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1. PLANT STRESS PHYSIOLOGY DAYS SCIENTIFIC BOOKLET

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📅 *April 16, 2025*
📍 *Ahmet Muhip Dıranas Application Hotel, Conference Hall*

PROGRAM FLOW

09:00–09:15 Prof. Dr. Burcu SECKIN DINLER – Sinop University, Department of Biology

09:20–09:50 Recent Innovative Strategy for Mitigating Drought Stress
Prof. Dr. Saad FAROUK – Mansoura University, Department of Agricultural Botany

10:00–10:30 Global Climate Change and Salt Stress Effects on Plants
Assoc. Prof. Dr. Volkan GUL – Bayburt University, Department of Food Processing

10:30–10:50 ☕ **Coffee Break**

10:50–11:20 Molecular Priming By a Biostimulant Derived from Ascophyllum Nodosum Mitigates Drought Stress in Vegetable Crops
Dr. Nikola STAYKOV – Center of Plant Systems Biology and Biotechnology (Bulgaria)

11:30–12:00 From Field to Market: Taşköprü Garlic and Its Challenges
Assoc. Prof. Dr. Nezehat TURFAN – Kastamonu University, Department of Biology

12:00–13:30 🍽️ **Lunch Break**

13:30–14:00 Determination of Salinity Tolerance Degree of Some Potato Genotypes under in Vitro Conditions
Assoc. Prof. Dr. Firat SEFAOGLU – Kastamonu University, Department of Genetics and Bioengineering

14:10–14:40 Stress-Mediated Shifts in Plant Functional Strategies: The Role of Grazing in The Kızılırmak Delta
Assoc. Prof. Dr. Emire ELMAS – Sinop University, Department of Biology

14:40💬 **Discussion**

Organizing Committee
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SİNOP ÜNİVERSİTESİ


1. Giriş - Introduction


Recent Innovative
Strategy for mitigating
Drought Stress


Taşköprü sarımsağı üretiminde temel
sorunlar

LIST OF VOLUNTEERS

ELIF SUDE TARAK
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BANU ÖZBŐLÜK
NAGEHAN AKTAŞ
ŞAZİYE İREM AKTAŞ

RECEP BÜLBÜL
SONAY YOKTAN
DAMLA KILIÇ
FURKAN SÜZER
OSMAN EMRENUHOĞLU

We would like to sincerely thank the students of the Department of Biology who volunteered in the preparation, organization and execution processes of our workshop named “I. Plant Stress Physiology Days. We are grateful to all of you for making this scientific event meaningful by contributing with dedication, a sense of responsibility, and team spirit. The success of our workshop was possible thanks to your efforts. We wish you many more successes in your future academic and professional life with the same determination and excitement.

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PREFACE

Nowadays, global climate change and the increase in environmental stress factors seriously threaten agricultural production systems. In this context, it is important to understand the physiological, biochemical, and molecular adaptation mechanisms plants develop against abiotic and biotic stress conditions. Scientific studies in the field of plant stress physiology constitute the basis for the development of strategies for the development of plant varieties with high stress tolerance.

Accordingly, the 1st Plant Stress Physiology Days were held on 16 April 2025 at Ahmet Muhip Dıranas Application Hotel, Sinop University. The workshop enabled researchers, academicians, and plant physiology and agriculture students to share current scientific developments, exchange ideas, and develop interdisciplinary collaborations.

The programme included academic and poster presentations from undergraduate and graduate students. This booklet contains summaries of the scientific contributions presented during the event. It is anticipated that the scientific outputs of the workshop will contribute to the existing knowledge in the field of Plant Stress Physiology.

We want to thank all researchers, students, and everyone who contributed to the workshop with their participation and contributions.

Prof. Dr. Burcu SECKIN DINLER

Assoc. Prof. Volkan GUL

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After completing his undergraduate education at Ege University, Faculty of Science, Department of Biology, she started his master's degree in the same year. She completed her doctorate at the same university in 2010. Then he started to work at Sinop University, Faculty of Science and Literature, Department of Biology. In 2016, she received the title of Associate Professor, and in 2022, she received the title of Professor. She is currently working at Sinop University, Faculty of Arts and Sciences, Department of Biology.

She participated in many meetings and congresses both at home and abroad. She has articles both in SCI-Expanded and in national and international refereed journals. She has congress papers, scientific research projects, and international journals. She has lectured in the field of plant physiology, such as Molecular Biology, Stress Physiology in Plants, Germination Physiology, Plant Growth Regulators, and has conducted many studies in this field. She continues her academic studies, training, and projects at Sinop University. She is married and has one child.

Research Areas: Plant Stress Physiology, Reactive Oxygen Species, Salinity, and Antioxidant Enzymes

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He was born on 23.05.1979 in Samsun. He completed his primary, secondary, and high school education in Samsun. He completed his undergraduate education at Ondokuz Mayıs University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation in 2002. Between 2005-2017, he worked as a Police Officer in the Provincial Organisation of the General Directorate of Security. He completed his master's degree at Ordu University Institute of Science and Technology, Department of Field Crops in 2008. He received his doctorate degree from Atatürk University Institute of Science and Technology, Department of Field Crops in 2013. In 2017, he was appointed as Dr. Lecturer to Bayburt University Faculty of Applied Sciences, Department of Organic Agriculture Management. He was appointed as a lecturer. In 2020, he became an Associate Professor at Bayburt University Faculty of Applied Sciences, Department of Organic Agriculture Management. In 2022, he graduated from the Anadolu University Open Education Faculty Sociology Department. He is currently working as the Head of Department at Bayburt University, Aydıntepe Vocational School, Food Processing Department.

He attended many meetings and congresses in Turkey and abroad. He has articles both in SCI-Expanded and in national and international refereed journals. He has congress papers, scientific research projects, and international journal referees. He has given many lectures on Industrial Crops, Organic Agriculture, Good Agricultural Practices, Oil Crops, Plant Stress Factors, Medicinal and Aromatic Plants. He carries out studies in many fields such as organic farming, oil crops, medicinal and aromatic plants, which may be suitable for the climate and environmental conditions of the Bayburt region and the world. He continues his academic studies, training, and projects at Bayburt University.

Research Areas: Industrial Crops, Organic Agriculture and Organic Plant Nutrition, Oilseed Crops, Medicinal and Aromatic Plants, Plant Stress Physiology

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He was born on 11.11.1979 in Erzurum. He completed his primary, secondary and high school education in Erzurum. He completed his undergraduate education at Atatürk University, Faculty of Agriculture, Department of Field Crops in 2003. In 2008, he graduated from Atatürk University Institute of Science and Technology, Department of Field Crops. He worked as an Agricultural Engineer in Mersin and Erzurum Regional Directorate of Agricultural Credit Cooperatives between 2008-2011 and in Eastern Anatolia Agricultural Research Institute affiliated to the General Directorate of Agricultural Research between 2011-2017. He received his doctorate degree from Atatürk University Institute of Science and Technology, Department of Field Crops in 2017. In 2018, he was appointed as Dr. Lecturer to Kastamonu University Faculty of Engineering and Architecture, Department of Genetics and Bioengineering. He was appointed as a Lecturer. In 2023, he became an Associate Professor at Kastamonu University, Faculty of Engineering and Architecture, Department of Genetics and Bioengineering.

He attended many meetings and congresses in Turkey and abroad. He has articles both in SCI-SCI-Expanded and in national and international refereed journals. He has congress papers, scientific research projects and international journal referees. He has given many lectures on Plant Tissue Culture, Agricultural Biotechnology, Medicinal and Aromatic Plants. He has been carrying out studies in many fields such as oil crops and medicinal and aromatic plants that may be suitable for the climatic and environmental conditions of the Eastern Anatolia region and the world. He still continues his academic studies, trainings and projects at Kastamonu University.

Research Areas: Industrial Plants, Oilseed Crops, Medicinal and Aromatic Plants, Plant Stress Physiology

PART 1

RECENT STRATEGY FOR MITIGATING DROUGHT STRESS

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ABSTRACT

Recent climate changes pose a significant risk to sustainable worldwide food production. Of the abiotic stressors, drought attracting awareness owing to its undesirable impacts on plant establishment, crop productivity. To address the negative impact of drought on plants, specific strategies are implemented to enhance drought tolerance, i.e., decreased transpiration rate, leaf rolling, variation of root/shoot ratio, accumulation of compatible solutes, osmotic and hormonal regulation and postponed senescence. Therefore, it is essential to explore the untapped adaptive traits in various plants and their integration into genotypes that could withstand the negative effect of drought to maintain productivity.

To enhance drought resistance, specific breeding approachs along with molecular, genomics insights, and omics technologies are highly beneficial. Certain strategies are gaining increased focus for managing drought in dry and semi-dry districts. Since drought is an intricate phenomenon, it is essential to analyze different mechanisms at the physio-biochemical and molecular levels to create drought resistant crops without compromising yield. The restricted effectiveness of physio-molecular responses indicates the need for a more comprehensive strategy, taking into account the interplay of drought with various stressors. Moreover, physiological, genomic, and transgenic features, could enhance crops drought resistance. Additional practices including the external medulators, like plant growth hormones, osmoprotectants, ions, biochar, nanoparticle and hydrogel are beneficial in drought-affected plants.

This review clarifies the intricate impacts of drought on plants, emphasizing the existing data regarding advancements in genetic attributes, and agricultural practices while examining potential strategies to generate drought-resistant plants and boost crop productivity.

Keyword: Abiotic stress, Climate change, Drought stress, Nanoparticles, Omics technologies

INTRODUCTION

Plants are exposed to constantly changing environmental conditions due to global warming and climate change (Gul et al., 2024). Climate change and human activities present numerous obstacles to agricultural sustainability and food security, alongside the worldwide population projected to hit 10 billion by 2050 (Foresight, 2011; Figure 1). Additional improvement in crop productivity relies on enhanced yields instead of expanding the cropping area. It is anticipated that global climate change will lead to greater variability in rainfall, accompanied by more frequent droughts (IPCC, 2007).

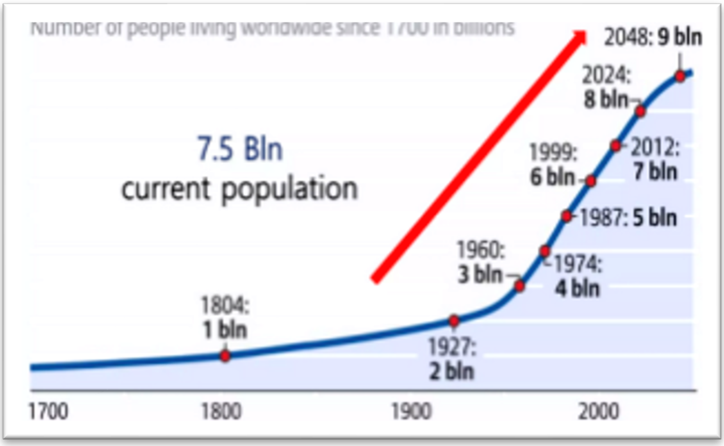

Figure 1. Global population in billions since 1700 (UN World Population Prospects; Deutsche Stiftung Weltbevölkerung)

Drought is a naturally extended period of aridity occurring anywhere on the planet. It is a gradually developing disaster marked by insufficient rainfall, leading to a shortage of water. In various parts worldwide, drought prone areas and desertification are increasing because of restricted and changed rainfall patterns (Figure 2). Drought is a significant climate-related issue that greatly diminishes crop yields across 1.9 billion hectares (ha), thereby impacting the living standards of approximately 1.5 billion individuals globally (C2ES, 2021). Rising temperatures exacerbate dryness in arid regions while intensifying precipitation in moist areas (https://www.who.int), leading to a surge in food costs (NWS, 2021).

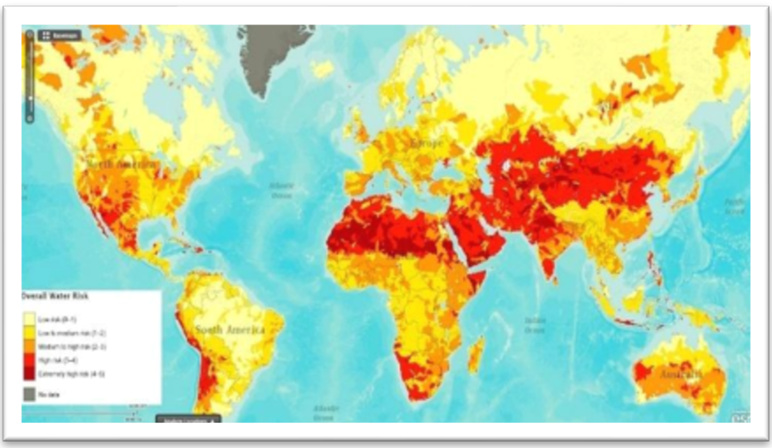

Figure 2. Drought-prone regions distribution worldwide

Water scarcity represents the primary abiotic stress in arid and semi-arid regions that endangers crop productivity (Diatta et al., 2020). Over the last decade, the worldwide economic losses from drought-related crop production have increased to around US $ 30-44 billion, while fresh water availability is expected to decrease by 50%; conversely, agricultural water needs are predicted to double by 2050 (Gupta et al., 2020). The rise in food costs may lead to social turmoil, starvation, or displacement in nations that are facing food insecurity (C2ES, 2021; NWS, 2021).

The erratic nature of drought relies on inconsistent and unreliable distribution of rainfall, and water retention ability within rhizosphere (Devincentis, 2020). Various morph-biochemical and molecular features of plants are adversely affected within water scarcity. These replies are crucial to address the growing requirement for worldwide food security, that regrettably coincides with the decrease in cultivated areas caused by extended drought and shifts in precipitation patterns triggered by climate alteration and highlights the necessity to boost crop productivity (Seleiman et al., 2021; Ullah et al., 2022).

Drought tolerance is defined as a plant's capability to endure when water availability is limited. Enhancing crop drought resistance through genetic methods represent a primitive economical and sustainable ways to boost plant productivity. Yet, drought tolerance represents a complicated trait influenced by numerous genes, rendering it one of the hardest characteristics to investigate, define, and enhance.

Recently, urgent investments must be made for creating climate-resilient and higher-yielding crops (Sahoo et al., 2025). To improve water productivity, when physical adaptation of plant organs fails to withstand with drought signals, it involves a gene encoding a regulatory protein, which influences numerous genes via crosstalk based on various regulatory strategies (Yadav et al., 2020). To address upcoming food requirements, promoting initiatives on drought-resistant cultivars adopting affordable and effective agriculture management will be essential. Although several reviews emphasize the impact of drought on crop establishment and productivity (Zahra et al., 2021; Shaffique et al., 2024), there is an absence of reports discussing recent advancements in molecular and agronomic strategies for drought resistance.

1. REASONS OF DROUGHT OCCURRENCE

Future global climate change is anticipated to intensify due to the ongoing increase in air temperatures and atmospheric CO_2, which ultimately modify rainfall patterns and their distribution. Although inadequate precipitation typically represents the main reason for water stress, soil moisture depletion caused by evapotranspiration prompted by elevated temperatures and intensified sunlight can further aggravate water stress episodes (Cohen et al., 2021). Drought can be described as a lack of water necessary for plants, attributed to physical (unsatisfactory rainfall, elevated temperatures, etc) or physiological (salinity, ion imbalance, osmotic regulation, etc) reasons. Certain factors contributing to water scarcity are briefly emphasized

1.1. Global Heating

Elevating air temperatures could result in glacier melting, along with potential flooding of cultivated areas with gentle inclines. Moreover, glaciers' disappearance is causing a decline in water reserves, limiting the water accessibility for plants, a pattern that worsens over time. Indeed, under different rain-dependent farming regions, the annual total rainfall has diminished due to global warming (Warner and Afifi, 2014). Ray et al. (2019) revealed that a rise in air temperature by about 2°C by the century's end will lead to significant water shortages for about one-fifth of the global population.

1.2. Precipitation Irregularities

Greater water deficit is expected in areas where plant farming relies exclusively on precipitation rather than in irrigated areas. Therefore, in rain-dependent regions, drought occurrences are closely associated with the yearly precipitation distribution, and there is a significant likelihood of water scarcity in specific years over a certain timeframe (Ingrao et al., 2023). Nonetheless, rainfall distribution and intensity throughout the years greatly affect water resources management and often acclerate water deficit (Karandish and Šimůnek, 2016).

1.3. Changes in Monsoon Patterns

In the summer, the monsoon pattern is viewed as a precipitation resources within different regions worldwide. It is expected that in rain-fed regions, summer rainfall will declined by 70% throughout the early XXII century if current trend persists (Yu et al., 2013). Accordingly, the variability of monsoon rainfall intensity, occurrence and duration influencing rhizosphere water level, consequently influencing crop establishment. Alongside the naturally unpredictable and random character of precipitation distributions, recent climate changes might worsen current situation regarding water shortages or surpluses in certain climatic regions, potentially affecting the duration and flexibility of the rainy season. As agronomical practices, plant cultivation methods should be adapted to the monsoon conditions and transitioned towards sustainable agriculture. Effective crops management scheduling are two approaches to address changes in quantity, shifting from scarcity to surplus and, conversely, to monsoon cycles.

2. DROUGHT STRESS AND PLANTS

Drought severely disrupts morpho-anatomical, physio-biochemical, and molecular features, leading to declines in relative water content, diminishes membrane stability, and changes photosynthesis efficiency, that finally hinder crop productivity (Khan et al., 2025). Sufficient moisture represents an essential needs for crop establishment, as variations in soil moisture beyond ideal levels can affect crop productivity and quality, and this situation is expected to deteriorate further due to climate change (Elemike et al., 2019).

Ongoing drought severity restricted several morphophysiological traits; including wilting and leaf rolling, plant stunted, ion homeostasis, disrubtion of photosynthetic activity, and yield attributes as well as harvest index (Bhattacharya, 2021). Under water deficit, photosynthetic capacity and water status diminish, resulting in a decline in leaf area (Nieves-Cordones et al., 2019). To cope with drought, the osmotic adjustment of stressed plants is sustained by a rise in sugar levels of plant organs, and it has been noted that drought-affected plants exhibit relatively greater growth in roots than in the shoots (Miranda et al., 2020).

Plant photosynthesis drops as relative water content and leaf water potential decline (Farouk and AlGhamdi, 2021). Within drought, photosynthesis decline is typically linked with stomatal limitations (Farouk and AlGhamdi, 2021). The reactions of photosynthesis triggered by drought indicate that as drought intensifies, the stomata gradually closed, ultimately causing a declined in photosynthetic rates. Water shortage prompts biochemical signaling (ABA) from root to leaf, causing stomatal closure and decreasing transpiration rate (Tardieu et al., 2006). Conversely, a significant degree of co-regulation can be observed within stomatal function and photosynthetic processes (Hubbard et al., 2001). Consequently, stomatal functions are variable and influenced by various environmental factors, making stomatal conductance a crucial metric for assessing photosynthetic reactions to drought. In different plants, the photosynthetic rate is influenced by rubisco activity and RuBP assimilation (Tezara et al., 1999).

