different aggregate-size fractions in greater detail and determine the heavy metal content of wind-transported sediments under different environmental conditions to more accurately assess contamination risks. It was also recommended that wind erosion should be evaluated not only in terms of physical soil loss but also in terms of pollutant redistribution.

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Declaration of interests
The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions
Sema KAPLAN: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; writing— original draft; writing—review and editing.

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Original Article

Farm-Level Efficiency Analysis of Confectionery Sunflower Production in The Pasin Plain: A Data Envelopment Approach

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ABSTRACT

This study evaluated the technical, allocative, and economic efficiency levels of 140 confectionery sunflower farms in the Pasin Plain, Erzurum province, using Data Envelopment Analysis (DEA). Primary data were collected through face-to-face surveys during the 2022 production season. The bootstrapped DEA technique was employed under both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions. According to the findings, the farms classical technical efficiency score was 0.88, whilst bootstrapped technical efficiency score was 0.83, their allocative efficiency score was 0.82, and their economic efficiency score was 0.72. These results indicate that farms manage their production processes relatively efficiently with existing technology and resources (17.00% savings potential in pure technical efficiency), but there are significant areas for improvement in selecting the optimal input mix at correct prices (18.00% savings potential in allocative efficiency) and in overall cost performance (28.00% savings potential in economic efficiency). Furthermore, approximately 24.00 % of the overall inefficiency was attributed to scale inefficiency. The study presents concrete policy recommendations focused on cost management and market analysis in agricultural extension services. The recommendations include encouraging land consolidation and the formation of cooperatives, promoting the widespread use of existing digital applications among producers, and providing low-interest loan opportunities for small-scale businesses. These findings provide a solid scientific foundation for developing strategies to enhance the sustainability and economic efficiency of sunflower seed production in the region.

Key words: Confectionery sunflower, efficiency analysis, data envelopment analysis (dea), pasin plain.

Pasin Ovası'nda Çerezlik Ayçiçeği Üreticilerinin Etkinlik Analizi: Veri Zarflama Yaklaşımı

ÖZ

Bu çalışma, Erzurum iline bağlı Pasin Ovası'nda çerezlik ayçiçeği üretimi yapan 140 işletmenin teknik, tahsis ve ekonomik etkinlik düzeylerini Veri Zarflama Analizi (VZA) yöntemiyle değerlendirmeyi amaçlamıştır. Araştırmanın birincil verileri, 2022 üretim döneminde yüz yüze anket yöntemiyle toplanmıştır. Analizlerde, Ölçeğe Göre Sabit Getiri (CRS) ve Ölçeğe Göre Değişken Getiri (VRS) varsayımları altında teknik etkinliğin ölçümünde Bootstraplı DEA tekniği kullanılmıştır. Bulgulara göre, işletmelerin klasik teknik etkinlik ortalaması 0.88 iken bootsraplı teknik ortalaması 0.83, tahsis etkinlik ortalaması 0.82 ve ekonomik etkinlik ortalaması 0.72 olarak belirlenmiştir. Bu sonuçlar, üreticilerin mevcut teknoloji ve kaynaklarla üretim süreçlerini nispeten etkin yönettiklerini (saf teknik etkinlikte %17.00 tasarruf potansiyeli), ancak girdi bileşimini doğru fiyatlarla seçme konusunda (tahsis etkinlikte %18.00 tasarruf potansiyeli) ve genel maliyet performansında (ekonomik etkinlikte %28.00 tasarruf potansiyeli) iyileştirme alanları olduğunu göstermektedir. Ayrıca, işletmelerin genel etkinsizliğinin yaklaşık %24.00'ünün ölçek etkinsizliğinden kaynaklandığı tespit edilmiştir. Çalışma, tarımsal yayım hizmetlerinde maliyet yönetimi ve pazar analizi odaklı somut politika önerileri sunmaktadır. Öneriler arasında, arazi toplulaştırmasının ve kooperatifleşmenin teşvik edilmesi, üreticiler için mevcut dijital uygulamaların kullanımının yaygınlaştırılması ve küçük ölçekli işletmelere düşük faizli kredi imkanlarının sağlanması yer

almaktadır. Bu bulgular, bölgedeki çerezlik ayçiçeği üretiminin sürdürülebilirliğini ve ekonomik verimliliğini artıracak stratejilerin geliştirilmesi için sağlam bir bilimsel temel sağlamaktadır.