Water scarcity, along with the resulting decline in cellular water homeostasis greatly diminish photosynthetic rate via restricting CO_2 diffusion within stomata, and may also trigger oxidative burst, which may harm photosynthetic pathways (Yang et al., 2021). Dehydration may additionally lead to the acidification of the chloroplast stroma, which inhibiting the activity of rubisco (Amaral et al., 2024). Within water stress, carbohydrate levels, and photoassimilates are altered (Yuan et al., 2009). It seems that water scarcity modifies starch/sucrose ratios within chloroplast biomembranes, resulting in modified inorganic phosphate (Pi) flow. Due to declined chloroplasts Pi, ATP assimilation is hindered, leading to a more significant effect on photophosphorylation (Zheng et al., 2023).

As a consequence of drought, the excessive assimilation of reactive oxygen species was boosted with plant organelles i.e. chloroplasts. As ROS levels rise, cellular redox homeostasis is regulated through a multifaceted and collaborative antioxidant system that affects intracellular ROS concentrations. Reactive oxygen species changes serve as a key alert indicator that evokes an adaptive defense reaction via transduction pathway signals, including H_2O_2 as a secondary messenger

(Cruz de Carvalho, 2008). However, when drought stress persists for an extended duration, elevated ROS levels can surpass the antioxidant system, leading to extensive cellular injury and mortality. Maintaining low levels of ROS might integrate them into stress signaling pathways, evoking stress defense and acclimatization responses (Vranova, 2002). Overproduction of ROS like hydrogen peroxide, superoxide, hydroxyl, and singlet oxygen triggered oxidative burst (Juan et al., 2021). Plants possess an antioxidant defense system to manage the assimilation of reactive oxygen species and mitigate their injury (Vranova, 2002). Water deficit can be described within 3 consecutive stages: (1) ROS steady-state levels are altered, (2) ROS assimilation rises alongwith stomatal closure, and (3) following extended drought stress, ROS production escalates, overhelming the antioxidant system, which leads to oxidative burst and ultimately cell death. The initial defense strategy against ROS buildup is the superoxide dismutase that converts singlet oxygen to H_2O_2 (Hasanuzzaman et al., 2021). Ascorbate peroxidase and catalase enzymes help in eliminating H_2O_2, converting it into water and oxygen. They exhibit varying affinities for H_2O_2 removal; catalase is primarily accountable for most H_2O_2 elimination due to its low affinity; while APX displays a high affinity for H_2O_2, which may influence the regulation of ROS (Hasanuzzaman et al., 2021). Additionally, ascorbate peroxidase is a component of ascorbate-glutathione system that requires ascorbic acid for H_2O_2 scavenging (Cruz de Carvalho, 2008). In drought-affected plants, antioxidant capacity may contribute to enhancing stress resistance (Vranova, 2002). These antioxidants contribute a direct or indirect role in enhancing drought tolerance of different crops.

3. DROUGHT STRESS TOLERANCE IN PLANTS

Plant responses to water deficit are intricate, and they have developed various strategies to mitigate the negative impacts of challenging environments by modifying their physio-biochemical, molecular, and cellular processes (Liaqat et al., 2021). The three main survival strategies that plants employ under drought are avoidance, escape, and tolerance (Figure 3; Galindo et al., 2020). Breeding for drought resistance has largely been on agricultural and physiological attributes, including biomass production and crop productivity, photosynthetic features, plant anatomy, osmotic adjustment, hormonal balance, and redox homeostasis (Rapacz et al., 2019). The subsequent part discusses plant drought tolerance mechanisms.

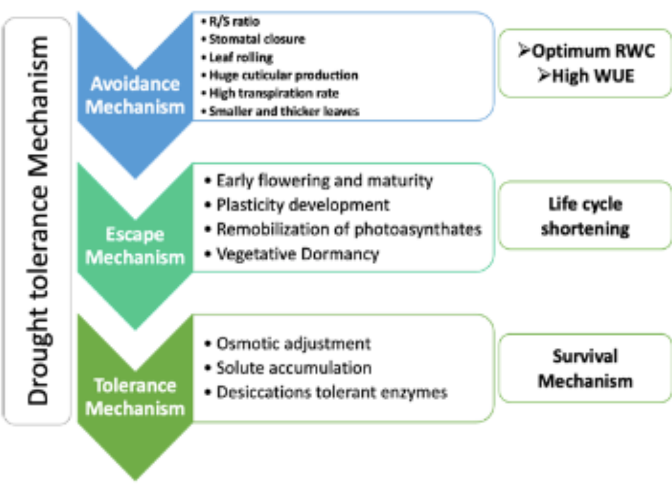

Figure 3. Drought tolerance mechanisms in plants

3.1.Escape Mechanism

Drought escape is a traditional adaptive strategy that entails rapid plant growth to ensure the entire life cycle is completed prior to the onset of an upcoming water deficit. Within the escaping strategy, certain plants employ strategies that entail accelerated and reduced life cycle duration, self-reproduction, and growth during the season prior to the onset of the driest season (Álvarez et al., 2018). Among these strategies, early blooming represents the most effective plant escape strategy, though this approach might result in a notable decline in plant life span and productivity (Tekle and Alemu, 2016). Key features of drought escape comprise developmental plasticity, swift phenological progression, and the reallocation of photoassimilates produced before anthesis to developing fruits (Shavrukov et al., 2017).

Typically, a decline in photosynthetic pathways under drought accelerated the movement of stem reserves to wheat developing grains. Accordingly, van Herwaarden et al. (1998) noted that 75–100% of stem reserves contributed to the wheat grain development during drought. Additionally, Ehdaie et al. (2008) revealed that the stem reserves accounted for 19.1–53.6% and 36.6–65.4% of grain yield in well-watered and drought environments, correspondingly. Fructans rank as one of the most abundant stored carbohydrate sources for grain development (Ershadimanesh et al., 2024). Consequently, fructan reduction in wheat peduncles was noted within the grain filling stage, as anticipated in source-restricted conditions, nevertheless, boosted in sink-restricted scenarios (Ershadimanesh et al., 2024).

3.2. Avoidance Mechanisms

Plant avoidance strategy is defined as the capacity of plant to maintain relatively elevated tissue water potential under drought condition. The plant cells employ 2 strategies for sustaining their water status alongside rising evaporation and diminishing soil water availability, either by reducing water loss or by holding onto the water source. Under the avoidance strategy, plant water potential remains elevated by minimizing stomatal transpiration and enhancing water uptake (Blum, 2017). In other cases, xerophytic features like fuzzy leaves and thick cuticle layers on the epidermis can assist in preserving elevated plant cell water potential (Boulard et al., 2017).

Relative water content serves as a crucial selecting protocol for drought tolerance in several cultivars. The relative water content has been extensively utilized to assess water deficits in plant leaf in relation to full turgid pressure, particularly when evaluating plants exposed to different drought stress levels, with an emphasis on drought-tolerant crops individuals (Hu and Xiong, 2014). Re-evaluating relative water content might yield improved drought resistance assessment criteria for creating drought-tolerant cultivars (Teulat et al., 2003). Water use efficiency is vital for regulating the balance between transpiration and photosynthetic carbon bioassimilation (Farquhar et al., 1982).

Plants that have deeper root systems might be more adapted to soils experiencing water scarcity than those featuring shallow root systems (Oyiga et al., 2020). Root adaptations to drought involve lengthening of main roots, development of deep roots, inhibition of lateral root development, and modifying secondary root density from shallower to deeper layers (Lynch et al., 2014). These interconnected characteristics could be affected by molecular networks that regulate gene expression (Hrmova and Hussain, 2021).

3.3. Tolerance Mechanisms

The capability of the plant to endure reduced water levels in its tissues is known as drought tolerance. Drought tolerance in plants is a multifaceted process governed by various genetic factors and intricated morpho-physiological strategies, including sustaining cell turgor pressure, enhanced cell softness, and decreased cell size (Li and Xu, 2007). An adaptable tolerance system within photosynthesis pathways includes restrictions of cell expansion and leaf area. Similarly, leaf trichome formation signifies external exomorphic features that enable the plant to endure water shortages in arid regions. These features lower leaf temperature by boosting the light reflection rate on the leaf and by providing an additional layer of resistance to water loss (Zhang et al., 2019). Nonetheless, Tzortzakis et al. (2020) recognized that root system modifications such as root size, density, proliferation, and growth rate, are the prime issue for drought-tolerant plants to manage water shortages.

Osmotic adjustment (OA), enhanced antioxidant capacity, over-production of organic osmolytes, and a rise in root/shoot ratio are prevalent methods that enable plants to endure drought injury (Farouk and Omar, 2020). Drought-affected plants accumulate several organic osmolytes for maintaining and stabilizing cellular structure and function, alongside regulating water and mitigating dehydration impacts via maintaining cellular turgor potential (Turner, 2018). Research on crop cultivars within drought conditions showed that genotypes with elevated OA maintain cellular turgor potential, whereas genotypes with low OA exhibited lower yields, and protein content (Vahamidis et al., 2017).

Limited water availability enhances oxidative injury through the excessive ROS production within drought conditions, whereas the antioxidant capacity (enzymatic and nonenzymatic components) assists in ROS detoxification (Farouk and Omar, 2020). Modification of the antioxidant defense system is a key strategy contributing to drought resilience in plants.

4. DROUGHT STRESS MANAGEMENT APPROACHES

Several approaches have been developed to alleviate drought injury, i.e., developing drought-tolerant genotypes (conventional breeding or genetic engineering); however, plants remain vulnerable to stress mutilation owing to their restricted genetic self-defense aptitude. This clarifies why plant researchers are exploring alternatives to boost plants' resilience to withstand harsh environmental conditions via utilization of innovative methods that involve modern watering methods, and some modulators application along with genetic issues (Figure, 4; Adeyemi et al., 2020; Dinler et al., 2024; Kucukkalyon and Dinler, 2025).

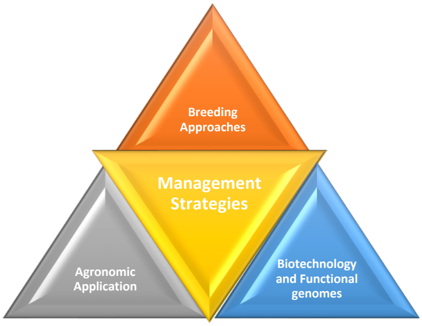

Figure 4. Management strategies for improving drought tolerance

4.1. Selection and Breeding Approaches

Conventional genetic protocols used previously relied on the practical selection of yield features in semi-arid and arid environments (Galaitsi et al., 2016). Traditional breeding techniques have successfully enhanced crop drought resistance (Yahaya and Shimelis, 2022). Accordingly, incorporating drought-tolerant wild sunflowers into selected genotypes led to unique accessions. Throughout 6 distinct generations, careful selection of essential agricultural features resulted in improvements like higher oil yield, greater cuticular wax precipitation, and enhanced pollen fertility. The F6 lines produced yields comparable to control ones, showed decreased water loss from detached leaves, and displayed water conservation features (Hussain et al., 2019). Zhang et al. (2013) recorded the progress in traditional sugarcane breeding throughout the lst fifty years, resulting in the development of drought-tolerant genotypes with elevated yield and sucrose levels. Genome-wide associations (GWAS), extensive genotyping, microenvironment modeling, and genomic selection techniques have aided the discovery of quantitative trait loci (QTLs) linked to drought resistance (Srivastava et al., 2022). Accidentally, Gautam et al. (2021) incorporated an imperative yield QTL into 4 Indian wheat varieties, which contributed to almost 20% of the yield variability under drought conditions. Additionally, GWAS aids in identifying potential nominees for gene-based association mapping, which involves cloning and validating transcription factors linked to drought resistance.

Marker-assisted selection (MAS) and genomic selection (GS) represent the two primary methods used in genomic-assisted breeding. Nonetheless, GS relies on advancements in selection models that utilize genetic markers found across the entire genome and selection of genome estimated breeding values (GEBVs) within breeding populations. MAS plays an imperative role in several crop breeding initiatives for many years, while GS is comparatively recent since it has only been utilized solely for plants. Molecular markers contribute to MAS by being located near QTL or specific genes associated with the target characteristics, which can help identify the individuals with favorable alleles (Varshney et al., 2014). By utilizing these protocols, QTLs associated with drought tolerance are discovered within plants (Hwang et al., 2014). The genomic selection utilizes all markers present in the GEBV population, and GS models facilitate the selection of elite cultivars without genotyping (Varshney et al., 2014). Nevertheless, GS needs denser marker data compared to MAS. This can be achievable due to the presence of affordable and genome-wide marker coverage genotyping approaches (Hayes and Goddard, 2001).

4.2. Molecular approaches

Bio-molecular pathways that are crucial in activation processes designed to lessen drastic effects of drought encompass transcription, stress-responsive genes, and ABA (Osakabe et al., 2020). The identification of stress-associated genes has been achieved by isolating specific genes via a conventional cloning protocol, aiming to broaden the strategy for extensive gene expression research to explore drought stress response. Major progress in this area has arisen from employing various "omics" (transcriptomics, metabolomics, and proteomics) methodologies (Yan et al., 2022). Plant cultivars control drought-responsive genes through complex signaling pathways for generating diverse proteins such as molecular chaperones and several purposeful proteins (Hu and Xiong, 2014). Lu et al. (2022) introduced the C-repeat-binding factor (AmCBF1) gene from *Ammopiptanthus mongolicus* into upland cotton. The transgenic approach involves moving one or multiple genes from one cultivar to another to achieve specific traits, and plants that acquire these foreign genes are referred to as transgenic plants. Transgenic crop varieties exhibited significantly higher levels of soluble carbohydrates, photosynthetic pigments, relative water content, transpiration rates, stomatal conductance, net photosynthetic rate, and decreased ion leakage under drought conditions, enhancing drought resistance. Moreover, wheat and *Arabidopsis* cultivars that overexpressed the VQ-motif gene (TaVQ4-D) showed improved drought tolerance, boosted antioxidant aptitude, preserved cellular membrane integrity, and activated the stress-responsive gene expression (Zhang et al., 2023). Also, Goyal et al. (2005) discovered 2 LEA proteins from wheat and nematode, that can inhibit protein denaturation under desiccating environments. Increased endogenous build-up of organic osmolytes through gene transfer from diverse species to transgenic plants is essential for raising drought resistance, as it provides better OA and safeguards macromolecules (Zhu et al., 2005). Additionally, transgenic wheat containing betA gene displayed reduced damage and exhibited longer roots along with growth improvement relative to wild types.

Genetic engineering approaches, i.e., clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR-related nuclease 9 (Cas9), have improved our knowledge and ability to modify plant genomes within drought condition. Accordingly, Park et al. (2022) utilized CRISPR/Cas9 approach for altering the gene related drought-triggered senescence protein (OsSAP) in rice. Collectively, genetic engineering and functional genomics offer innovative approaches to enhance plants' drought resistance, creating novel possibilities for sustainable agricultural practices in drought affected regions.

4.3. Agronomic practices

Plants utilize different agricultural practices to mitigate drought injury. Agricultural producers employ different methods to diminish water evaporation and surface runoff from soils, including mulching, biochar and crop rotations, conservation agriculture, rainwater harvesting and integrated crop–livestock systems (Sefaoglu and Ozer 2022; Ghadirnezhad Shiade et al., 2023; Ul-Allah and Farooq, 2023). Similarly, plant density, sowing dates, and nutrient management methods play a vital role in enhancing drought resistance (Ghadirnezhad Shiade et al., 2023). Furthermore, rhizobacteria can improve drought resistance through enhancing antioxidant system, activating drought stress-related gene expression, controlling transcription, and enhancing osmoregulation aptitude (Lephatsi et al., 2022). Recently, nanotechnology (nanopolymers, nanoclays, and nanosands) presented a promising approach for addressing drought resistance (Bisht et al. 2022; Al Masruri et al. 2023). The importance of externally-applied osmoreguulators, nutrient management, plant growth substances… etc in enhancing crops' drought tolerance is elaborated upon below.

4.3.1. Plant Growth Regulators

Utilization of phytohormones is applied to mitigate drought injury in different plants associated with enhancing growth, and productivity (Kamran et al., 2021). Phytohormones are crucial in altering the plant's response to stress with extremely low levels, and their chemical signaling features are generated in one plant organ and conveyed throughout the whole plant's organs.

Endogenous salicylic acid (SA) is substantially produced in drought affected plants, potentially reaching five times higher than the normal concentration in several plant tissues (Hamayun et al., 2021b). Also, their application boosts drought resilience and promotes plant growth and productivity (Miura and Tada, 2014). Commonly, SA supplementation positively controlled the ICS1 gene (isochorismate synthase) and improved drought resistance in *Arabidopsis*. Additionally, SA Application triggered WRKYs and TGAs gene expression, which subsequently boosted the plant's immune response to water deficit (Klingler et al., 2010). Additionally, SA application mitigated drought-induced oxidative bursts by boosting antioxidant capacity (Safari et al., 2021). Finally, SA promoted drought-affected *Portulaca oleracea* establishment and productivity by optimizing photosynthetic capacity and secondary metabolite production (Hamayun et al., 2021a).

Brassinosteroids (Brs) play a key role in stress responses and improve plant development and productivity under drought condition (Chen et al., 2017). It improves plant resilience to environmental stresses, via intricate pathways that control the plant defense strategies, by triggering the transcription factors of BZR1/BES1. Additionally their application regulates the production of reactive oxygen species in stress-affected plants and boosts stress tolerance (Tanveer et al., 2019).

4.3.2. Osmoprotectants

Osmoprotectants accumulate under stressful conditions to maintain the internal physio-biochemical pathways alongside survival under optimal conditions (Mandal et al., 2023). They serve an essential function in osmoregulation, preserving cell volume and mitigating drought injury, through enhancing water potential (Bhupenchandra et al., 2022). Additionally, they can influence signaling pathways related to stress response, potentially boosting stress tolerance even more. Osmoprotectants, often utilized for seed treatment or externally applied within plant growth stages, protect the microorganism, enhance antioxidant capacity, and facilitate osmotic adjustment capacity of drought-affected crops (Elkelish et al., 2020). Their effectiveness renders them an appealing substitute to chemical inputs in modern agriculture. Additional investigations are required to refine the application of osmoprotectants and to create novel formulations.