Anahtar kelimeler: Çerezlik ayçiçeği, etkinlik analizi, veri zarflama analizi (vza), pasin ovası

INTRODUCTION

Agriculture is an important sector in Turkey due to its functions and scale (Demir et al., 2023). The contribution of agriculture to the national economy has a significant share in developing countries such as Türkiye (Palabicak and Ödemis, 2026). Global population growth and pressure on natural resources have made productivity and sustainability primary priorities in the agricultural sector. Efficiency can be defined as achieving a given output level with minimal input use or maximizing output with available resources. It is one of the most critical determinants of the profitability and economic sustainability of agricultural enterprises. In this context, Farrell (1957) was the first to measure enterprise performance, laying the foundation for modern efficiency analysis as linear programming techniques developed. In Türkiye efficiency analyses have gained importance since the 2000s for the sustainability of agricultural enterprises (Özden, 2017; Savaş and Işın, 2024).

Agricultural efficiency is examined in three subcomponents: technical efficiency, which refers to obtaining a certain output with the least possible input, allocative efficiency, which measures the ability to choose the lowest-cost input combination under current input prices and economic efficiency, which reflects the overall cost performance, which is the combination of these two (Coelli et al., 2005). Agricultural economics studies analyze these activities and aim to achieve current production levels with the least possible input or at the lowest cost (Doll and Orazem, 2005; Gündüz et al., 2011).

Sunflower cultivation, which stands out globally for its production, is closely related to the principles of this study. Sunflowers are grown in two categories: for confectionery and for oil (Hladni and Miladinovic, 2019). While Russia, Ukraine, and European Union countries lead in the production of oilseed sunflowers, Argentina and China lead in the production of confectionery sunflowers (Liuxi Yi et al., 2025). While oilseeds account for 90.00%–95.00% of global sunflower production, the share of sunflowers grown for confectionery is reported to be below 5.00% in some sources (Semerci and Durmuş, 2021) and below 10.00% in others (Hladni, 2016). China accounts for a large portion of this 10.00% share (Feng J. et al., 2022). In fact, the Food and Agriculture Organization (FAO) database does not distinguish between sunflowers grown for oil and those grown for confectionery. According to 2022 FAO data, Turkey ranks fourth in global sunflower production, accounting for 4.80% of the total production (53.09 million tons). The global average sunflower yield is 1,855.00 kg/ha, while Turkey's average yield is 2,602.90 kg/ha. Turkey's yield is above the global average. In global sunflower seed exports, Russia and Romania lead the way, while Bulgaria and Turkey are the leading importers (FAO, 2022).

Sunflower cultivation, which holds a prominent position in the Turkish economy, exhibits significant economic variations depending on its intended use. The market value of sunflower oil produced for industrial use depends on its oil content and is traded on national and international oilseed markets. Confectionery sunflowers, which are grown specifically for human consumption, are priced in the market based on physical characteristics such as seed size, shell color, uniformity, and overall appearance. It is primarily traded in the snack nut sector and local food markets. As a result, in recent years, the production of confectionery sunflower seeds in Turkey has shown a notable growth trend. In 2022, the total cultivated area of sunflowers was 980.972.20 hectares, and the production quantity was 2.550.000 tons. While confectionery sunflower constituted only 8.21% (80.456.50 hectare) of this cultivated area and 7.84% (200.000 tons) of the production quantity, by 2024, there was an increase of 47.65% in cultivated area and 70.00% in production quantity for confectionery sunflower, reaching 118.798.50 hectare and 340.000 tons, respectively (TÜİK, 2025). This remarkable growth, contrary to the contraction in oilseed sunflower production, highlights the market potential of confectionery sunflowers and its increasing economic importance for producers.

Looking at the geographical distribution of this production, the Central Anatolia Region (Konya, Kayseri, Aksaray, Sivas) leads, but Erzurum in the Eastern Anatolia Region also stands out as an important production center. According to 2024 data, Erzurum ranks fourth in production quantity and fifth in cultivated areas nationally. The determinant of this increase is the Pasin Plain, which alone accounts for more than 83.00% of the province's total production. The performance of producers in the Pasin Plain is strategically important for both regional development and national production targets. However, despite this quantitative increase in production, it remains unclear to what extent producers in the region can efficiently use their resources. Decreases in efficiency increase production costs, and in this context, input usage levels and the operator's production efficiency play a determining role. (Yeni and Dağdemir, 2022). While sustainable agriculture and

environmental awareness necessitate the optimal use of inputs such as chemical fertilizers and pesticides, adverse conditions can lead to environmental damage and reduced product quality (Sarı and Külekçi, 2024).

At this point, a significant gap is evident in the current scientific literature. Although there are numerous efficiency studies focusing on oilseed sunflower production (Grazhdaninova and Brock, 2004; Günden et al., 2006; Külekçi, 2010; Parlakay et al., 2016; Nijiku and Nyamsogoro, 2018; Semerci and Yurt, 2023; Semerci, 2024), confectionery sunflower production, which has different market dynamics, production structure, and economic returns, has largely remained outside these analyses. Despite the region's expanding production areas and economic importance, there is no scientific data on how efficiently confectionery sunflower producers use their resources, the extent of their inefficiencies, or the sources of these inefficiencies. The contribution of this study to the literature lies in the fact that it is the first to measure technical efficiency using the bootstrap method in confectionery sunflower production and to calculate the allocative and economic efficiency of farms. Accordingly, the study aims to measure the levels of technical, allocative, and economic efficiency among confectionery sunflower producers in the Pasin Plain and to identify the sources of scale inefficiency. The study aims to establish a scientific foundation for developing policy recommendations regarding the sustainability and profitability of agricultural production by demonstrating how efficiently producers in the region utilize their current resources.

MATERIALS AND METHODS

Research Area

Pasin Plain, located to the east of Erzurum province, extends to the east and west of the Erzurum-Kars plateau. Covering the districts of Pasinler, Köprüköy, and Horasan, and having an area of 700 km², the Pasin Plain constitutes the research area (Figure 1). The study focused on the districts of Pasinler and Köprüköy, where confectionery sunflower production is concentrated. These two districts are of strategic importance to the research, as they account for 77.76% of the total confectionery sunflower cultivated area, 83.36% of production, and 91.60% of the number of farms in Erzurum province. Horasan district was excluded from the study area due to its low production volume.