Pipecolic acid (Pip) is a non-protein heterocyclic amino acid that originates from lysine and is frequently present in several biota (Zabriskie and Jackson, 2000; Fletcher et al., 2001). It is assimilated from L-Lys through an aminotransferase AGD2-like defense response protein (ALD1) (Hartmann et al., 2018). Flavin-dependent monooxygenase (FMO1) functions as a pipecolate N-hydroxylase, facilitating the hydroxylation of Pip into N-hydroxypipecolic acid (NHP) (Hartmann et al., 2018). Hartmann et al. (2018) recorded that Pip plays a critical role in activating systemic acquired resistance (SAR). Additionally, Pip sets the stage for plants to effectively produce SA and coordinates SAR via both SA-dependent and SA-independent signaling pathways (Bernsdorff et al., 2016). Ubiquitous hormone SA has several functions under abiotic stresses, while its functions under abiotic stresses, particularly drought, are still mostly unknown. Datasets of gene expression profiling indicate that drought substantially alters the expression of ALD1 and FMO1 (Arruda and Barreto, 2020).

4.3.3. Nutrient

Numerous studies emphasize the possibility of using macro- and micro-nutrients in enhancing crop drought tolerance. Silicon (Si), the most prevalent element on the planet's surface, may serve as a mineral nutrient to enhance plant tolerance against various stresses and improve plant mechanical potency under normal or stressful environments (Yan et al., 2018). Additionally, Si supplementation has shown the ability to improve RWC (Hurtado et al., 2020). Furthermore, Si supplementation enhanced the rate of photosynthesis, stomatal conductance, and antioxidant capacity in comparison with non-treated plants (Ali et al., 2019). Therefore, Si applying to drought-affected crops can significantly contribute to maintaining root growth and facilitating water transport.

Selenium (Se) application induces the hyper-accumulation of compatible solutes in drought-affected plants (Ebeed et al., 2017). Their use can preserve biomembrane integrity and activate antioxidant capacity (Mostofa et al., 2020). Additionally, Se supplementation improves plant growth, diminishes oxidative burst, stimulates antioxidant capacity, and manages water balance to withstand drought conditions (Kaya et al., 2019).

4.3.4. Hydrogel: A Water Absorbing Polymer

Hydrogels have become a useful method for improving the soil's water-holding capacity, principally in drought-affected regions (Neethu et al., 2018). They enhance soil water accessibility, lessen loss from evaporation and percolation, and boost crop growth and productivity (Nnadi and Brave, 2011). Additionally, Satriani et al. (2018) discovered that watering at 70% of crop evapotranspiration with hydrogel supplementation optimized water productivity without negatively impacting bean yield. Moreover, Suresh et al. (2018) examined how tomato plants reacted to Superab A200 and recorded that their yield was boosted by 50% at 0.5% hydrogel over non-amended plants. Hydrogel application offers an innovative approach to reduce leaching of micronutrients and enhance water productivity; furthermore, it decreases fertilization requirements.

4.3.5. Nanoparticles

Nanotechnology has the potential to transform multiple features of agriculture, including soil cleanup and food packaging (Sefaoglu et al., 2025; Al-Khayri et al., 2023). Nanoparticles (NPs) can enhance agricultural productivity through bolstering plants' resilience to stressors and upregulating genes associated with cell differentiation (Al-Khayri et al., 2023). This can be achieved by stimulating several enzymes, boosting chlorophyll content along with photosynthesis activation, and managing plant diseases (El-Saadony et al., 2022). Also, nanoparticles can modulate defense strategy against oxidative stress by enhancing enzymatic and nonenzymatic antioxidant capacity (Djanaguiraman et al., 2018). Advanced research suggests that application of nanoparticles alleviates drought injury by reducing oxidative injury, while also enhancing the levels of organic osmolytes, which aid in osmotic adjustment under drought stress conditions (Van Nguyen et al., 2022). Additionally, NPs' capability to cross cellular barriers renders them appropriate for use in agriculture, including their function in enhancing resistance to abiotic stress (Shekhawat et al., 2021).

Several investigations noted that NPs supplementation causes different plant morpho-physiological adaptations associated with an enduring drought environment, such as improving water absorption, ROS detoxification, and stressful signaling (Kandhol et al., 2022). Likewise, zinc nanoparticle application on eggplant led to enhanced growth characteristics and productivity over nontreated well-watered plants (Semida et al., 2021). Zinc nanoparticles accelerate gene expression and hormone levels (ABA and cytokinins), which regulate cell division and root development, as well as help cope with drought stress (Ahmad et al., 2017). As per Bisht et al (2022), hematite nanoparticles decreased the concentrations of proline, nitrate, and ammonia by 22.4%, 25%, and 37%, respectively. Furthermore, within water deficit, the dual use of Chitosan-Coated Iron Oxide NPs and Kitoplus® growth stimulant enhanced mint plant oil yield (Giglou et al., 2022). Additionally, the use of Si-NPs on drought-affected pomegranate plants enhanced several trials, including nutrient status, photosynthetic capacity, osmolyte levels, and antioxidant enzyme activity (Zahedi et al., 2021). Additionally, Hassan et al. (2022) revealed that treating moderately stressed 'Kalamata' olive trees with nano-silicon (200 mg/l) enhanced their growth and productivity. In summary, employing NPs to lessen the drought injury on crop productivity has demonstrated promising findings in earlier research.

4.3.6. Biochar application

Biochar has emerged in roles in enhancing crop productivity in both normal and stressful circumstances (Moragues-Saitua et al., 2023). Biochar possesses significant functions in plants including improved cation exchange aptitude, increasing nutrient accessibility, carbon assimilation, and antioxidant activities, and boosting water productivity which consequently supports crop productivity within stressful environments (Wang et al., 2020). Biochar improves chlorophyll assimilation, promotes stomatal conductance, preserves cellular membrane integrity, and restricts the excessive reactive oxygen species generation, facilitating better crop productivity in drought conditions (Haider et al., 2020). Additionally, biochar improves soil physiological and biochemical characteristics, thus enhancing crop growth under drought (Agbna et al., 2017).

4.3.7. Elicitors or signaling molecules application

Significant attention has been given to nitric oxide (NO), following its identification as a widespread plant signaling molecule that functions as a new category of regulatory agents (Borhannuddin Bhuyan et al., 2020). It performs an essential role in many biochemical and developmental activities in plants within normal and stressful environments, such as regulating water balance, decreasing ion loss, and enhancing photosynthetic ability (Borhannuddin Bhuyan et al., 2020; Farouk and Al-Huqail, 2020). As a stable free radical, NO is crucial for neutralizing ROS and lessening oxidative stress (Sohag et al., 2020). Besides its roles in triggering transcriptional gene changes related to signal transduction (Ahmad et al., 2016). Additionally, NO enhances phytopharmaceuticals and secondary metabolites generation in medicinal herbs (Mohasseli and Sadeghi, 2019).

Chitosan (CHT) is a natural biodegradable substance that is non-toxic, and cost-effective, making it eco-friendly, with multiple applications in agriculture as a fertilizer to improve plant productivity under stressful conditions (Farouk et al. 2008, 2011). Comparable findings were identified in sweet pepper and radish (Farouk et al., 2011). Bittelli et al. (2001) noted that applying CHI reduced transpiration in pepper plants and lowered water usage by 26-43% along with sustaining biomass and productivity. The mechanisms by which CHI mitigates the negative impact of water deficit are not well comprehended, and limited studies are addressing this issue. The activation of gene transcription for PAL and protease inhibitors, prompted by CHI and jasmonic acid, suggests that CHI may influence jasmonic acid-related pathways (Doares et al., 1995).

Melatonin (MT), is a plant hormone historically recognized for its involvement in numerous plant functions, where it is crucial for enhancing growth, handling stress responses, and mitigating environmental stressors (Faizan et al., 2024). Consequently, plants riched in MT and their extracts offer a promising option for biostimulation in sustainable agriculture (Rehaman et al., 2021). MT spraying influences photosynthesis efficiency, nutrient equilibrium, and antioxidant capacity, and improves crop tolerance to abiotic stressors (Arnao and Hernández-Ruiz, 2015). Numerous investigations have demonstrated the beneficial impact of MT in enhancing plant drought resistance and highlighted its role as a powerful molecule in improving plant drought tolerance by affecting physio- anatomical characteristics (Cai et al., 2025). Wheat grain treated with MT enhanced germination, activates antioxidant enzyme, raises soluble protein and photosynthetic pigments, and boosts grain yield within water deficit (Li et al., 2025). In a similar manner, the spraying of MT on *Platycrater arguta* notably improved drought tolerance by preserving water status, improving photosynthesis pathway, and regulating gene expression to minimize cellular membrane dysfunction and oxidative burst (Zhang et al., 2025). Additionally, the simultaneous application of MT and Zn-NPs in strawberries significantly enhanced biomass, photosynthetic pigments, and enzymatic activities, emphasizing a possible integrated approach for addressing water scarcity (Anwar et al., 2025). Collectively, these findings highlight MT's varied functions in drought resistance, offering promising prospects for its broader application in sustainable agriculture

5. Conclusions and Future Outlook

Drought initiates a series of adaptive reactions in plants, allowing them to adjust their growth under harsh conditions. To mitigate the severe effects of drought, various strategies are utilized, including genetically engineered approaches associated with agricultural practice and agrochemicals. Advancements in breeding approaches and genome editing technologies presents promising opportunities for manipulating new genes, leading to sustainable strategies for improving drought tolerance. Recently further research is required for beter understanding of agrochemical usage in lessening drought injury.

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PART 2

GLOBAL CLIMATE CHANGE AND SALT STRESS EFFECTS ON PLANTS

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INTRODUCTION

Global warming is defined as the long-term climate change that occurs worldwide due to industrial development, human activities, and the increase in the greenhouse gas effect in the atmosphere (Masson-Delmotte et al., 2021). In this process, many human-induced factors such as the intensive use of fossil fuels with the industrial revolution, the rapid destruction of forests, the transformation of natural areas into industrial zones by concretizing them, the intensive use of chemical fertilizers and synthetic pesticides in agriculture have caused the global temperature to increase (Valentela, 2023). Global warming is one of the leading global disasters caused by climate change, with its consequences such as an increase in temperature and drought, melting of glaciers and rise in sea water level, increase in floods, storms, landslides, acidification of oceans, threat to living life, and serious damage to the ecosystem (Trenberth et al., 2014; Hansen and Sato, 2016; Steffen et al., 2018). It has been stated that the average surface temperature increase has been measured as 1.2 °C worldwide in recent years (Stocker et al., 2019).

The environmental and socio-economic impact of climate change on the world in recent years has begun to threaten countries, societies, regions, economies, and ecosystems (Cubuk, 2023). During this process, developing or underdeveloped countries are more vulnerable to the adverse effects of climate change than developed countries and face serious problems in critical areas such as food security, water resources, and biodiversity conservation (Thomas et al., 2004). As a matter of fact, to prevent climate change, which is the effect of global warming, it has become necessary to take urgent measures all over the world. For this purpose, many measures such as the use of renewable energies instead of fossil fuels, the introduction of policies to reduce carbon emissions by governments, sustainable agricultural policies, accelerating afforestation activities by stopping forest massacres should be put into effect (Canadell and Raupach, 2008).

Climate change due to global warming has become a serious threat to agricultural production, which is an area of human nutrition. Extreme temperature events, changes in precipitation regime, and increases in the frequency of climatic events due to global warming have caused serious changes in agricultural production activities and ecosystems (Fuglie et al., 2024). During this period, major changes in weather events have directly affected the growth and development processes of plants (Sefaoğlu et al., 2021), leading to an increase in environmentally induced plant stress factors. Environmental changes due to climate change often lead to stresses such as drought, temperature, and salinity, which negatively affect the physiological and biochemical processes of plants and cause serious yield losses (Munns and Tester, 2008; Gül, et al., 2023).

Plants need optimum environmental conditions for good development. Considering the flexibility of plant species in their metabolism, they continue their development against daily and seasonal changes throughout their life processes. However, plants continuously or partially exposed to adverse environmental events may cause damage or physiological changes in their development because they may negatively affect their developmental processes (Shao et al., 2008). The factors caused by these unfavorable conditions are called stress. Among abiotic stress factors, mineral stress (20%) is one of the stress factors that affect agricultural lands the most after drought stress (26%). Most of the mineral stress is caused by salt stress, with an average of 20% of the world's agricultural land (more than 9 million ha) and 20% of irrigated land (227 million ha) exposed to salinity (Pitman and Lauchli, 2002; Tuteja, 2007). In Turkey, barren areas constitute 2% of the surface area. In these barren areas, 74% (12 thousand ha on average) consists of saline soils (Kendirli et al., 2005). Salt stress causes osmotic pressure in the roots because it surrounds the root structure of the plant and makes it difficult for the roots to take water. Since this process causes ion imbalance, it causes toxicity in the roots and disrupts the cellular structure of the plant. The amount of salt formed in the root structure causes physiological drought in the plant because it causes a decrease in the available water intake with the external osmotic pressure it creates (Parida and Das, 2005; Tuteja, 2007). This results in inhibition of photosynthesis, slowing plant growth and ultimately plant death. Drought caused by global warming, reduced water resources and evaporation due to improperly timed irrigation increase salt accumulation in the soil, threatening agricultural sustainability in such landscapes (Rengasamy, 2010).

The adaptation mechanisms developed by plants against the adverse conditions caused by salt stress vary depending on the genetic structure, physiological structure and biochemical properties of plants (Flowers and Colmer, 2008). For example, halophytes, which are salt tolerant, show resistance to salt by maintaining ion homeostasis and synthesizing osmoprotectant compounds, while glycophyte plants, which are sensitive to salt, experience serious growth retardation and yield reductions in the face of salt (Gül et al., 2024; Munns et al., 2020).

Therefore, it is of great importance to develop plant species that are more resistant and tolerant to salt stress due to global warming and climate change and to adopt sustainable agricultural practices (Ashraf and Harris, 2004).

This review study aims to evaluate the physiological, biochemical and genetic effects of increasing salt stress on plants with global climate change and to evaluate the strategies and solutions that can be developed against these adverse effects.

1. GLOBAL CLIMATE CHANGE

Global warming is defined as the increase in the temperature of the atmosphere and the earth due to the rapid increase in greenhouse gases released into the atmosphere by human activity or natural means, such as the excessive use of fossil fuels with intensive industrialization, deforestation, increased urbanization (Kocaman, 2009). In short, global warming, which occurs in this way, can be defined as the increase in the earth's temperature, which seriously threatens the whole world and living things and causes environmental disasters and changes in nature (Ogut, 2008).

Climate is defined as the combination of the average characteristics of weather events observed over long periods of time in any part of the world, as well as the frequency of their occurrence, their distribution over time, their severity and all variables related to them (Turkes, 2008). Climate change, on the other hand, is defined as the change in the climate due to the increase in temperature caused directly or indirectly by humans on the earth in addition to these climate processes (Selcuk, 2009). Regardless of the cause of climate change, these changes are large-scale changes that develop slowly over a long period of time with significant local effects (Turkes, 1997). Global climate change, on the other hand, is defined as the rapid change in air movements in a short period of time due to global warming caused by some human activities and affected by other important climate factors such as precipitation and humidity (Yonten, 2007; Kurt et al., 2025).

Increasing temperatures due to global warming have started to be experienced in the 21st century, and it is seen in recent years that this temperature increase will lead to climate change in a short time (Albek, 2007). It is seen that global warming has increased continuously over the years, and this increase has increased by 0.5-0.8 °C since 1860. In the last 50 years, it is clear that these increases have reached irreversible points by showing their effect rapidly. If no measures are taken against increasing temperatures during this period, it is estimated that the global temperature will increase by 2 °C (Kadıoğlu and Dokumacı, 2005). These temperature increases also cause changes in other climate factors. The serious negative effects caused by the physical effects of global warming will bring about significant economic, sociological, psychological, and political impacts on the world.

Global climate change is defined as the long-term increase in temperatures and changes in climate factors due to the increase in the greenhouse gas effect of the Earth, due to natural events occurring on Earth, and some destruction caused by humans. The effect of global warming as a result of natural events occurring on Earth is almost negligible. However, especially with the beginning of the industrial revolution, the increase in the greenhouse gas effect caused by human beings has been the main reason for the rapid transformation of climate change, as it causes an increase in natural disasters due to destruction (Masson-Delmotte et al., 2021). One of the main causes of human-induced change is the intensive use of fossil fuels. With the industrial revolution, the industrial sectors intensively used fossil fuels such as oil, coal, and natural gas in the production phase, and greenhouse gases were released into the atmosphere at a rate that the Earth could not tolerate. This emitted greenhouse gas density is one of the important factors triggering the temperature increase in the world. The most important greenhouse gases emitted to the Earth are carbon dioxide (CO2), methane (CH4), and nitrogen oxides (NOx). Fossil fuels are among the gases that cause the highest greenhouse gas effect. While the temperature increase on the Earth due to global warming is 0.9 °C recently, the temperature increase in greenhouse gases from day to day is expected to reach 4 °C in 2060 (Sen, 2022). Another important factor is the deforestation of the world. Forests worldwide try to maintain the balance of the world by releasing oxygen into the atmosphere. Especially during the daytime, trees play an important role in maintaining the balance of the world by absorbing carbon dioxide from the atmosphere for photosynthesis and releasing nutrients, oxygen, and water into the environment. Our forests, which have such an important place, are destroyed by humans to encourage concretization by opening areas such as agriculture, animal husbandry, residential areas, and industry. Such seemingly insignificant forests are being slaughtered by hunters, and the decrease in forests increases the amount of CO2 in the atmosphere, leading to a significant increase in global warming. In addition, deforested areas become arid and cause desertification (Fuglie et al., 2024). Another important factor is that a number of activities carried out by the industrial and agricultural industry cause an increase in greenhouse gases. Especially industrial production facilities, energy and transportation activities emerge as an important factor. In addition, synthetic and chemical fertilizers and herbicides used in agricultural production activities, methane gas released into nature over time by animal feces in animal husbandry sectors will increase global warming and contribute greatly to climate change (Masson-Delmotte et al., 2021). Population growth and the resulting urbanization that has occurred in the world in recent years have put great pressure on energy consumption and natural resources. Population growth increases more destruction and greenhouse gas output to fulfill the demands of humanity. Especially with urbanization, natural resources will be destroyed and concrete formations will be increased, which will create heat islands in cities and cause temperatures to increase more (Cubuk, 2023). Although the human factor has a great impact on global warming, natural factors also contribute to the acceleration of this process. For example, important factors such as solar radiation, volcanic eruptions, and ocean currents can cause short-term fluctuations in climates around the world (Hoyt and Schatten, 1997). However, the long-term temperature differences caused by such naturally occurring factors are not seen as a cause of heat increase.

Biological diversity refers to the diversity and variability between the ecological environments in which living organisms are found. Ecosystem diversity refers to a dynamic whole in which plants, animals and microorganisms live together in communities and interact with structures such as soil, water, air and minerals (Cepel and Ergun, 2002). Biological diversity refers to a historical process that has occurred since the existence of the world and the emergence of living things, which includes genetic diversity, species diversity and ecosystem diversity. Ecosystems represent an important component of this process. Biodiversity and ecosystems constitute the whole of the functions that make up the life cycle of the world and contribute to the formation of ecological balance. Biodiversity and ecosystems ensure the continuity of the life process of humanity by restoring themselves in the face of the change of the world and ensuring the formation of a new balance. In recent centuries, biodiversity and ecosystems have lost their sustainability in the face of environmental and social degradation, reaching a level of damage unprecedented throughout history. The main reason for this slow and irreversible deterioration is global climate change caused by anthropogenic activities such as misuse of land, pollution of the environment and soils, and deforestation. These endless destruction activities destroy the structure and function of ecosystems and cause the natural biological balance to deteriorate. In the face of the change in ecosystems and biodiversity due to global climate change, some species disappear, some move to other habitats and some increase in population. With the change in natural biodiversity that occurs in this way, it disrupts the vitality in the ecosystem and leads humanity towards the compression of the food chain and an unknown natural ecological disaster in the future (Demir, 2009). Global climate change has a negative impact on ecosystems and biodiversity, affecting diversity in aquatic and terrestrial ecosystems in different ways. Since the global climate change occurring to day causes the earth to warm rapidly, it is estimated that the average temperature increase to day is 1 °C, and if measures are not taken immediately, this temperature may be around 3-

5 °C. This increase will be felt especially strongly at the poles and will seriously affect the species found there (such as polar bears, seals and walruses) and may lead to the restriction of their food chain and natural habitats and even their extinction (Edwards et al., 2001; Cepel and Ergun, 2002). With the change in climate change in the last 30 years, terrestrial ecosystems have started to under go a serious transformation. Increasing temperatures due to climate change will cause plant species to adapt or migrate to other ecosystems (Clarke, 2007). However, rare species that have the opportunity to grow at high altitudes will face extinction as they will not be able to migrate elsewhere. These results may become threatening by disrupting business areas such as medicine, food, raw materials, shelter, as areas of utilization of plants (Demir, 2009). For example, a decrease in precipitation may lead to an increase in forest fires, an increase in soil erosion events, a decrease in plant species richness in the Mediterranean region due to the inability to replace extinct species, while endemic species in Northern Europe may disappear and be replaced by invasive species (Bakkenes et al., 2002; Bakkenes et al., 2006).

2. SALT STRESS AND PLANTS

Plants face various biotic and abiotic stress factors throughout their life cycle. Since climate change due to global warming in recent years has brought drought, soil salinity in agricultural lands has increased excessively. Soil salinity is one of the most important abiotic stress factors that cause yield and quality loss in plants. Accumulation of soluble salts in soils occurs due to various reasons. Although the most important effects of this are known as climate and geological changes, the decrease in precipitation regimes due to global climate change, especially in arid or semi-arid regions, results in salt accumulation at high rates due to excessive evaporation in soils with poor drainage. In addition, the unconscious use of low-quality and salty water for irrigation brings about a serious salt problem in agricultural lands (Kiremit et al., 2017). These consequences affect more than 8 million ha (6% on average) of worldwide agricultural land (Yang and Guo, 2018). In calculating the salinity of soils, the electrical conductivity values of soil solutions are measured. In the calculations made to understand whether a soil is saline or not, the soil solution should be 40 mM (4 dS m^{-1}) and above. Since the high amount of salt in the soil prevents plants from taking water and minerals, plants are exposed to salt stress (Isayenkov, 2012; Acosta-Motos et al., 2017).

Salt stress is an abiotic stress factor that negatively affects the plant's metabolism in all growth and development processes from the first germination to harvest time. Salt stress is a process that affects the cells and organs of plants, in short, all levels of plants by creating osmotic stress, which reduces the amount of water and the amount of water that plants can use, and ionic stress, which causes ion levels to reach toxic levels (Muchate et al., 2016). Under high salt stress, oxidative stress occurs indirectly due to ionic and osmotic stresses that occur directly in plants. Osmotic stress, which begins these processes, occurs within a few hours or days, depending on the salt level, and prevents the plant from taking water and minerals. Root growth, cell development and elongation, leaf development and leaf number decrease in plants that cannot take water and minerals (Carillo et al., 2011). Since the plants grown in saline soils are exposed to high salt concentrations, the selective and permeable properties of the cell membranes in the plant roots are destroyed and the plant cannot take water and nutrients and nutrient deficiency problems occur. Dehydration and loss of turgor in the plant leads to the death of leaf separators and tissues (Isayenkov, 2012). The long-term term effects of water scarcity in plants, such as closure of leaf stomata and disruption of photosynthetic electron transport processes to impair carbon assimilation as a result of closure, are due to the oxidation of atmospheric (Na+) and chlorine (Cl-) ions in tissues exposed to high salt temperature (Muchate et al., 2016). The high influx of Na+ prevents the uptake of energies required for growth and development, causing many functions in the cell to be negatively affected, even leading to death. In addition, oxidative stress occurs in plants as salt stress leads to oxidative damage to various options such as proteins, lipids and nucleic acids (Singh et al., 2015).

Soil salinity is one of the major problems in the world. Every year, an average of 10 million hectares of land becomes unusable due to salinity (Kwiatowski, 1998). Due to global climate change in recent years, the drought problem has increased exponentially. Researchers have stated in their study results that an average of 40% of the world's agricultural lands are under the threat of salinity, approximately 20% of irrigated agricultural lands have salinity problems, and approximately half of the irrigated lands in the world face salinity problems (Serrano and Gaxiola, 1994; Akkuş Binici, 2005). Today, the effects of global warming are felt more clearly, and the profound climate changes indicate that agricultural areas are becoming more dangerous. Water scarcity and excessive evaporation resulting from increased drought due to climate change further accelerate the salinization of agricultural lands. Soil salinity is more common in arid and semiarid areas, especially in heavy soils where drainage is inadequate. Since excess water cannot be evacuated through irrigation in agricultural areas with drainage problems, the soil salinization problem occurs due to the evaporation of accumulated water. In addition to these problems, the soluble salts dissolve with water and are carried upwards through the soil, accumulating on the soil surface. In addition, irrigation with excessively saline water, incorrect irrigation practices, and inadequate drainage bring about these problems (Oster and Jayawardane, 1998). Salinity problems are usually encountered in arid and semiarid regions. The reasons for the problems in these regions can be said to be insufficient rainfall and excessive evaporation (Greenway and Munns, 1980). For years, human beings have been doing wrong things around the world, such as industrialization, deforestation, wrong agricultural practices, and fossil fuel use, and they continue to do so, causing global warming and climate change. As climate change causes arid and semiarid regions to cover larger areas, the number of regions rapidly approaching desertification has begun to be observed worldwide. This has generally led to the rapid desiccation of agricultural lands, the drying up of wetlands, and, in short, to water scarcity. The excessive use of scarce resources and water unsuitable for irrigation in agricultural areas due to drought causes the groundwater to rise with salty water in soils that do not have good drainage. The emergence of extreme temperatures and rapid evaporation of these waters with global warming causes an increase in salinity on soil surfaces (Hanson et al., 1999). According to the classification standardized by the US National Salinity Laboratory, the parameters that indicate whether the land is saline or not are pH, electrical conductivity

(EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) values (Odeh and Onus, 2008). According to this classification, soils are classified as non-salty, saline, saline-alkaline, and Sodic soils (Table 1) (Budak, 2012).

Table 1. Classification of saline soils (Staff, 1954)

Class	pH	EC (dS/m)	ESP (%)	SAR	Total Physical Special
Unsalty	< 8,5	< 4	< 15	< 13	Good
Salty	< 8,5	> 4	< 15	< 13	Good
Salty-Alkaline	< 8,5	> 4	> 15	> 13	Good
Sodik	> 8,5	< 4	> 15	> 13	Bad

In this way, when expressing the salinity rate of soils, the water-soluble salinity rates in the A and B horizontal layers, which are the first steps of the soil profile, are generally considered. As seen in Table 1, to express that a field soil is salty, the electrical conductivity of the saturation extract of the soil sample taken from the A and B horizontal layers must be greater than 4 dS/m.

2.1. Effects of Salt Stress on Plants

Salt stress has some negative effects on the growth and development processes of plants. Considering these processes, the first is the osmotic stress and the plant water relationship. Salinity caused by excessive Na+ and Cl- ions reduces the amount of water in the soil, causing the plant to enter hyperosmotic stress, disrupting the permeability of plant root membranes and thus preventing water uptake.

The decrease in osmotic potential has an important effect on the water content used in plant cell structure, leaf water potential by reducing leaf turgor, and plant growth rate by inhibiting plant cell division. The increase in salinity decreases both processes by showing a parallel relationship between plant osmotic potential and water potential in the face of salt stress. Osmotic stress caused by increased salt stress in the plant causes the closure of plant stomata, a decrease in CO2 diffusion, the disruption of the photosynthesis mechanism, and an increase in ROS (Shahzad et al., 2019).

Secondly, ion toxicity and nutrient imbalance come. Salt stress disrupts the plant's ion balance and slows its growth and development as it disables many life functions of the plant, such as photosynthesis and cell division (Hao et al., 2021). Soluble salts accumulated in the soil structure are taken up through the plant root system and accumulate in the tissues and organs, causing ion toxicity in the plant (Shahzad et al., 2019). The shoot parts of the plant, such as the leaves, are also sensitive, and the roots are transported to the Na+ and Cl- shoots by xylem and transpiration. Excessive sodium accumulation in leaves and shoots during this transport process leads to osmotic and metabolic problems and causes the aging of leaves by causing the death of leaf cells/tissues (Munns, 2005). Excessive accumulation of Cl in the leaves is indicated by chlorotic coloration, which can turn into necrotic lesions. In the face of this situation, the leaves begin to fade. Since the high Cl- density in the cytosol can disrupt chloroplast homeostasis, it can prevent the formation of photosynthesis and lead to a toxic structure (Geilfus, 2018). Salt ions accumulated in plants prevent the intake of mineral nutrients such as potassium (K), calcium (Ca), nitrogen (N), phosphorus (P), magnesium (Mg) that the plant needs, leading to nutrient deficiency in plants (Parihar et al., 2015). Sodium ions easily pass through the cell membrane, leading to toxicity. As a result of its toxicity, turgor pressure prevents potassium uptake, which is necessary for membrane activity, many enzyme activities. Depending on the salinity density and type, it can prevent the intake of most micronutrients necessary for the plant, as well as lead to serious decreases in its level (Parihar et al., 2015).

Thirdly, plant germination, early seedling development and growth are very sensitive to salt stress. Germination rate, germination speed, root and shoot length cause serious decreases under salt stress. The reason for the decreases is the combination of osmotic effect and ion toxicity (Ibrahim, 2016). The most important reasons why salt stress reduces plant growth and yield are that salinity slows down the growth of the plant by reducing the water intake capacity of the plant due to osmotic or lack of water in the plant. Secondly, salt ions entering from the plant roots are carried to the leaves, causing damage to the leaves. Damage to leaves inhibits plant growth by reducing photosynthesis (Munns and Tester, 2008). Salt stress causes a decrease in growth parameters such as plant height, leaf area and biomass accumulation (Saleh, 2012).

Fourthly, photosynthesis, chloroplasts and photosynthetic pigments are greatly affected by salt stress. The accumulation of salt ions in chloroplasts, which are the main center of photosynthesis, causes their photosynthetic activity to be negatively affected. Many components such as thylakoid membrane proteins, membrane lipids and various enzymes that are involved in photosynthesis in the chloroplast are negatively affected (Hameed et al., 2021). High salt ions cause a decrease in photosynthetic pigments such as chlorophyll and carotenoids. Since it disrupts the electron flow in the thylakoid membranes, which are the electron transport region in the chloroplast, it causes an increase in ROS such as hydroxyl radical (OH) and hydrogen peroxide (H_2O_2) by swelling the thylakoids. Due to damage to enzymes involved in starch degradation in chloroplasts, starch grains accumulate in the stroma. Since swelling occurs in chloroplasts due to osmotic imbalance between stroma and cytoplasm, salt stress causes deterioration in the outer membrane structure, disintegration of thylakoid membranes and grana and thylakoids in palisade and sponge parenchyma tissues (Bejaoui et al., 2016). Closure of stomata in the face of salt stress prevents diffusion of CO_2 from the external environment to the chloroplast, causing a decrease in photosynthesis rate.

Fifthly, salt stress has a great effect on oxidative stress, membrane damage and antioxidants. Since salt stress increases ROS that oxidize plant metabolism, it disrupts the balance between antioxidant defense systems and causes oxidative stress in plants. As a result of this process, cellular damage occurs, resulting in cell death (Shahzad et al., 2019; Hasanuzzaman et al., 2021). The formation of ROS (reactive oxygen species) under salt stress causes damage such as lipid peroxidation of cell membranes, nucleic acid (DNA and RNA) damage, protein denaturation, carbohydrate oxidation, pigment destruction, enzyme inhibition and cell death (Zhao et al., 2020). The increase in reactive oxygen species under salt stress disrupts the balance of the antioxidant defense system. As a result of the increase in reactive oxygen species, the redox homeostasis of the plant is regulated by providing an increase in antioxidants that provide detoxification (Paciolla et al., 2016). As a result, many studies prove that salinity stress causes an increase in changes in the enzyme activities of antioxidants (Ahmad et al., 2016).

2.2. Defense Mechanisms of Plants Against Salt Stress

The ability of plants to fulfill their growth and life cycles against high doses of soluble salts is called salt tolerance. The sensitivity of plants to high doses of salt tolerance varies according to their species, environment, and surroundings. Plants are divided into halophytes and glycopytes according to their resistance to salt stress. Halophytes (such as *Salicornia herbacea, Atriplex vericaria, Suaeda maritima*) are plants adapted to high salt concentrations and can survive under these conditions. Glycophytes (such as corn, onions, beans, and sunflowers) are salt-sensitive plants whose life cycles are terminated by high salt concentrations.

2.3. Ion Regulation and Compartmentalization

Maintaining ion balance in plants under salt stress is essential for their survival. The salinity problem in plants is attributed to secondary stresses such as ion stress, osmotic stress, oxidative stress, and nutritional imbalance. Under high salt stress, plants store excess salt in vacuoles in their cytoplasm to maintain their life functions (Turkan and Demiral, 2009; Parida and Das, 2005). Considering the regulatory role of SOS (salt hypersensitive) genes against salt stress, the SOS signaling pathway provides Na+ and K+ ion balance. The SOS signaling pathway stimulates cytoplasmic Ca2+ signaling by excessive intracellular or extracellular salt ions. By activating SOS1, ion balance and salt tolerance are balanced (Yokoi et al., 2002; Sairam and Tyagi, 2004).

3.2.2. Biosynthesis of Osmolytes (Compatible Solutes)

Osmolite balance is required to maintain cellular structure under salt stress. Sugars, organic acids, polyols, soluble proteins, and nitrogenous compounds in plants constitute the main osmolytes (Munns, 2005). The main task of osmolytes is to protect the macromolecules in dehydrated cells by maintaining turgor. Osmolytes stabilize the structures of membranes and macromolecules by balancing the potential of increased osmotic pressure (Smirnoff, 1998; Holmberg and Bulow, 1998). The most important functions of sugars such as glucose, fructose, and sucrose that accumulate in plants under salt stress are osmotic protection, stabilization, carbon storage, and elimination of oxygen radicals (Parida and Das, 2005). Nitrogen-containing compounds generally accumulate in response to salt stress. Their main functions are osmotic stabilization, protection of cellular macromolecules, nitrogen storage, maintenance of cellular pH, cell detoxification, and removal of free radicals (Ashraf and Harris, 2004).

3.2.3. Activity of Antioxidative Enzymes

The osmotic pressure that occurs with salt stress causes water deficiency in plants and leads to the formation of some ROS (Parida and Das, 2005). During this process, plants utilize various antioxidant and antioxidative enzymes to maintain their life cycle (Chinnusamy et al., 2005). In a study, which is a good example of global warming and climate change, it was reported that SOD, APX, CAT and APX, GPX and GR increased in wheat genotypes exposed to salt stress under drought and high temperature, while SOD and CAT activities increased in fixed GR roots compared to the control (Sairam and Tyagi, 2004).

3.2.4. Induction of Plant Hormones

Plants generally accumulate hormonal synthesis of abscisic acid (ABA) under salinity, drought, and frost stress (Borsani et al., 2003). Abscisic acid hormone activates various genes in response to salt stress. Abscisic acid hormone minimizes the inhibition of functions such as photosynthesis, assimilation, growth, and development that occur in the developmental processes of plants against salt stress. It is also an abscisic acid hormone that slows down the ion flow in the cell structures of stomata to prevent water loss through transpiration in the leaves in the face of salt stress and ensures the closure of stomata (Parida and Das, 2005; Bressan, 2008). ABA regulates K+ uptake and accumulation in plant roots and Ca2+ accumulation in the cytoplasm, which is necessary for ion balance (Borsani et al., 2003).

3.2.5. Changes in Gene Expression Induced by Salinity in Plants

Plants cause some changes in gene expression in the face of salt stress. Plants produce the necessary proteins by activating the necessary genes according to the abiotic stress factors. For example, warmth-giving proteins called chaperones and late embryogenesis proteins are proteins that are triggered by plants in case of temperature, salinity and water deficiency (Sairam and Tyagi, 2004). Late embryogenesis abundance (LEA) proteins have been characterized in seed embryos and have protective properties (Holmberg and Bulow, 1998). LEA proteins belong to the group of proteins promoted by ABA. These proteins are located in the stasis and protect cellular structures in case of stress. Under stress conditions, LEA proteins have important factors in protecting structures and components such as cellular membranes, proteins, enzymes by retaining useful water and providing water that the plant cannot take under salt stress (Yildiz et al., 2010). Chaperones show an important function in the synthesis, processing and degradation of proteins. Especially in case of significant stresses experienced by plants, they help proteins to refold (Wang et al., 2003; Sairam and Tyagi, 2004).

3.2.6. Signal Transduction during Drought and Salinity

It is obvious that there are many pathways of signal transduction systems that influence the regulation of genes on a cellular basis. The best known signal transduction pathway component is ABA (Sairam and Tyagi, 2004). In plants, the stress event is first detected by sensors in the cell membranes, then converted into other signaling responses and terminated by second messengers such as calcium, ROS and inositol phosphate. These alter the intracellular calcium level. The change in cytoplasmic Ca_2+ is detected by sensors. Such stress genes lead the plant to adapt to the stress environment and survive. In addition, different molecules such as ABA, salicylic acid and ethylene are produced depending on the stress (Mahajan and Tuteja, 2005). Genes that emerge in response to water or salt stress are expressed as early response genes and delayed response genes. Early response genes are transiently activated within minutes without the need for new protein synthesis since all signaling components are present. Delayed response genes are activated more slowly by stress because they constitute most of the salt-sensitive genes (Kalefetoğlu and Ekmekci, 2005; Kaur and Gupta, 2005).

3.2.6. Role of Transcription Factors in Stress Tolerance in Plants

Stress-induced gene products are divided into two groups according to their function.