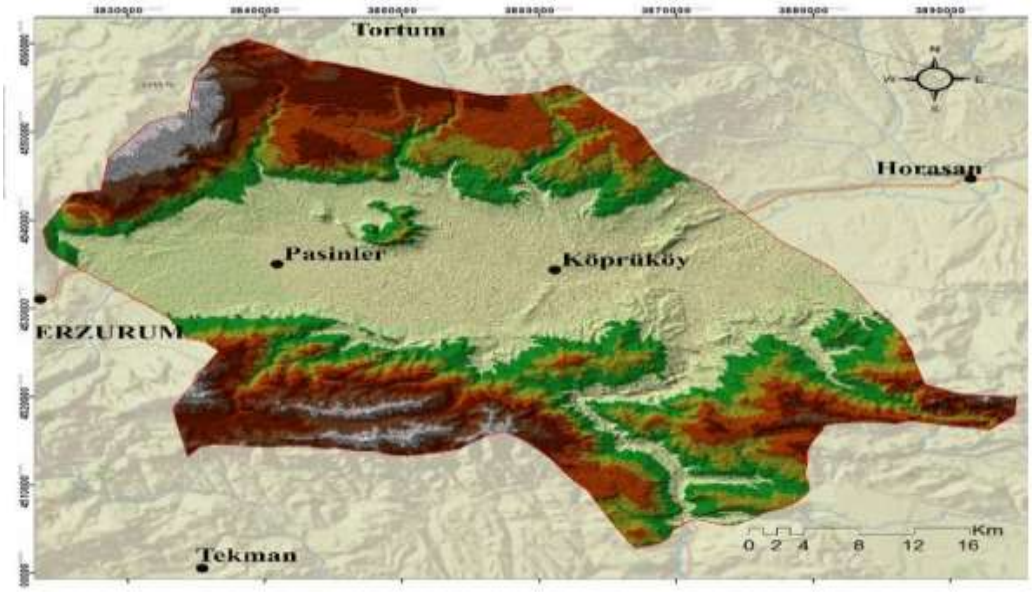

Figure 1. In the Pasin Plain, within the borders of Pasinler and Köprüköy (Koç and Yılmaz 2020).

Primary data for the research were collected through face-to-face surveys with confectionery sunflower producers in Pasinler and Köprüköy districts during the 2022 production season. Through these surveys, detailed information was obtained regarding the farms' production activities, input usage levels, and cost structures. Secondary data for the study were obtained from the Turkish Statistical Institute (TÜİK), the United Nations Food and Agriculture Organization (FAO), records of relevant Provincial and District Directorates of Agriculture and Forestry, and previously conducted scientific studies (theses, articles, reports) on the subject.

Sampling Method Used

It was determined that there are 2,816 farms registered in the Farmer Registration System (FRS) in the districts of Pasinler and Köprüköy within the study area. Farms with less than 1 decare that produce for household consumption were excluded from the population because they were deemed to have no economic value, and farms with more than 50 decares were excluded because they were expected to compromise the homogeneity of the sample and increase variance, thus, a total of 2,581 agricultural farms growing sunflowers for confectionery production on plots ranging from 1 to 50 decares were included in the analysis.

In agricultural economics studies, random sampling is much more preferred than other sampling methods. The advantage of the random sampling method is that the statistics obtained from the sample can represent the population parameters within a certain confidence interval and with a known margin of error (Newbold, 1995; Tuvanç and Dağdemir, 2009; Kumbasaroğlu and Dağdemir, 2011).

The sample size was calculated using Equation 1 under simple random sampling, assuming a 90% confidence level and a 10% margin of error (Yamane, 2001; Tuvanç and Dağdemir, 2009).

$$n = \frac{N*S^2*z^2}{(N-1)*d^2+S^2*z^2} = \frac{2581*0,7555*2,706}{(2581-1)*0.01383+0.755*2.706} = 140 \qquad \text{(Eq.1)}$$

In the equation: n = Sample size, N = Total number of farms in the population (2.581), S^2 = Population variance (0.7555), z = Confidence level coefficient (1.645), d = Acceptable margin of error (1,176*0,10= 0.1176), d^2 =0.01383.

As a result of Equation 1, the sample size was determined as 140 farms. Considering the districts' weights in the main population, 100 (71.43%) surveys were conducted in Pasinler and 40 (28.57%) in the Köprüköy district.

Efficiency Analysis

Efficiency refers to the degree to which activities are carried out in the most appropriate manner within a production process that involves both inputs and outputs. Efficiency measurement is performed using a ratio that indicates the extent to which actual performance approaches the theoretical target level; a value of 1 (or 100%) indicates full efficiency. An efficiency value below 1 indicates non efficiency, while it cannot exceed 1 (Aşkan, 2023). Efficiency analyses can be conducted using two distinct approaches: input-oriented and output-oriented. In agricultural production, farmers have greater control over inputs than over outputs (Işgın et al., 2020; Gündüz et al., 2011; Hajime et al., 2016). Consequently, Farrell (1957) approached technical efficiency from the input perspective, focusing on achieving a specific output level using the minimum possible inputs. Indeed, it is evident that the risks and uncertainties inherent in the production process lead producers to intervene in inputs, and that input-oriented efficiency analysis is more widely used in the agricultural sector (Bravo, U., and Pinheiro, 1993).