- **Functional Proteins:** Membrane proteins that maintain the movement of water in membranes are enzymes involved in osmolyte biosynthesis, detoxification enzymes and other proteins involved in the protection of macromolecules.
- **Regulatory Proteins:** Transcription factors are protein kinases and proteases and are essential for the regulation of gene expression and signal transduction (Agarwal et al., 2006). Transcription factors function in ABA-dependent or ABA-independent regulatory pathways (Wang et al., 2003; Agarwal et al., 2006). DELLA, another nuclear protein, has emerged as an effective factor against most stress signals necessary for regulating plant growth against salt stress (Agarwal et al., 2006).

4. PLANT RESISTANCE STRATEGIES AGAINST SALT STRESS

Climate change, which has manifested itself more and more in recent years, brings drought and thirst. Excessive salt accumulation, which increases in agricultural areas due to thirst, causes plant salt stress. During this process, plants try to continue their life processes by developing physiological, biochemical, and genetic mechanisms to protect themselves against salt stress. The survival strategies developed by plants against abiotic stress factors are being further enhanced by biotechnology and agricultural applications.

4.1. Genetic Reclamation and Development of Resistant Species

Global climate change and increasing soil salinity seriously threaten agricultural production. To cope with salt stress, traditional reclamation methods and modern biotechnology methods should be used to develop salt-tolerant plants. In this way, by increasing the resistance of plants to salt stress, it is likely that sustainable agricultural systems will be maintained (Munns and Tester, 2008; Negrão et al., 2017

4.1.1. Traditional Genetic Reclamation Methods

The traditional methods of genetic reclamation include selecting salt-tolerant species and developing salt-tolerant varieties by crossbreeding.

- **Selective Reclamation:** The most salt-tolerant species among plant populations are selected and included in hybridization programs. For example, since some wild rice species are more resistant to salt stress than cultivated ones, these wild species are evaluated in genetic reclamation programs (Flowers and Colmer, 2008).
- **Mutation Reclamation:** Individuals resistant to salt stress are identified by random mutations using chemical mutagens such as ethyl methane or radiation. For example, thanks to these methods applied in barley varieties, varieties resistant to high salt stress have been obtained (Mickelbart et al., 2015; Jha et al., 2019).

Although traditional breeding methods require a long time to find suitable varieties, they are important for conserving genetic resources and ensuring sustainability in the agricultural sector.

4.1.2. Molecular Reclamation and Marker Assisted Selection (MAS)

In the molecular reclamation method, the aim is to determine the genetic markers that will enable the identification of species that are more resistant to salt stress and to evaluate them in plant breeding studies. This method gives faster and more precise results than the classical selection method.

- **The Use of Molecular Markers:** Quantitative trait loci (QTL) mapping is a method for identifying salt-tolerant gene regions. For example, the "saltol locus" in rice is one of the important gene regions showing resistance to salt stress (Thomson et al., 2010).
- **Genomic Selection:** Next-generation sequencing (NGS) technology enables the rapid identification of genes that can withstand salt stress. For example, salt stress-tolerant genes have been identified in wheat and maize using this technology (Varshney et al., 2014).

4.1.3. Genetic Engineering and Gene Editing with CRISPR/Cas9

One of the studies in the field of genetic engineering, direct intervention in the genome of plants, has made them more resistant to salt stress (Zhang et al., 2020). This field provides a great opportunity to develop efficient breeding programs quickly by providing gene editing, specific and controlled changes.

- **Transgenic Approaches:** In this method, the genes that provide salt tolerance are taken from halophyte (saline) plants and transferred to the plants that need to be salt-tolerant. In this way, the salt tolerance of plants is increased. Overexpression of the OsHKT1;5 gene in rice increases the plant's resistance to salt stress by regulating Na^+ transport in roots (Ren et al., 2005).

- **CRISPR/Cas9 and Gene Editing:** CRISPR/Cas9 technology makes plants more resistant to salt stress by making targeted mutations in specific gene regions (Zhang and Showalter, 2020). For example, new variants against abiotic stress were obtained due to editing the OsRR22 gene in rice with CRISPR/Cas9.

4.1.4. Salt-Tolerant Plant Species and Agricultural Utilization

Some plant species are more salt tolerant, and these traits are being utilized in agriculture. Genetic breeding and biotechnological approaches are being developed to increase the use of such species in agricultural areas.

- **Halophytes:** The quinoa plant is highly resistant to salt. Thanks to this feature, it can be easily cultivated in saline soils (Hariadi et al., 2011). Salt tolerant genes obtained from such plants can be transferred to model plants.
- **Salt Tolerant Genetic Variants:** Among wheat varieties, Triticum turgidum ssp. is salt tolerant and widely used in genetic breeding programs (James et al., 2012).

4.2. Agricultural Management and Irrigation Techniques

Drought and water scarcity due to global climate change brings along soil salinity. The low yield in agricultural production due to salinity has become a serious threat to global food production.

Developing agricultural management strategies and irrigation techniques against salt stress due to global climate change is of great importance to increase resilient crops and agricultural productivity (Munns and Tester, 2008). The use of efficient water use methods under drought and water scarcity conditions is very important in terms of reducing soil salinity and using water more efficiently (Qadir et al., 2014).

4.2.1. Management of Saline Soils and Soil Improvement Techniques

The management of salinity in soils due to global climate change includes various chemical, biological and mechanical applications in order to minimize the salinity in soils and increase plant growth and yield.

4.2.1.1. Soil washing and drainage systems

The extreme temperature due to global climate change causes the limited amount of water on the soil surface to evaporate rapidly, causing salt accumulation in the upper layers of the soil. In such cases, in order to remove the salt accumulation on the soil surface, irrigation with a little more fresh water than the plant needs, which we call washing, is expressed as the process of transporting the salt accumulated in the soil to the deep layers (Shahid et al., 2018). Another important issue is to use effective drainage systems. The drainage system is the process of removing the salty water accumulated in the plant root zone without toxic effects. Thanks to the system, which is usually installed two meters deep in the soil, it is of great importance in discharging the salty water formed as a result of the salt accumulated on the soil surface being transmitted to the soil depths with excess irrigation (Qadir et al., 2014). For example, in rehabilitation projects to improve saline soils in agricultural lands in India and Pakistan, 40% efficiency in agricultural production was achieved by using washing and drainage systems together (Rengasamy, 2010).

4.2.1.2. Use of Organic Fertilizers and Biofertilizers

It is very important to use organic fertilizers to improve agricultural lands. It is especially important to introduce renewable energies to minimize the greenhouse gas effect that causes global climate change. The addition of valuable inputs such as animal manure, plant residues, green manures in agricultural production to the soil structure in the form of compost, fermented or as it is, improves the soil structure, enriches the organic matter content of the soil, and increases the solubility of salts in the soil (Tejada et al., 2006). Rhizobacteria and mycorrhizal fungi, which provide the acquisition and easy uptake of nitrogen fertilizers necessary for plant growth, support root development and allow plants to grow comfortably in saline environment (Nadeem et al., 2020).

4.2.2. Irrigation Techniques and Water Management

Due to global climate change, irrigation methods need to be optimized both to solve the problem of salinization in agricultural areas and to save water.

With the global climate change that has made itself felt more in recent years, drip irrigation systems, which are the most economical irrigation system, come to the fore. Drip irrigation systems are one of the most effective methods to prevent excessive water loss and salinization that may occur in the root zone of the plant by giving water only to the root zone of the plant according to the water requirement. For example, in studies carried out in saline soils in Israel, it was stated that drip irrigation method used water efficiently and increased yield in saline soils (Yermiyahu et al., 2007). The use of such irrigation systems integrated with today's technologies brings great success. As a matter of fact, the integrated use of soil moisture sensors and artificial intelligence-supported devices with irrigation systems ensures optimum water use despite the water scarcity experienced in recent years, increasing yields in saline soils and preventing the formation of saline soils (Sikka et al., 2018). The second irrigation method, sprinkler irrigation, is one of the most effective irrigation methods, especially against drip irrigation methods. In principle, as the name suggests, plants benefit from the water given in the form of rain droplets to the maximum extent. In addition, the salt accumulated on the salty soil surface is washed away by the sprinkler system and salt accumulation on the soil surface is prevented (Zaman et al., 2018). Another important and somewhat costly system is underground irrigation systems. In these systems, the water needed by the plant is given directly to the root system of the plant under the soil and the water needs of the plant are met at all times. Since these systems irrigate certain areas as much as the plant needs, they also prevent the salinization of the soil and prevent the plant from entering salt stress.

In areas where saline water is used for irrigation, saline water with a certain salt concentration can be used alternately with fresh water to increase the salt tolerance of plants (Grattan and Grieve, 1998). It has been reported that there is no yield loss in cotton plants when a certain level of saline water and fresh water is irrigated alternately and such an application can be made (Sharma and Minhas, 2005).

4.2.3. Selection of Salt Tolerant Plants

Drought caused by global warming and the desertification of agricultural lands have brought the selection of salt tolerant plants to the forefront. In this process, in addition to the selection of species resistant to salt stress, it is necessary to develop new salt-tolerant species by using these characteristics of the species for the development of salt tolerant plant varieties.

High yields can be obtained by encouraging the cultivation of salt-tolerant barley and some wheat species (*Triticum aestivum*) in saline soils in cereals, one of the main food sources (Munns et al., 2020). Quinoa, which can be an alternative to these, has increased its cultivation in Latin America, Asia, and Africa due to its high salt tolerance (Hariadi et al., 2011). Another important factor is that plant species such as Atriplex spp. and Distichlis spp., which have high salt tolerance and can grow in saline soils, can be grown to provide the grass necessary to meet the nutritional needs of animals in animal husbandry.

Thanks to these measures, it offers a sustainable solution to the threat of global climate change and salinization of soils, which has become increasingly severe in recent years.

5. CONCLUSION AND RECOMMENDATIONS

Global climate change, which has shown its impact in recent years, and the consequent excessive salinization of agricultural lands are among the leading environmental stress factors that threaten agricultural production and ecosystems worldwide. Many important events such as the increase in temperatures on earth due to global warming, irregularity of precipitation regimes, melting of the poles due to temperature increase and unexpected rises in sea level and climate change cause rapid salinization of agricultural areas in the world, making the growing conditions of plants difficult due to their salt sensitivity. Especially coastal areas and arid and semi-arid areas where most of the agricultural production takes place are more vulnerable to salinity events.

Plants respond to the salt stress that occurs in the world due to global warming through various physiological, biochemical and genetic systems. However, in cultivated plants that are sensitive to excessive salinity, salt stress causes ion imbalance, increased osmotic stress, inhibition of nutrient uptake by the roots of plants and disruption of cell metabolism, resulting in a significant decrease in growth, development and yield levels. Excess salinity causes major yield losses, especially in staple crops such as cereals, vegetables and legumes. Different strategies have been developed to help plants cope with salt stress. Genetic reclamation and biotechnological approaches have been developed to develop salt stress tolerant plants. In addition, salinity problem can be eliminated by optimizing water use and effective irrigation methods.

In the future, in the fight against climate change due to global warming, it is necessary to turn to sustainable agricultural systems, to spread plant varieties tolerant to climate irregularity and salt stress, and to use irrigation systems that can use water resources more economically against water scarcity. In this context, it is necessary to identify and disseminate species resistant to salt stress and include them in genetic reclamation programs. With gene editing technologies such as CRISPR/Cas9, genes resistant to salt stress should be revealed and integrated into other plants. Local and endemic plant species resistant to salt stress should be supported for the continuity of genetics. Irrigation systems resistant to saline water, such as drip irrigation, should be developed to reduce salt accumulation. The use of organic fertilizers and fertilization methods should be encouraged instead of chemical fertilizers to prevent excessive salinization of the soil. The resistance of plants to salt stress should be increased by using beneficial microorganisms such as rhizobacteria and mycorrhizal fungi. Sustainable agricultural policies to reduce carbon footprint should be supported to combat global warming. Water management and soil conservation strategies should be developed by integrating agricultural and environmental policies on a global scale. Farmers should be trained on agricultural management and methods of combating salt stress. Universities, research organizations, and the private sector should develop new solutions to salt stress separately or in cooperation. Resistant systems against abiotic stress factors in agricultural production can be created by considering gene editing and new agricultural technologies in biotechnological applications. To effectively use the solution proposals that need to be addressed in the fight against salt stress, multidisciplinary research should be carried out more, and the development of the agricultural policies of the state in this direction will be of great importance in creating more efficient and resilient agricultural ecosystems in the future.

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PART 3

MOLECULAR PRIMING BY A BIOSTIMULANT DERIVED FROM *ASCOPHYLLUM NODOSUM* MITIGATES DROUGHT STRESS IN VEGETABLE CROPS

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ABSTRACT

With the ever-widening consequences of the climatic changes, the question of the detrimental effects of abiotic stresses and their negative influence on the agricultural crops' yield and hence food supply security becomes even more important. Of all abiotic factors, a major role in crop yield loss is occupied by the lack of accessible water. Therefore, worldwide efforts are devoted to devising various strategies for overcoming drought consequences by addressing its limitations and mitigating its effects. One such strategy is treating the crops with the renowned biostimulants of recent years, representing biological extracts from sustainably harvested natural products. An example of such a biostimulant is the commercially available SuperFifty Prime (SFP), a metabolic enhancer known to have growth-stimulating and stress-relieving properties. In this study, SFP was used to treat three important crop cultures, consequently subjected to drought stress, and several properties related to their yield were examined. We are supplying proofs that Wilting status, RWC, Fruit set, Fruit harvest, and yield are significantly rescued by SFP during drought stress, and even their values are improved in some cases.

Keywords: Molecular priming, *Ascophyllum nodosum*, Abiotic stress, Water Deficit.

INTRODUCTION

Abiotic stresses like drought, extreme temperatures, salinity, and pollutants (industrial chemicals) are major limiting factors in agriculture and cause damage to crop plants (Gul et al., 2024). Importantly, it affects plant growth, overall yield, and quality of marketable product (He et al., 2018). Among these limiting factors, drought is posing a global threat to food productivity due to climate change. Crops are more prone to drought stress due to the effect of species homogeneity and can suffer up to 48% reduction in their productivity (as reviewed by Cohen et al., 2021; Alqudah et al., 2011).

Drought stress severely affects plant physiology and morphology. At the cellular level, the metabolic changes induced by drought can lead to adverse impacts on cell division, cell elongation, and cell turgor pressure. It can also hinder photosynthesis, inducing reactive oxygen species (ROS) (Gupta et al., 2020; Kerchev et al., 2020). Over the years, a number of approaches have been suggested to alleviate the effects of drought on plants (Dinler et al., 2024). However, continuous efforts are still needed to develop sustainable crop improvement strategies. Drought can severely affect the transition from flower to fruit, fruit development, marketable grade, and yield in vegetable crops. Biostimulants are widely used in crop yield improvement due to the fact that they act as plant growth regulator and/or as fertilizers. These can be organic/inorganic products containing bioactive ingredients and may include microorganisms.

Biostimulants can fine-tune plants’ response to available resources and to stresses while preserving their yield potential (Bulgari et al., 2019;

Rouphael and Colla, 2019). Inexpensive organic biodegradable biostimulants have gained much popularity due to their priming effect on plants for an upcoming stress and also increase root and shoot growth, increase yield, and improve fruit quality and shelf-life in case of vegetable and fruit crops (Kerchev et al., 2020). Biostimulants derived from seaweed like *Ascophyllum nodosum* have also been used extensively in crop health and their yield improvement because of their proven priming ability in model and different crop plants (Goñi et al., 2018; Shukla et al., 2018). Biostimulant-based molecular priming may induce stress mitigation mechanisms in crops. The attributed benefits and potential of these biostimulants, particularly those derived from *Ascophyllum nodosum* seaweed extracts, have been described in several studies. Additionally, they enhance plant response to oxidative and drought stress (Omidbakhshfard *et al*., 2020; Rasul *et al*., 2021; Staykov *et al*., 2021).

In the current study, an extensive trial was performed using three crop species (tomato, pepper, and eggplant) to assess the response of plants pre-treated with SuperFifty Prime (SFP) before drought stress at the fruiting stage.

1. MATERIALS AND METHODS

1.1. Plant material, growth conditions, and treatments

Seeds of commercial varieties of Tomato (cv. Salzitsa), Pepper (cv. Amaretta F_1), and Eggplant (cv. Black Pearl) were germinated on peat moss in seedling trays under standard greenhouse conditions. Upon germination, seedlings were transplanted to soil pots (12 L) using a mix of potting/compost soil and Perlite. Plants were randomized (randomized plot design with three replicates/treatment) in the greenhouse trial area (145 m^2). Growing conditions were kept at 22-25 ºC, 50-60% relative humidity. The light intensity of 15-18 lux with day length (natural) of ~14 hrs was maintained during the growing season. SFP was applied by foliar application on leaves at a concentration of 0.4 (v/v) using an automatic knapsack sprayer with a nozzle at a delivery rate of 1 L/min. SFP was applied by spraying from the top, from a 20 cm distance, and care was taken to ensure that a fine mist of spray covered the whole leaves to avoid foliage overdose. The first biostimulant application was performed at the early fruit initiation stage when the fruit-to-flower ratio reached more than 50% for all three crops. Plants were regularly watered using a drip irrigation system (drip flow rate of 2 liters of water/hole/hour). Two days after the SFP application, plants were exposed to drought stress by stopping irrigation for 18 days at ~20% soil capacity. Later, irrigation was continued as normal for both control and stressed plants. Leaf and fruit samples were collected for relative water content from all biological replicates. Since the crop varieties selected were indeterminate (with multiple harvests), second and third applications of biostimulant SFP were performed at three-week intervals, and data were recorded for yield parameters.

1.2. Sampling and data collection

Relative water content of the leaves was determined multiple times to set up a critical time point, where primed plants showed considerably superior drought-tolerant phenotype compared to unprimed control plants. For RWC, leaf fresh weight, turgid leaf weight, and dry weight were calculated according to the method as described (Hummel *et al*., 2010), and finally, RWC was calculated.

Data for yield parameters such as Fruit Set, average Fruit Weight, and harvest Yield were recorded. Total fruit number and fruit weight from each individual plant were recorded, and final values were expressed as mean across all three biological replicates.

1.3. Statistical analysis

Comparison of mean values of treatment groups with the control and among each other was performed using GraphPad Prism 10.0 (GraphPad Software, San Diego, CA, USA; www.graphpad.com) by means of One-Way ANOVA, followed by Unpaired t-test with Welch's correction for multiple comparisons.

2. RESULTS

Tomato, Eggplant, and Pepper plants treated with SFP at a concentration of 0.4% (v/v) showed better tolerance to drought than untreated (i.e., unprimed) control plants. Unprimed control plants (droughted plants sprayed with water) showed clear visual symptoms of leaf wilting and, in severe cases, associated with it, damages, as shown in Figure 1, for Tomato, Pepper, and Eggplant. Results from physiological assays, such as relative water content (RWC, %), demonstrated that under drought conditions, unprimed control plants showed a severe reduction in RWC. This effect was mitigated by SFP priming in the experimental group of plants (Fig. 2). SFP-treated plants were able to retain significantly higher water content under drought in all three crop species. Lack of water typically inhibits plant growth and severely affects the crops at the fruiting stages. Notably, the transition stage from flowering to fruiting in vegetable crop plants such as Tomato and Pepper is highly sensitive to extreme environmental conditions such as drought (Petrović et al., 2019).

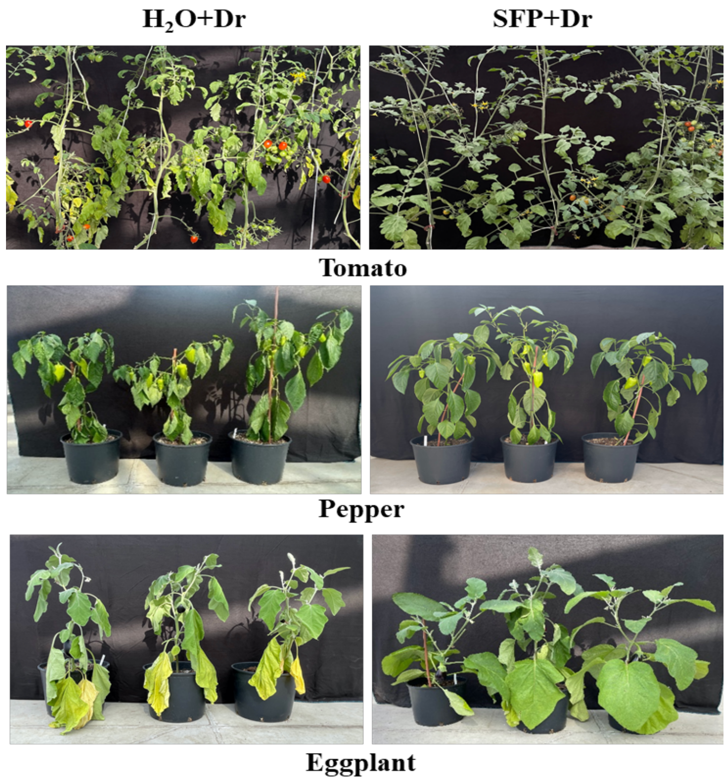

Figure 1: Phenotypical comparison of the effect of the algal biostimulant SuperFifty Prime (SFP) on drought-stressed vegetable plants.

Note: Phenotypes of Tomato, Pepper, and Eggplant representative plants under drought conditions in the presence and absence of SFP priming. Note the clear and more severe leaf wilting and stress-induced senescence symptoms in unprimed control plants compared to plants primed with SFP. Images were taken on day 18 of water deficit (no irrigation), and for each plant species, representative plants were taken for images.

As an indicator of water status in terms of the physiological consequence of cellular water deficit condition, relative water content (% RWC) was measured on day 18 of irrigation withholding. RWC was significantly reduced in the control plants, not pre-treated with SFP and exposed to drought stress (H2O+Dr) (Fig. 2). This correlates with phenotypic data where unprimed control plants showed the severe effect of drought on leaves (Fig. 1). This effect was mitigated by SFP priming in treated plants. Notably, RWC (%) was maintained to a significantly higher level in SFP primed plants under drought, compared to unprimed control treatment (i.e., H2O+Dr), as shown in Figure 2 in all three vegetable crop species.

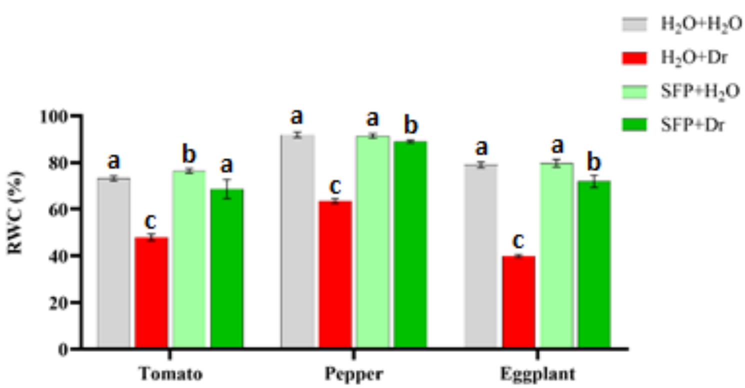

Figure 2: Protective effect of SFP over water retention during drought stress in three vegetable crops.

Note: Relative water content (RWC) as a measure of stress response in SFP-treated and control plant leaves under water deficit. SFP-primed and stressed plants were able to maintain considerably higher RWC compared to unprimed controls. Different letters indicate significant differences among the treatment means ($p < 0.05$). Error bars denote standard error of the mean (SEM). The mean values are expressed as an average across three biological replicates ($n = 3$) and were analyzed by One-Way ANOVA, corrected for multiple comparisons (GraphPad Prism 10).

Trial results of investigating the effect of SFP under water deficit conditions showed that foliar application of SFP helps the plants withstand drought, without adversely affecting the growth and fruit set. Our results in Tomato, Pepper, and Eggplant demonstrate that under normal conditions, SFP treatment significantly increased fruit set in Tomato (Table 1). However, in Pepper and Eggplant, only a trend for fruit set increase was observed. Under drought stress conditions, in all three crop species (Tomato, Pepper, Eggplant), the fruit set was not affected by the stress. However, a significant reduction in marketable fruit number was observed in the case of Tomatoes. Also, average fruit weight per plant was affected by drought in Pepper and Eggplant. Notably, SFP treatments were able to mitigate the above-mentioned stress impact (Table 1).

SFP priming by foliar application before the onset of drought and subsequent post-drought treatments (twice at three-week intervals) during fruiting helped the plants with stress prevention and/or stress recovery. The SFP sprayed plants (both unstressed and stressed) showed considerable improvement in fruit-set, fruit weight, and average yield per plant under normal greenhouse conditions and under drought (Table 1).

The treated plants (i.e., SFP-primed) were able to maintain fruit set and showed considerably higher fruit yield, which in turn results in better total yield across all three crop species (Table 1). Total yield was significantly reduced by drought in all crops (Tomato, Pepper, and Eggplant). Timely and critical applications of SFP (3 applications) at an interval of ~15 days during the fruit set period in all plant species resulted in drought stress mitigation and significantly improved the intrinsic yield potential in crops.

Table 1: Yield properties across all three vegetable crops and treatment blocks.

Crop	Control (H_2O+H_2O)	Drought (Dr)	SuperFifty (SFP +H_2O)	SuperFifty + Drought (SFP+Dr)
Fruit Set				
Tomato	25.05^{a}	24.71^{a}	31.76^{b}	32.19^{b}
Pepper	5.46^{ab}	5.15^{a}	6.10^{c}	5.83^{bc}
Eggplant	1.86^{a}	1.86^{a}	2.05^{a}	1.90^{a}
Fruit Harvest (g of marketable fruit/per plant)				
Tomato	136.63^{a}	99.77^{b}	162.80^{a}	141.63^{a}
Pepper	343.50^{a}	262.07^{b}	347.08^{a}	318.50^{a}
Eggplant	547.84^{a}	354.59^{c}	557.67^{a}	446.94^{b}
Yield (tonnes/ hectare)				
Tomato	9.83^{ac}	7.81^{c}	12.30^{b}	10.82^{ab}
Pepper	20.61^{a}	15.58^{b}	20.82^{a}	19.11^{a}
Eggplant	16.44^{ab}	10.64^{c}	16.73^{a}	13.41^{b}

Note: Values presented in the table are averages of three biological replicates. Mean values were compared between groups by applying one-way ANOVA followed by Fisher's LSD post hoc test. Treatment sharing the same letters indicates nonsignificant differences, while treatments with different letters indicate significant differences ($p < 0.05$; GraphPad Prism 10).

3. DISCUSSION

SuperFifty Prime is a biostimulant, extracted with high temperature treatment (greater than 125°C) from the brown intertidal alga of the north Atlantic region *Ascophyllum nodosum*. It is highly concentrated (500g/L) and is rich in antioxidants and polyphenols (Guinan et al., 2012). It contains a bouquet of various organic compounds, such as mannitol and sorbitol (osmoprotectants and ROS scavengers) (DiStasio et al., 2018), phlorotannins and fucoidans (possessing antioxidant properties) (Shukla *et al.*, 2019), and others, which may be involved in diverse signaling pathways in plants (Omidbakhshfard *et al*, 2020; Ghaderiardakani *et al*., 2019). From a practical point of view, SFP is known to positively influence plant growth and development of a large variety of plant species, most of which are important crops, and to improve their fruit quality, yield, root growth, fruit size and number, fruit set, and other important agricultural features. (Kazakov *et al*, 2024; Kanojia et al, 2024; Shukla *et al*., 2019; DiStasio et al., 2020, (Guinan et al., 2012; Popescu, 2016). One possible mechanism of achievement of these impressive characteristics is the reported stress-mitigating properties of SFP, acting against oxidative stress (Omidbakhshfard *et al*, 2020; Staykov *et al*., 2021), drought stress (Rasul *et al*., 2021), and other abiotic stresses (DiStasio et al., 2020; Guinan *et al*., 2012).

As the drought stress is one of the most responsible factors for reducing the agricultural yield worldwide (Cohen et al., 2021; Alqudah et al., 2011), we are extending our knowledge about crop protection from water deprivation by gathering additional data about the role of SFP in this important process, with the goal to confirm and enrich the available information, used for practical purposes. We have experimented with three vegetable crops, economically very important for the temperate climate zone in the northern hemisphere, all of which are heat-adapted and water-sensitive at the same time. The study of several different plant species at a time is enabling us to compare the simultaneous effect of SFP on the same yield characteristics and to determine if there is particular specificity over any one of them. In this regard, the phenotypical and physiological comparison of the stress-induced reactions of the different crops reveal highest level of wilting and drought-induced senescence in Eggplant and lowest – in Pepper (Fig. 1). These data are confirmed by the water-retaining potential of the separate plants, where Eggplant shows the higher water loss and Pepper – the lowest (Fig. 2). The displayed differences might be due to variations in the water deficit sensitivity of the crops or eventually to alterations of the effect, that SFP is inflicting over the diverse plant species. Considering the influence of SFP over the Yield, drought stress naturally decreases it heavily across all species, while SFP treatment rescues completely its values for Tomato and Pepper and almost completely for Eggplant (Table 1). Interesting fact is observed in Tomato, where SFP treatment alone (without drought stress) significantly increases the Yield on its own. Breaking down the Yield to its parameters Fruit Harvest and Fruit Set, reveals their different behavior under drought. While Fruit Harvest massively decreases under water deprivation, Fruit Set stays practically unchanged. Fruit Harvest follows the trend of the Yield and is also completely rescued by SFP treatment for Tomato and Pepper and nearly completely – for Eggplant. In this case SFP priming alone does not increase additionally the fruit mass per plant. The Fruit Set from another hand, is remarkably resistant to drought, as it completely keeps its values, while SFP treatment has a differential effect over different crops: Eggplant is practically not sensitive to it and maintains same numbers of fruits, regardless of the treatment, Pepper is somehow sensitive and moderately increases the fruit sets and Tomato shows the highest sensitivity with significant increase of the fruit numbers.

Overall, SFP has a positive effect on all three tested crop species, not only during drought, but also on its own, acts similarly to all of them (with minor variations), and unambiguously improves their yield characteristics, water retention, and stress resistance under drought.

4. ACKNOWLEDGEMENTS

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PART 4

FROM FIELD TO MARKET: TAŞKÖPRÜ GARLIC AND ITS CHALLENGES

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1. INTRODUCTION

Garlic (*Allium sativum* L.), a species belonging to the Amaryllidaceae family, is the second most cultivated biennial vegetable worldwide, following onions (*Allium cepa*). Used as a flavour enhancer and spice in kitchens for millennia, it has also been employed in traditional medicine due to its phytochemical content. It is consumed in its entirety when fresh, including the green parts of the plant, whereas in its dried form, only the cloves that make up the bulb are consumed (Ünal, 2024a). Garlic is also used in various forms such as powder, chips, puree, extract, tablets, sauces, and oil, and serves as an antioxidant and flavor-enhancing additive in the production of products like sausage, fenugreek, pastirma, spices, canned goods, brine, pickles, yogurt, tomato paste, and similar items. Further, dried garlic can be stored for a longer period and retains its phytochemicals more intensely and for a longer duration (Akan et al., 2019). Therefore, its dried form has a greater potential for processing in the pharmaceutical and cosmetic industries (Canbolat, 2017).

Garlic is distinguished by its unique properties, including organosulfur compounds such as allicin, sulfur-containing amino acids like cysteine and methionine, phenolic acids, flavonoids, essential oils, a variety of vitamins, and essential minerals (Yarali Karakan, 2022; Turfan, 2025). It has been reported that 100 grams of garlic contains 33.06 grams of carbohydrates, 6.36 grams of protein, 17 mg of Na, 401 mg of K, 181 mg of Ca, 1.7 mg of Fe, 31.2 mg of vitamin C, 1.7 µg of vitamin K, and 3 µg of folic acid. Garlic has a very low fat content, while its water and fiber content are relatively high (Sufer and Bozok, 2019).

The listed properties position it as one of the most important natural resources for the treatment of various diseases. Recent clinical studies have suggested that garlic, due to its antioxidant properties, offers protective and inhibitory effects against cancer, as well as the ability to reduce blood pressure, blood sugar, and cholesterol levels while enhancing the immune system (Canbolat, 2017). Additionally, it has been proposed that garlic may provide both protection and suppression against viral diseases, including COVID-19 (Khubber et al., 2020). These findings emphasise the importance of including garlic in daily dietary habits to harness its therapeutic potential (Ünal, 2024a).

In this regard, Taşköprü garlic, renowned for its strong aroma and long shelf life, is the most widely cultivated garlic variety in Turkey and is referred to as "white gold" by the local population (Turfan et al. 2024). In Taşköprü, around 4,000 families sustain their livelihoods through garlic production, meaning that 75% of the local population relies on income from garlic. Research has shown that garlic (38.19%) is the local product most strongly associated with Kastamonu, and it has been determined that Taşköprü Garlic is the city's most recognised food product (Akan and Ünüvar, 2020; Ünal, 2024b). The unique characteristics that distinguish Kastamonu Taşköprü garlic from other varieties include its tolerance to climatic conditions during production, its morphological traits that make it suitable for export, its high dry matter content (ranging from 33% to 37%) which results in minimal weight loss, its high selenium content (15 $\mu g\ kg^{-1}$) due to the soil properties of Taşköprü, and its long shelf life (allowing it to be stored for 10-11 months without the need for cold storage). The listed properties of

Taşköprü garlic have led to its particular preference and high demand in the market.

Nevertheless, Taşköprü garlic, with its exceptional qualities, faces many challenges in its journey from the farm to the market. In Turkey, the provinces producing garlic have fluctuated over the years due to climatic changes and marketing conditions. In 2022, garlic production was carried out in 56 provinces (TUİK, 2023). The top five provinces were reported as Kastamonu, Gaziantep, Kahramanmaraş, Aksaray, and Tokat, with Gaziantep leading the production with 33,973 tons, followed by Kastamonu and Kahramanmaraş (Kastamonu Valiliği, 2023; Ünal, 2024a, 2024b). Despite the increase in global garlic production, Turkey's share in world garlic production has dropped from 4% to 0.4% over the past 30 years, while the share of Kastamonu garlic, which holds a geographical indication, has also decreased from 25% to 20% of Turkey's total production (Ünal, 2024). The main issues suppressing garlic production include climatic problems, the producers' lack of awareness regarding fertilisation and pesticides, theft, storage problems, and consumption habits.

2. CLIMATIC CHALLENGES IN GARLIC CULTIVATION

Although garlic is not highly selective in terms of climatic conditions, it requires an optimal temperature range of 15–20°C for best growth. The plant's leaf development accelerates when temperatures rise above 15°C, while temperatures exceeding 25°C or falling below -4°C suppress growth, leading to yield loss (Taban et al., 2013; Tufan et al., 2024). In Taşköprü, garlic planting typically starts in the last week of

February or the first week of March, with harvest generally taking place in the first week of July. According to meteorological data, the temperature at the onset of garlic planting is around 4.2°C. During the growing period, the temperature rises rapidly, reaching 14.1°C in May, which accelerates leaf development. In June, the temperature increases to 17.4°C, and during the harvesting month of July, it ranges between 22°C and 24°C, which are considered optimal for garlic cultivation (Turfan and Çiçek Aksoy, 2024). However, in recent years, especially after 2018, early and late spring cold spells, as well as hailstorms, have posed significant challenges for garlic production. For instance, the snowfall observed in March 2019 and 2024 caused the garlic bulbs planted in the soil to rot, while hailstorms in April damaged the leaves (Figure 1).

Figure 1. Damage caused by hailstorms to garlic seedlings

Experts highlight the need to raise awareness among garlic producers regarding climatic risks, particularly hail damage (Turfan et al. 2024; Taşköprühaber, 2025). To reduce such losses, they recommend researching leaf simulators, promoting agricultural insurance, and expanding the use of greenhouses and protective cover systems to safeguard crops from extreme weather conditions (Mansour et al. 2024; Turfan, 2025). Studies have investigated the effects of foliar applications of chitosan (Turfan and Çiçek Aksoy, 2024), glutamic acid (Turfan and Turan 2023), cysteine, phenylalanine (Turfan, 2025), glycine, betaine and selenium on garlic (Turfan, 2025) in press. These treatments not only enhance the initial yield but also play a significant role in improving the physicochemical properties of garlic after harvest, offering considerable benefits for its quality and shelf life (Dahule et al. 2024; Mansour et al. 2024).

3. CHALLENGES IN DISEASE AND WEED MANAGEMENT IN GARLIC CULTIVATION

One significant issue in garlic cultivation is the high cost of pesticides used to manage diseases and invasive weeds, along with a lack of knowledge among producers about proper pesticide application (Turfan et al. 2024). Common diseases in garlic include rust (mildew), fungal diseases, smut disease, and wheat disease (Figure 2). To minimise the effects of these diseases, excessive pesticide use accumulates in the soil, potentially creating problems for the following year's crops (Taban et al. 2013; Mansour et al. 2024). Since garlic is not planted in the same field for consecutive years, producers often attempt to solve this issue by applying excess nitrogen, phosphorus, and potassium fertilizers (Figure 3).

Figure 2. Rust disease and bulb rot in garlic

However, this can lead to soil degradation and the accumulation of pesticide residues in garlic. Moreover, the cultivation of other crops near garlic can be adversely affected, as the chemicals used can disrupt pollinator activities, reducing flowering and fruiting in nearby plants.