To assess the efficiency of the farms using the collected data, Data Envelopment Analysis (DEA), a nonparametric method, was employed. DEA measures the relative performance of decision-making units that produce similar outputs using similar inputs, with a linear programming-based approach (Charnes, Cooper, and Rhodes, 1978). The ability of this method to handle datasets with multiple inputs and outputs, and to do so without requiring a prior assumption about the production function, is the main reason for its widespread use in agricultural economics studies (Temur and Bakırcı, 2008; Özden, 2010). Producers target high profits. To achieve this goal, they either try to achieve the highest output with a certain level of input usage or try to produce a certain level of output with the least input usage level. Data Envelopment Analysis is one of the methods used to determine the extent to which producers are successful in achieving their goals. DEA is one of the methods used to measure input usage efficiency (Parlakay and Çimrin, 2021).

In parametric methods, the production process is expressed by means of a mathematical function. Within the scope of this function, it is envisaged that the relationship between inputs and outputs can be established and that the relevant parameters can be estimated using econometric methods. With these methods (Cobb-Douglas and Translog), production curves are plotted based on predefined parameters. However, DEA is a non-parametric method used to determine the relative efficiency of decision-making units (DMUs) when their inputs and outputs are known and at the appropriate time (Kafi, A. et al., 2020). For this reason, there is no functional form. Production constraints are determined based on the observed data according to the DMU. In this context, the scope of the study has been defined according to decision-making units (DMUs) (Coelli et al., 2005; Mergoni A., 2025).

The analysis was conducted under both Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) assumptions. Whilst the CRS model measures overall efficiency, the VRS model adjusts for scale effects by acknowledging that farms may operate at different scales. The ratio between the two models (CRS / VRS) reveals scale efficiency.

The relationship between the increase in production factors and the increase in total production determines the returns to scale (RTS). Returns to scale is measured as the ratio of the percentage change in total output to the percentage change in total inputs (RTS = % change in total output / % change in total inputs). When the increase in inputs is proportional to the increase in output, returns to scale are constant. If the rate of increase in output is lower than the rate of increase in inputs, this indicates diminishing returns to scale; if it is higher, it indicates increasing returns to scale. (Dinler and Zeynel, 2006).

In this study, a bootstrap DEA model for inputs was employed to enable confectionery sunflower producers to optimize their current production volumes and to determine the most suitable quantity and the lowest-cost input mix. For this reason, only the general formulation of this model is provided below.

$$\theta^* = Min\ \theta \quad \text{(Eq.2)}$$

$$\sum_{j=1}^{140} \lambda_j x_{ij} \leq \theta x_{i0}\ i = 1, \dots, 5; \quad \text{(Eq.3)}$$

$$\sum_{j=1}^{140} \lambda_j Y_j \geq Y_0 \quad \text{(Eq.4)}$$

$$\sum_{j=1}^{140} \lambda_j = 1 \quad \text{(Eq.5)}$$

$$Y_j \geq 0\ \ j = 1, \dots, 140; \quad \text{(Eq.6)}$$

θ It represents the technical efficiency score. Y_j represents the different decision units j that produce the output ($j = 1, \dots,$). In this study, the output considered was the quantity of confectionery sunflower production in a production period. x_{ij}represents the inputs used by each j decision unit. λ_j , j. It represents the intensity value determined by the decision-making unit.

Considering that standard DEA estimators can be biased and affected by random errors, the Bootstrapped DEA technique developed by Simar and Wilson (2000) was also preferred in this study, in addition to classical DEA analysis. In this study, bias correction was performed using 5,000 repetitions. The sufficiently large number of repetitions enhances the reliability of the estimated efficiency scores (Simar and Wilson, 2000). By creating 95.00% confidence intervals, it ensures that more robust and reliable efficiency scores are obtained. The specified confidence interval is not required, but the narrower the interval, the more robust the analysis will be (Tone, K. and Ouenniche, J., 2017). All analyses were carried out using R version 4.4.1.

In this study, the technical, allocative, and economic efficiencies of the farms were calculated separately, and the input and output variables used for each analysis are detailed in Table 1. The fact that the production areas of the farms included in the study range from 0.10 to 5.00 hectares, and that there are differences in scale between the farms, has the potential to distort the results of the scale effect. For this reason, the analysis was conducted on a per unit area basis.

Table 1. Variables taken into account in efficiency analysis.

Type of analysis	Output variable	İnput variable
Technical efficiency	Confectionery sunflower production amount (kg ha^{-1})	1. Seed quantity (kg ha^{-1}) 2. Amount of chemical fertilize (kg ha^{-1}) 3. Labor use (at ha^{-1}) 4. Number of irrigations (units year^{-1}) 5. Pesticide application rate (lt ha^{-1} or kg ha^{-1})
Economic efficiency	Confectionery sunflower production value (₺ ha^{-1})	1. Seed cost (₺ ha^{-1}) 2. Fertilizer cost (₺ ha^{-1}) 3. Labor cost (₺ ha^{-1}) 4. Irrigation cost (₺ ha^{-1}) 5. Pesticide cost (₺ ha^{-1})

In this study, calculations were performed based on an input-oriented (minimization) efficiency approach. Technical efficiency (TE) refers to the extent to which decision-making units (DMUs) can minimize the inputs used to achieve a given level of output, considering the existing technology and available resources. Allocative efficiency (AE) reflects the ability of farms to use inputs in optimal proportions, taking into account prevailing input prices, in order to minimize production costs for a given level of output. Economic efficiency (EE), on the other hand, represents a farm's ability to produce a given level of output at the minimum possible cost. Economic

efficiency is achieved when a farm is both technically and allocatively efficient and is calculated as the product of technical efficiency and allocative efficiency (EE = TE × AE) (Mohapatra, 2013; Yeni and Dağdemir, 2022).

RESULTS AND DISCUSSION

Basic descriptive statistics for the input and output variables included in the efficiency analysis are presented in Table 2.

Table 2. Descriptive statistics of variables

Variables	Mean	Std.dev.
Output		
Y: Confectionery sunflower production amount (kg ha^{-1})	2 700	92,38
Physical inputs (Technical efficiency)		
X_1: Labour (EİB ha^{-1})	26.00	20.20
X_2: chemical fertilizer (kg ha^{-1})	542.60	288.70
X_3: Seed (kg ha^{-1})	8.50	1.40
X_4: Number of irrigations (number)	3,03	1.15
X_5: Pesticide (lt ha^{-1})	5.50	2.80
Monetary inputs (Economic efficiency)		
X_6: Labor cost (₺ ha^{-1})	1 737.50	685.60
X_7: Fertilizer cost (₺ ha^{-1})	8 139.00	3 140.70
X_8: Seed cost (₺ ha^{-1})	3 400.00	706.20
X_9: Irrigation cost (₺ ha^{-1})	1 248.40	722.40
X_{10}: Pesticide cost (₺ ha^{-1})	4 125.00	2 515.10

An analysis of Table 2 shows that farms produce an average of 2,700 kg of sunflower seeds per hectare. Looking at physical inputs, it is evident that the highest input is the use of chemical fertilizers, followed by labor and pesticide use. When examining monetary inputs, it is observed that the highest cost item is chemical fertilizers, followed by pesticide and seed costs, significant differences were noted between farms in terms of production techniques and resource management.

Technical Efficiency Analysis

Technical efficiency scores, which measure how efficiently farms use their inputs under existing technology and production scale, were calculated under both CRS and VRS assumptions, using both classical (non-bootstrapped) and bias corrected (bootstrapped) methods. The results are summarized in Table 3.