Figure 3. Fertilization of garlic during the early growth season

3. STORAGE CONDITIONS PROBLEMS IN GARLIC

Garlic is classified as a semi-perishable vegetable, meaning its storage conditions are crucial for preserving its quality and extending shelf life after harvest (Purwanto et al. 2019; Akan and Ünüvar, 2020). Improper storage can lead to a decline in flavour, texture, and overall quality, resulting in significant yield losses, primarily influenced by factors such as temperature, humidity, and ventilation (Dahule et al.

2024) (Figure 4). In Taşköprü, despite having a high mechanisation level and technological infrastructure for garlic production similar to other garlic-producing countries worldwide, adequate storage facilities have not yet been fully established (Turfan et al. 2024; Ünal, 2024a).

Figure 4. Image of sprouting and rotting of garlic during storage

Although Taşköprü garlic can be stored for extended periods due to its high dry matter content, it is estimated that around 25% of the garlic is lost due to inappropriate and traditional storage practices (Akan et al. 2019). In this context, there is a significant need for the establishment of large cold storage facilities for garlic in the region, public awareness campaigns regarding their use, and comprehensive scientific studies to optimise the conditions required for garlic storage in cold storage systems (Purwanto et al. 2019; Turfan, 2025**).**

4. GARLIC THEFT

Garlic theft is an emerging issue in garlic cultivation, particularly in regions where garlic is a valuable crop, such as Taşköprü. This illegal activity poses a significant threat to both farmers' livelihoods and local economies (Genç, 2018). Garlic, being a high-demand agricultural product, is increasingly targeted by thieves for its market value. Traditionally, garlic farmers leave their harvested crops to dry in the fields using familiar, long-established methods (Kastamonu Valiliği, 2023). The purpose of this drying process is to achieve the optimal moisture level necessary for proper storage, which is critical for extending the shelf life and preserving the chemical quality of the garlic. After approximately 10 days of drying, the garlic is taken to the farmers' homes, where it is cleaned of the soil using manual labour. It is then sorted according to size, braided, and stored in shaded areas (Turfan et al. 2024; Ünal, 2024a). However, during this drying period, garlic is vulnerable to theft, leading to significant losses for the farmers**.** To address this issue producers wait in their fields until the garlic is fully dried, reducing the risk of theft. However, these measures are sometimes insufficient and can lead to economic losses for the producers.

5. CONSUMPTION HABİTS OF GARLIC

Garlic is widely known for its use in kitchens to enhance the flavour of food, in the food industry for extending shelf life and preventing bacterial spoilage, in cosmetics as solutions or creams, and in medicine as extracts or drugs (Acanbolat, 2017; Ünal, 2024a). However, the interest in the use of peeled garlic in brine form is growing day by day. Despite this growing interest, the storage of peeled garlic remains a significant challenge, as it has a very short shelf life. During this process, factors such as temperature and humidity can lead to sprouting, respiration, microbial activity, and chemical degradation, affecting the quality and longevity of the garlic Peeled garlic is commonly marketed in packaged forms, particularly in regions like Ankara, the

Mediterranean, and the Aegean, where the pickling industry is prevalent (Tokatlı, 2013) (Figure 5). However, during transportation, issues such as condensation within the packaging and sprouting can cause significant negative impacts, leading to losses in the physicochemical quality of the garlic.

In this context, there is a crucial need for scientific studies to minimise potential losses during both storage and transport, as well as to optimise conditions to preserve the quality of peeled garlic throughout the supply chain.

Figure 5 Image of peeled garlic from the packaging

Garlic, once cleaned from stems and roots, is passed through a rotary drum system to a garlic calibration unit for size sorting. The separated garlic's dust and skins are removed through a suction ventilation system and transferred to the non-productive waste chamber. The sorted cloves undergo a conditioning process in a conditioning oven at 35-40°C to soften the skins. Once processed, the garlic is transferred to the peeling unit, where the cloves are peeled and packaged as peeled garlic (Ünal, 2024). The packaged garlic is then stored at 0°C until it is ready for distribution (Figure 5).

People have traditionally used pickling or brining techniques to store food for long periods, especially in regions and seasons where food is scarce or hard to find. Pickling and brining primarily involve immersing vegetables and fruits in a mixture of vinegar and salt (Özer and Kalkan Yıldırım, 2018). The amount and type of salt used play a significant role in determining the quality of the final product (Tang et al. 2024). Salt not only inhibits the growth of undesirable microorganisms (Figure 6) but also adds flavour to the food. When vegetables and fruits are placed in brine, they quickly absorb salt and release the ir juices. Initially, the salt concentration in the brine decreases rapidly, then gradually stabilises around 4-5%. At lower salt concentrations (5-8%), fermentation is accelerated, whereas higher concentrations (10% and above) slow fermentation and can even cause the vegetables to rot (Yang et al. 2020). Therefore, research into the automation of salt concentration for pickling and brining is crucial for maintaining quality and consistency. In some regions in Turkiye, the brine used for pickling vegetables is changed twice a week to remove any bitter flavours that may accumulate in the solution. However, research on the optimal frequency and number of times the brine should be changed is limited. The water and sugar content of each plant species affects the concentration of salt required for preservation (Wang et al. 2024). Additionally, frequently opening the lids of pickling or brining containers to allow for ventilation can trigger contamination due to exposure to air, potentially compromising the quality and safety of the product (Akan et al. 2019). In our study aimed at determining the optimal salt concentration for the brining of Taşköprü garlic (Figure 6), we observed that brine solutions with garlic that had been changed more frequently resulted in a higher flavour profile (Figure 6). However, this also led to an increased risk of contamination. Since this is an ongoing study, the findings are currently represented only through figures.

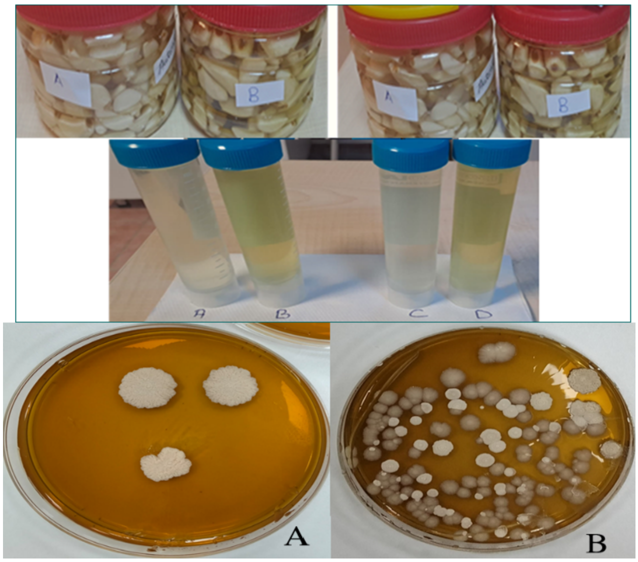

Figure 6. Image of peeled garlic from the packaging. **A:** Water samples that have been renewed (lighter color), **B:** Water samples that have not been renewed (darker color).

6. PROBLEMS IN GARLIC MARKETING

Taşköprü garlic is an important variety that contributes to both the producer and, indirectly, the economy of Kastamonu. After being harvested from the fields, the garlic bulbs are classified based on their size and are offered to consumers in local markets in their raw form, without undergoing any processing, typically in bundles (Akan et al. 2019; Ünal, 2024b). The garlic industry in Kastamonu is generally composed of small-scale individual or family-owned businesses, with the garlic processing sector primarily consisting of garlic peeling facilities (Ünal, 2024a). In addition, peeled garlic, garlic puree, and black garlic, primarily used in products such as sausage, pastrami, pickles, and the food industry, are processed in local facilities in Kastamonu and exported (Akan and Ünüvar, 2020; Ünal, 2024b). Although limited in number, some companies produce products such as garlic flakes, black garlic, garlic puree, and garlic extract (Canbolat, 2017). However, processed forms such as dried or granulated garlic, garlic tablets, garlic oil, or garlic extracts are not widely known or produced. The main issues faced by existing firms, as noted by Ünal (2024b), include insufficient working capital, inadequate labour force, fluctuating market prices, unfair competition, difficulty in reaching new markets, and high input costs.

7.CONLUSION

Although Taşköprü garlic from Kastamonu is a globally recognized product with brand value and a geographical indication, and despite the fact that it accounts for approximately 20% of Turkey's total garlic production, it faces significant challenges from production to marketing. In addition to state support to counteract climate-related adverse conditions during production, garlic producers should be educated and encouraged through scientifically research-based innovative approaches. To reduce economic losses while preserving post-harvest physical and chemical properties, large-scale cold storage facilities should be established. It is also necessary to move beyond traditional consumption habits and develop value-added products. Another important issue in garlic agriculture is the need for workers and high labour costs. Therefore, there is a need for the development and use of modern technology-based machinery to reduce these costs.

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PART 5

DETERMINATION OF SALINITY TOLERANCE DEGREE OF SOME POTATO GENOTYPES UNDER IN VITRO CONDITIONS

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ABSTRACT

This research was carried out in Erzurum Eastern Anatolia Agricultural Research Institute Tissue Culture Laboratory with 4 replications according to the "Random Plots Trial Design". In the study, single-node cut explants of Agria and Can potato cultivars were used, and NaCl was added to MS medium at concentrations of 0, 250, 500, 750, 1000, 1500, and 2000 mg/l. Plantlets were kept in long day photoperiod (16 hours light, 8 hours dark) conditions for 6 weeks. In plantlets, plant height (cm), number of internodes, stem thickness, and leaf length (mm) were measured. According to the results obtained, it was determined that the longest plant height was obtained from the control (22,26 cm) group, and that the Can variety (18,79 cm) produced longer plantlets than the Agria variety (13,90 cm). The highest number of internodes was obtained from the variety Can (8,90). The highest leaf length was obtained from the control group (0,7 cm) and the Can variety (0,46 cm). According to all these data, it was determined that the Can cultivar was more tolerant to salty environments than the Agria cultivar, but vegetative growth was negatively affected due to increasing salt concentration.

Keywords: Potato, *Solanum tuberosum* L., tissue culture, in vitro, salinity tolerance

INTRODUCTION

Potato, which is in the *Solanacae* (nightshade family), is one of the most important plants in the world with its high amount of nutritional value and antioxidants. In terms of production in Turkey, according to 2021 data, it ranks fourth after wheat, corn and barley. In 2008, it was named "hidden treasure" by FAO. In recent years, potato plant is among the plants that have difficulties in production due to the increase in the harmful effects of environmental stress factors and diseases (Abed and Demirhan, 2018).

Crop production needs to be increased in order to ensure adequate nutrition and economic income for human beings. Crop production can be increased by increasing production areas or by obtaining high yields per unit area. In this case, the use of fertilizers, herbicides and insecticides will increase in the future. The increase in chemical inputs negatively affects sustainable agriculture. As a result, it is important to apply new techniques called Biotechnological Methods in order to increase yield in crop production (Sürmen, 2016).

Biotechnological methods have achieved positive results against many diseases and stress factors. Potato plant is a plant that is very suitable for the application of biotechnological methods in terms of its characteristic features (Arvas et al., 2018).

Lichtenhaler (1996) categorizes these stress factors to which plants are exposed into two groups: biotic and abiotic.

While the amount of yield obtained due to biotic stress factors decreases by %65-%87 compared to the amount of yield obtained from plants under optimum conditions, the yield loss due to abiotic factors varies between %51-%82 (Kacar et al., 2013). According to the amount of yield obtained from plants under optimum conditions; abiotic stress is the most important cause of agricultural crop loss all over the world, as the crop loss due to biotic stress factors is more than 50% of the crop loss due to abiotic factors mentioned above.

In the world, 23% of agricultural land is saline. Every year 10 million ha of land is lost due to salinity. In our country, salinity problem is observed in an average of 1.5 million ha of irrigated lands (Deliboran and Savsan, 2015).

Soil salinity is among the important abiotic environmental factors affecting plant life (Dinler et al., 2024). High salt levels significantly affect seed germination, plant life and crop yield. According to Kibria and Hoque (2019), 7% of the world's total land, 20% of cultivated agricultural land and about half of irrigated land are affected by soil salinity. Salinity is increasing due to global climate change, irrigation and accumulation of applied fertilizers in the soil (Rengasamy, 2010). Excessive intracellular uptake of chlorite, sulfate, sodium and other ions causes ion imbalance (Mudgal et al., 2010). Soil salinity is commonly caused by the accumulation of high concentrations of cations such as Na^{+}, K^{+}, Ca^{+2} and $Mg^{(+2)}$ and anions such as Cl^{-}, $HCO_{(3)}{}^{(-)}$, $CO_{(3)}{}^{(-2)}$, $SO_{(4)}{}^{(-2)}$ and NO_3 (Corwin, 2021). There are two main causes of soil salinity: primary (natural) and secondary (anthropogenic). Primary salinity occurs as a result of natural processes, while secondary salinity occurs as a result of human activities. Soil salinity increases through weathering of soil minerals, fertilizer and pesticide applications, industrial waste discharge, rainfall and irrigation (Corwin, 2021; Hassanuzzaman et al., 2013).

Reclamation of salinity-affected soils is long-term and costly. The use of salt tolerant species and varieties is necessary for successful agricultural production in these areas. Knowing the salt tolerance of the plant provides economic benefits for growers producing in saline soils (Akıncı and Akıncı, 2000).

Potato plant is produced in irrigated agricultural areas and the problem of salinization is increasing every year in these areas (Sürmen, 2016). *In vitro* methods are widely used to measure the salt tolerance of varieties and to develop salt tolerant varieties. Therefore, in this study, plantlets from two different potato genotypes were grown *under in vitro* conditions and their responses to different salt concentrations were investigated.

1. MATERIAL AND METHOD

Agria and Can potato varieties were used as material in the study. Both varieties were obtained from Eastern Anatolia Agricultural Research Institute and constituted the material of our research. Plantlets developed by applying meristem culture from potato (*Solanum tuberosum L.*) genotypes were used in the study. Single-node cuttings were taken from the plantlets obtained from Erzurum DATAE affiliated to the Ministry of Agriculture and Forestry.

Figure1 Single internode cut from plantlets obtained by meristem culture transferred to medium

Six different salt (NaCl) concentrations applied in the study. (Control, 250, 500, 750, 1000, 1500 and 2000 mg/l.). Single internode cuttings were taken from the seedlings developed by meristem culture method in a sterile cabinet. Then, the single internodes were transferred to jars containing medium. 3-4 explants were left in each jar. In the experiment carried out in four replicates, the jars in which explants were left were exposed to 2000 lux light intensity in 16 hours of light and 8 hours of darkness (24 + 2 "C) and the necessary observations were recorded.

2. RESEARCH FINDINGS and DISCUSSION

2.1. Plant Height

The average data obtained for plant heights of potato genotypes applied with different salt concentrations in vitro and the results of variance analysis are given in Table 2 and Table 3.

Table 2. Mean plant height (cm) and number of internodes of potato genotypes treated with different salt concentrations

Application Doses	Agria	Can	Average	Agria	Can	Average
Control	20.4 a	24.1 a	**22.3 a**	6.6 a	8.9 a	**7.8 a**
250	17.9 b	24.4 a	**21.2 b**	6.2 a	8.0 b	**7.1 b**
500	13.6 c	19.0 b	**16.3 c**	5.5 b	6.6 c	**6.1 c**
750	12.4 d	17.4 c	**14.9 d**	4.2 c	6.3 c	**5.3 d**
1000	11.6 d	16.7 c	**14.2 e**	2.5 d	4.1 d	**3.3 e**
1500	10.8 e	14.8 d	**12.8 f**	2.6 d	4.4 d	**3.5 e**
2000	10.7 e	15.1 d	**12.9 f**	2.4 d	3.0 e	**2.7 f**
Average	13.9 b	18.8 a	16.35	4.3 b	5.90 a	5.1

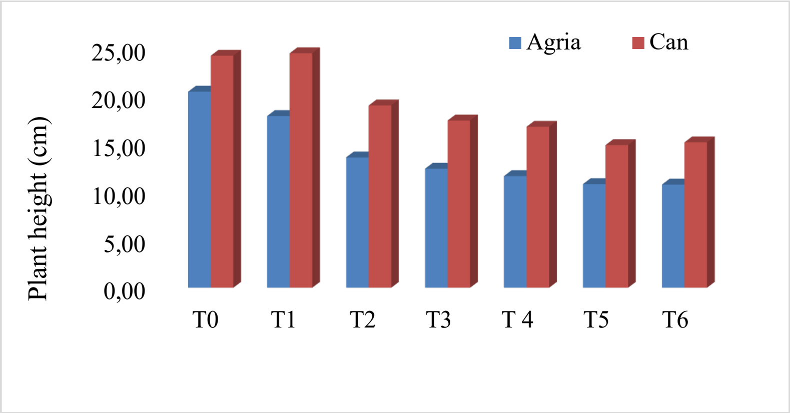
When Table 2 is examined, plant height was measured 13.90 cm in Agria variety and 18.79 cm in Can variety as the average of the experimental factors and this difference was found to be statistically significant ($p<0.01$) (Table 3). The results of the research show that potato genotypes have different degrees of tolerance to salinity.

Table 3. Analysis of variance results of plant height, number of internodes, main stem thickness, leaf length, number of leaves and leaf width of potato genotypes at different salt concentrations

Source of variation	**Degres of freedom**	**Plant height**	**Number of knuckles**	**Main stamp thickness**	**Leaf length**
Repetition	9	1.69	0.9	1.70 *	1.17
Variety (C)	1	655**	141.84 **	50.84 **	35.52 **
Salt (K)	6	391.90**	109.28 **	45.49 **	186.15 **
Variety x Salt	6	5.84**	2.39 *	0.46	47.51 **
Error	108				
General	139				

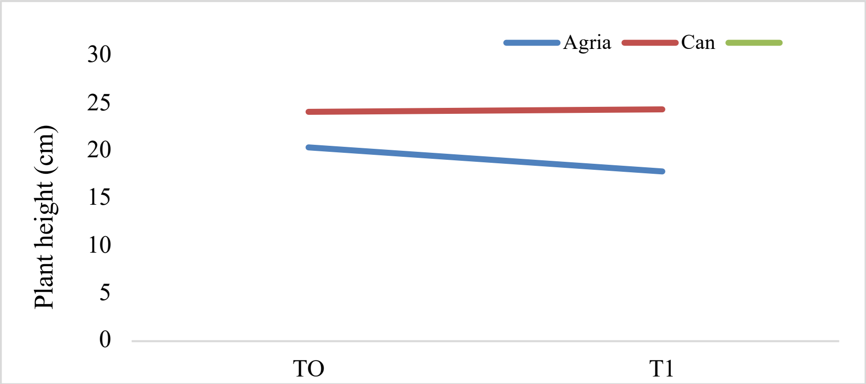
Plant height of Agria potato cultivar decreased steadily with increasing salt concentrations. Plant height of Agria variety varied between 10.72-20.39 cm at different salt concentrations, the longest plant height was obtained from the control group and the shortest plant height was obtained from 2000 mg/l NaCl treatment. This difference was statistically significant at $p<0.01$ probability level (Table 3 and Graph 1). A similar situation was observed in Can potato cultivar and it was determined that salt concentration treatments had a significant ($p<0.01$) effect on plant height (Table 3). In Can genotype, the shortest plant height was obtained from plants grown in 2000 mg/l and 1500 mg/l environments, respectively. The height of the plants grown in T1 medium was 24.39 cm (Table 2).