Table 3. Comparison of technical efficiency scores in CRS and VRS

	Constant return to scale (CRS)						Variable return to scale (VRS)					
	Mean	**Std.dev.**	**Min.**	**Max.**	**Obs.**	**disc**	**Mean**	**Std.dev.**	**Min.**	**Max.**	**Obs.**	**disc**
eff	0.69	0.20	0,33	1,00	140	0	0,88	0,13	0,61	1,00	140	0
bias	0,06	0.05	0,02	0,24	140	0	0,05	0,03	0,01	0,12	140	0
bceff	0,63	0.17	0,31	0,99	140	0	0,83	0,12	0,59	0,99	140	0
LowerCI	0,53	0,15	0,30	0,90	140	0	0,78	0,11	0,56	0,97	140	0
UpperCI	0,65	0,19	0,33	0,99	140	0	0,87	0,13	0,60	1,00	140	0

Considering the bootstrapped values in the analysis, the average technical efficiency under the VRS assumption was 0.83. This result indicates that the surveyed farms use their inputs efficiently, at 83.00%. In other words, farms can reduce their current input levels by an average of 17.00% to maintain the same production quantity, owing to managerial skills and performance in production processes. This demonstrates that producers in the Pasin Plain have achieved a certain level of success in resource management. The traditional knowledge and experience of farmers in the region are effective in managing the production process, thereby maintaining relatively high technical efficiency. However, a remaining improvement potential of 17.00% underscores the

importance of enhancing agricultural practices, adopting modern technologies, and engaging scientific consultancy services.

To better observe the differentiation in efficiency levels of farms, the technical efficiency distribution scores for confectionery sunflower-producing farms are presented in Table 4.

Table 4. Technical efficiency distribution in enterprises producing confectionery sunflowers.

	Constant return to scale (CRS)		Variable return to scale (VRS)	
Efficiency range	**Non-bootstrapped**	**Bootstrapped**	**Non-bootstrapped**	**Bootstrapped**
eff<=0.40	9	11	0	0
0.40<eff<=0.50	17	28	0	0
0.50<eff<=0.60	34	31	0	3
0.60<eff<=0.70	19	17	18	23
0.70<eff<=0.80	13	20	23	31
0.80<eff<=0.90	19	29	29	36
0.90<eff<1	11	4	12	47
eff=1	18	0	58	0

As shown in Table 4, whilst the VRS analysis results without bootstrapping identified 58 farms as fully efficient (eff = 1), the fact that this figure drops to 0 according to the VRS analysis results with bootstrapping demonstrates the function of correcting bias in bootstrap VZA scores and enhancing statistical reliability. As bootstrapping estimates the statistical distribution of efficiency scores by resampling the original data set thousands of times, the traditional VZA indicates that the efficiency scores of the 58 fully efficient farms are statistically significantly different from 1, suggesting that these farms are not actually fully efficient (Simar, L., and Wilson, P., 1998; Simar, L., and Wilson, P., 2000).

Although the bootstrap analysis results in the VRS do not indicate the presence of fully efficient farms, it is observed that 33.60% of farms have an efficiency score between 0.90 and 1.00. This indicates that a significant portion of the farms use their resources efficiently. 59.30% of the farms have an efficiency score above 0.80. In contrast, approximately 40.00% of farms with scores below 0.80 indicate significant potential to improve input use. In particular, 2.10% of farms (3 farms) have a score below 0.60, indicating a serious waste of resources. Examining socioeconomic factors such as land size, farmers' education levels, age, agricultural experience, and the financial status of these low efficiency farms could be important for developing targeted intervention programs.

Economic Efficiency and Allocative Efficiency

Economic efficiency is the determination of efficiency based on cost. The most economically efficient production method is the one with the lowest cost among the alternatives. Allocative efficiency, on the other hand, is an indicator of how producers operate both technically and economically, and it is obtained by dividing the economic efficiency value by the technical efficiency value.

The study examined not only how well farms managed their production process (technical efficiency) but also how accurately they made decisions regarding market conditions and input prices (allocative and economic efficiency). The distribution of economic and allocative efficiency scores for the farms is presented in Table 5.

Table 5. Comparison of technical, economic and allocation efficiencies of enterprises

	Constant return to scale (CRS)		Variable return to scale (VRS)	
Efficiency	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**
Technical efficiencies	0.69	0.20	0.88	0.13
Economic efficiencies	0.52	0.25	0.72	0.22
Allocation efficiencies	0.75	0.27	0.82	0.21

In Table 5, the average economic efficiency of farms under the VRS assumption was calculated as 0.72. This indicates that farms can reduce total costs by an average of 28.00% while maintaining current production levels. The source of this 28.00% total cost saving is both technical and allocative inefficiency. This situation

indicates that, although the surveyed farms largely know how to produce (e.g., how to cultivate, when to irrigate), they cannot achieve comparable success in selecting the optimal input combination at the right price.

The average allocative efficiency of 0.82 suggests that producers remain insensitive to changes in input prices or experience difficulties in accessing market information. This situation indicates that farms increase their costs by an average of 18.00% simply by choosing the wrong input combination. This inefficiency stems primarily from mismanagement of input timing and quantities, such as fertilizers and pesticides, and is accompanied by price fluctuations.

Overall, higher technical efficiency and lower economic and allocative efficiencies indicate that price imbalances and weaknesses in producers' economic decision making mechanisms significantly limit efficiency performance. Even if producers are technically more efficient, they increase their costs and reduce their profitability due to misallocations of inputs.

Külekci (2010), categorized farms according to their size, determining the technical efficiency score for small farms to be 0.58 and for large farms to be 0.73. He found the average technical efficiency score for farms to be 0.65. He stated that large-scale farms are more efficient in the region and that producers could reduce their inputs by approximately 56.00 percent by improving their technical efficiency without reducing sunflower production, based on these findings, he emphasized the need to improve extension services, such as farmer training programs, to enhance technical efficiency, alongside expanding production across larger areas. Parlakay, (2016), calculated the farms' technical efficiency scores as 0.82 under the CRS assumption and 0.83 under the VRS assumption. The VRS technical efficiency score in our study is higher than that found by Parlakay (2016), suggesting that the farms examined operate with greater technical efficiency. Savaş and Işın (2024) found that the technical efficiency score for farms using advanced irrigation technology was 0.72, for those producing without irrigation it was 0.81, and the overall technical efficiency score was 0.74. The CRS technical efficiency score in our study is lower than the overall average reported by Savaş and Işın (2024). However, our VRS technical efficiency score is higher than that of both groups in Savaş and Işın (2024). This suggests that the farms in our study have higher technical potential or could be more efficient if scale inefficiencies were eliminated.

CONCLUSION

The study reveals that while confectionery sunflower producing farms in the Pasin Plain exhibit high levels of technical efficiency, their economic efficiency remains comparatively low. This finding indicates that producers are capable of effectively managing the production process from a technical standpoint, however, farms fall short in achieving sufficient efficiency in input combination selection, cost control, and price-based economic decision making processes. A significant portion of overall inefficiency stems from scale inefficiency, highlighting that small scale farms, in particular, struggle to reduce unit costs and are more vulnerable to increases in input prices. In this context, existing digital platforms should be rolled out more widely and encouraged so that producers can closely monitor input prices and manage costs in the face of fluctuations in input prices. At this point, mobile apps such as the Tarım Cebim'de app developed by the Ministry of Agriculture and Forestry can offer significant benefits to producers. In addition, small-scale farms should be offered access to low interest loans. This will have a positive impact on the competitiveness of small farms and make it easier for them to access finance. In addition, agricultural extension and consultancy services should be restructured to go beyond the mere transfer of technical knowledge to encompass cost management, market information, and financial literacy. Furthermore, supporting structural arrangements aimed at mitigating scale issues, such as cooperativization and land consolidation, and developing targeted policy instruments for low efficiency farms are crucial for enhancing the sustainability and economic performance of confectionery sunflower production in the region.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

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