The average plant height was measured as 16.35 cm. When the cultivar x salt dose averages were examined, the longest plant height was obtained from Can cultivar in T1 medium with 24.39 cm and the shortest plant height was obtained from Agria cultivar in T6 medium with 10.72 cm. Shoot length is the most important parameter for salt stress (Bahrani and Hagh Joo, 2012). Because shoots utilize the water absorbed from the soil through the roots for plant organs. Therefore, shoot length is important in determining the reaction of plants to salt stress (Bahrani and Hagh Joo, 2012). As a result of the research, it was determined that shoot length decreased with increasing NaCl concentration (Özkan and Topçu, 2017; Patterson et al., 2009). This situation is thought to be caused by the decrease in the total amount of chlorophyll in the leaves as a result of salt stress and the slowing down of the rate of photosynthesis (Tuğlu, 2016). Exposure to stresses such as heavy metals, temperature, drought, and deterioration adversely affects (Kul et al., 2021). As a matter of fact, Süyüm (2011) reported that plants exposed to stress cause a decrease in photosynthesis rate because they activate their protection mechanisms and shortening of plant height due to antagonistic effects on the uptake of some elements as well as NaCl toxicity. It has also been reported by many researchers that plant height shortening occurs depending on NaCl dose (Aghaei et al., 2009).



Graph 1 Values of plant height of potato genotypes at different salt concentrations

Plant height values determined for different salt concentrations varied. Thus, the cultivar x salt concentration interaction was significant at $p<0.01$ probability level (Table 3). In addition, while there was a decrease in Agria cultivar from the control treatment to the T1 treatment, the opposite situation was observed in Can cultivar in the same treatments and a slight increase in plant height was observed. Therefore, this interaction was significant (Table 2; Graph 2).



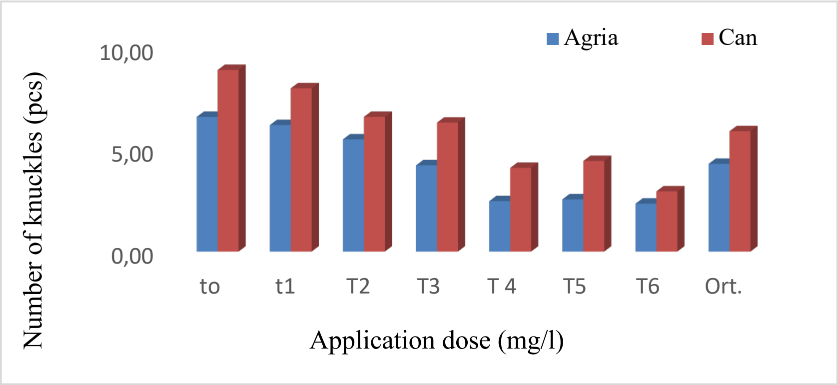
Graph . 1 Cultivar x salt concentration interaction of plant height as the mean of salt concentration in potato plants

2.2. Number of İnternode

The results of the analysis of variance on the number of internodes of the plant of potato genotypes grown at different salt concentrations are given in Table.3. As a result of the analysis of variance, it was determined that cultivar, salt concentration and cultivar x salt concentration interaction had a significant effect on the number of internodes.

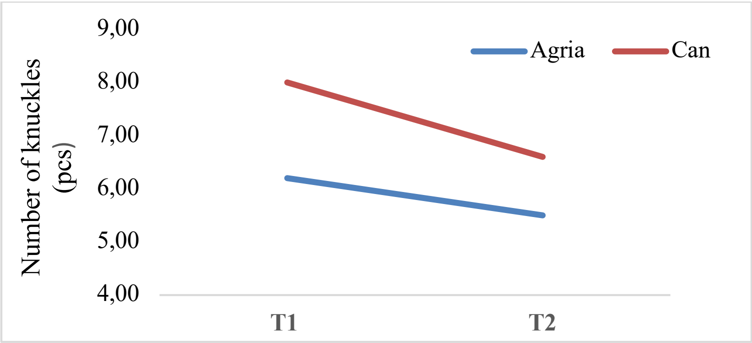
The number of internodes obtained from potato genotypes with different salt concentrations was 1.60 more in Can cultivar (5.90) than in Agria cultivar (4.30). As can be seen from the examination of Table 2, it is seen that the potato genotypes investigated in the study have different degrees of tolerance to salinity in terms of the number of internodes.

A significant decrease in the number of internodes in Agria potato cultivar in relation to increasing salt concentrations was determined (Table 2, Graph 3). The number of internodes of Agria variety varied between 2.35-6.6 at different salt concentrations applied. Accordingly, T6; T5 and T4 treatments had the lowest number of internodes (2.35; 2.56; 2.47, respectively), while T2 and T3 treatments had 5.5 and 4.23, respectively. The number of internodes of the control group and T1 treatment (6.6 and 6.2, respectively) were higher than the other salt dose treatments (Table 2 Graph 3). In Can variety, the number of internodes determined varied significantly according to the salt dose treatments and the highest number of internodes was obtained from the control group with 8.90 nodes. As can be seen when the figures in Table 2 are examined, the number of internodes decreased steadily with the increase in salt concentrations and the lowest number of internodes was obtained from the highest salt concentration, T6. This difference among the salt concentrations was found to be significant at $p<0.01$ probability level.



Graphic 2 . Number of internodes of potato genotypes at different salt concentrations

As an average of the varieties and salt dose treatments used in the study, 5.10 nodes were counted and the analysis of variance data showed that this difference between the varieties in terms of the number of nodes was very significant ($p<0.01$) (Table 3). The variation in the number of internodes for each genotype may be due to the different salt tolerance of the genotypes. Salt concentrations had a significant ($p<0.01$) effect on the number of internodes (Table 3). The highest number of internodes (7.75) was determined in the control group and the lowest number of internodes (2.65) was determined in the T6 treatment. When the cultivar x salt dose interaction was examined, the highest number of internodes was obtained from Can cultivar in the control group with 8.90 and the lowest number of internodes was obtained from Agria cultivar in T6 treatment with 2.35. As a result of the research, it was observed that the number of internodes decreased significantly with increasing salt concentrations. It was observed that the main reason for this may be due to the decrease in the physiological potential of the plant (Pour et al., 2009), especially with increasing salt stress.



Graphic 4. Cultivar x salt concentration interaction of number of internodes as the mean of salt concentration in potato plants

Potato genotypes formed different number of internodes according to the salt concentrations applied. For example, in Agria cultivar, the number of internodes in T2 treatment (5.5) decreased compared to the salt concentration in T1 treatment (6.2), whereas in Can cultivar, the decrease in the number of internodes was more significant for the same salt concentration. This caused the cultivar x salt concentration interaction to be significant (P<0.01) (Graph 4)

2.3. Main Stamp Thickness

The results of the analysis of variance of the main stem thickness values obtained from some potato genotypes at different salt concentrations are presented in Table 2, and the average data of the genotypes obtained as a result of the measurement are reported in Table 5.

Table 1. Average main stem thickness (mm) and leaf length (mm) of potato genotypes treated with different salt concentrations

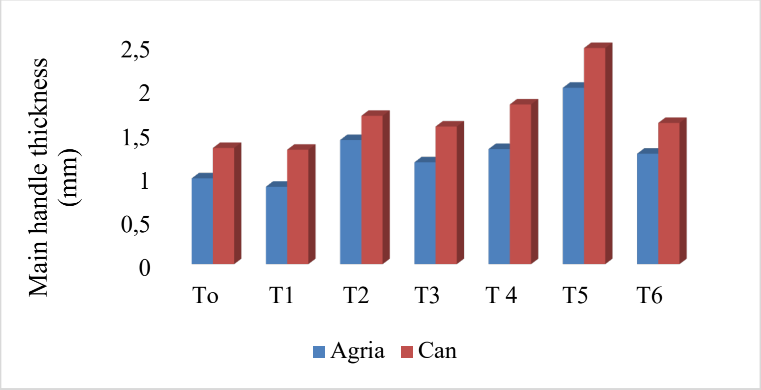
Application Doses	Agria	Can	Average	Agria	Can	Average
Control	0.98 de	1.33 d	**1.15 d**	0.6 a	0.8 a	**0.7 a**
250	0.88 e	1.31 d	**1.10 d**	0,5 b	0.6 b	**0.5 b**
500	1.42 b	1.69 bc	**1.61 b**	0.3 d	0.6 b	**0.5 c**
750	1.16 cd	1.57 c	**1.37 c**	0.5 b	0.4 cd	**0.4 d**
1000	1.31 bc	1.82 b	**1.57 b**	0.4 c	0.4 c	**0.4 d**
1500	2.01 a	2.47 a	**2.24 a**	0. 3 d	0.3 d	**0.3 e**
2000	1.26 bc	1.61 bc	**1,45 bc**	0.3 d	0.2 e	**0.2 f**
Average	**1.29 b**	**1.69 a**	**1.488**	**0.41 b**	**0.46 a**	**0.44**

The difference between the means indicated with the same letters is insignificant. The difference among genotypes in terms of main stem thickness was found significant at $p<0.01$ probability level (Table 4.6). As the average of the salt concentration treatments, 1.290 mm and 1.685 mm main stem thickness were obtained from Agria and Can varieties, respectively. Can variety had 23.4% higher main stem thickness than Agria variety (Table 5).

When the effect of different salt concentration treatments on the main stem thickness was examined, it was observed that the main stem thickness of Agria variety was affected at $p<0.01$ probability level. When the main stem thickness of Agria variety was compared, it was determined that T5 treatment had the highest main stem thickness with 2.013 mm, followed by T2 (1.417 mm). The lowest main stem thickness was obtained from T1 treatment with 0.884 mm (Table 5).

The main stem thickness of Can cultivar was determined as 1.326; 1.306; 1.306; 1.693; 1.571; 1.823; 2.467; 1.612 mm as a result of salt application at T0; T1; T2; T3; T4; T5; T6 rates, respectively (Table 5). These results show that the effect of salt doses on main stem thickness is an important factor. In salt dose treatments, the thickest main stem was obtained from T5 treatment. The main stem thickness determined at this concentration was 1.141 mm more than the control group (T0).

As the average of the varieties and salt dose treatments used in the study, the main stem thickness was determined as 1.488 mm and the results of the analysis of variance showed that this difference between the varieties in terms of main stem thickness was statistically significant at $p<0.01$ level (Table 2). As the average of cultivar and different concentrations of salt treatments, the main stem thickness was determined as 2.240 mm in T5 treatment, 1.153 and 1.095 mm in control and T1 treatments, respectively (Table 5). According to the data obtained in the T5 treatment, where the highest stem thickness was obtained, and in the control group, where the lowest stem thickness was obtained, it can be said that the increase in salinity stress encourages the development of the stem rather than shoot development and causes an increase in stem thickness.



Graph 5. Values of main stem thickness of potato genotypes at different salt concentrations.

As can be seen in Table 5, the interaction between salt concentrations and cultivars was significant at $p<0.01$. In both cultivars, main stem thickness increased with the increase in salt concentration. However, this decrease in main stem thickness was more significant in Can cultivar than Agria cultivar in the transition from T3 to T4 treatment and therefore the cultivar x salt concentration interaction was significant (Graph 5 and Graph 6).

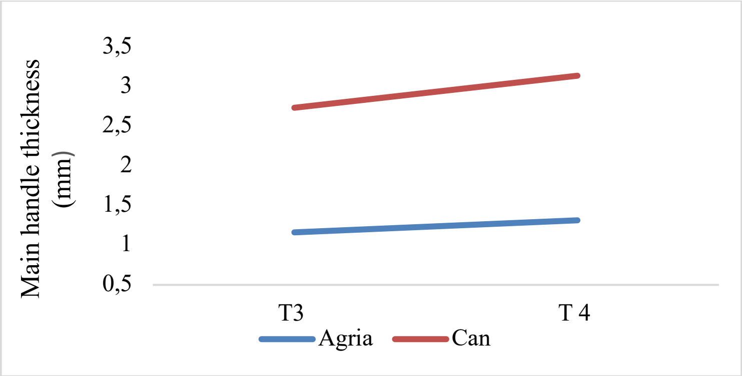


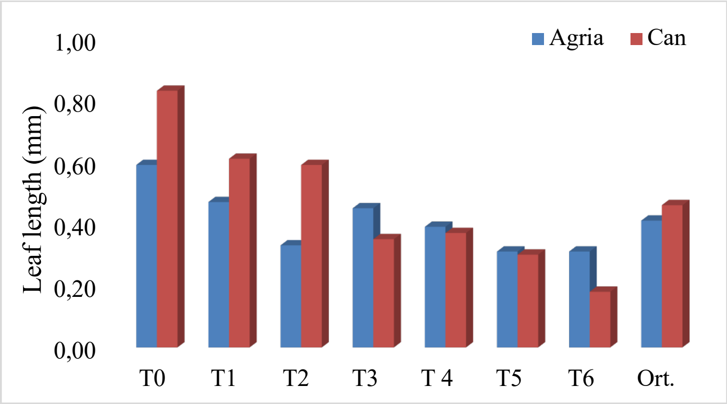
Figure 6. Cultivar x salt concentration interaction of main stem thickness as the mean of salt concentration in potato plants

2.4. Leaf Length

Analysis of variance data obtained from the plantlets of potato genotypes tested at different salt concentrations are given in Table 2 and average leaf length values are given in Table 5.

The potato genotypes used in the experiment had a significant ($p<0.01$) effect on leaf length (Table 2). As the average of salt concentrations, leaf length was determined as 0.41 mm in Agria variety and 0.46 mm in Can variety (Table 5). As can be seen from the examination of Table 5, although successive salt concentrations gave similar results on leaf length of Agria variety, the effect of increasing salt concentration on leaf length was observed (Table 5, Graph 7). While leaf length was 0.59 mm in the control group, it was 0.47 and 0.33 mm in T1 and T2 treatments. In the T3 treatment, leaf length increased slightly and reached 0.45 mm. The lowest leaf length was 0.31 mm in T5 and T6 treatments (Table 5).

The effect of salt concentrations applied to Can, another variety used in the experiment, on leaf length was found to be significant ($p<0.01$). Just as in Agria genotype, it was determined that increasing rates of salt application significantly decreased leaf length in Can variety. It can be seen in Table 5 that the leaf length of Can cultivar, which was applied salt at different concentrations, varied between 0.83 - 0.18 mm. The longest leaf length among the treatments was measured in the control group with 0.83 mm. The treatment with the shortest leaf length was T6 (0.18 mm) followed by T5 (0.30 mm) (Table 5).



Graph 7. Values of leaf length of potato genotypes at different salt concentrations

In the study in which Agria and Can varieties were used, 0.44 mm leaf length was measured as the average of salt dose treatments. Increasing salt concentration decreased leaf length. When Table 5 is examined, it is seen that the lowest (0.24 mm) value of leaf length was obtained from the T6 treatment and the highest (0.71 mm) value was obtained from the control group where no salt was applied. Plants exposed to salt stress try to prevent water loss by reducing transpiration and reducing leaf area by closing stomata. In this case, CO_2fixation decreases and respiration increases. The plant under salt stress spends too much energy to survive and photosynthesizes less than it needs, but cannot provide the necessary energy. In this case, the plant cannot fully realize its growth and development (Yaşar, 2003) and thus causes a decrease in leaf area and size. As a matter of fact, it has been reported by many researchers that leaf size decreases significantly with increasing salt concentration (Turan, 2000; Sürmen, 2016).

The leaf length values determined for different salt concentrations varied. Thus, the investigated interaction was found significant at $p<0.01$ probability level (Table 2; Graph 8). In addition, while there was a small decrease in Agria cultivar from T3 to T4 treatment, the opposite situation was observed in Can cultivar in the same treatments and a slight increase in leaf length was observed.

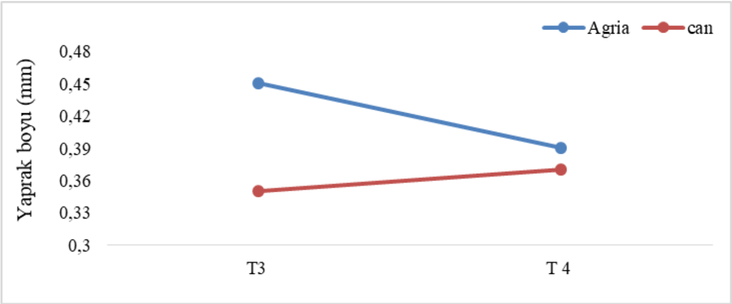


Figure 8. Cultivar x salt concentration interaction of leaf length as the mean of salt concentration in potato plants

3. CONLUSION

The research was conducted using Agria and Can potato varieties and 7 different salt (NaCl) concentrations (0; 250; 500; 750; 1000; 1500 and 2000 mg/l NaCl). The experiment was organized according to the "Randomized Plots" Experimental Design with four replications.

As a result of the research, it was determined that there were significant differences among the varieties in terms of the parameters examined. The applied NaCl dose significantly affected all the parameters examined. The values obtained in terms of plant height, number of internodes and leaves decreased significantly with the increase in salt dose, except for main stem thickness. The medium containing 1250 mg/l salt had a positive effect on main stem thickness. According to the results of the study, it was determined that salt stress had a negative effect on the vegetative development of potato plants.

According to all these data, it was determined that Can variety was least affected by increasing salt stress in terms of the traits considered in the research, while it showed more tolerance to saline environments. Although plants exposed to salt stress develop some tolerance mechanisms for protection, it was determined that the parameters subject to the research were negatively affected and stress conditions negatively affected the vegetative development of the plant. It can be said that it is necessary to test this study conducted under laboratory conditions in greenhouse and field conditions in order to obtain healthier results.

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PART 6

STRESS-MEDIATED SHIFTS IN PLANT FUNCTIONAL STRATEGIES: THE ROLE OF GRAZING IN THE KIZILIRMAK DELTA

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ABSTRACT

This study investigates the changes in functional strategies (CSR: Competitive, Stress-tolerant, Ruderal) of the same plant species caused by grazing pressure in meadow habitats of the Kızılırmak Delta, located on the Black Sea coast of Türkiye. In this study, within the framework of Grime's CSR theory, shifts in strategy types were determined by measuring functional traits based on leaf morphology (specific leaf area-SLA, leaf dry matter content-LDMC, leaf area-LA, etc.) on 19 plant species in microhabitats exposed to different grazing intensities. Results showed that some species shifted to stress-tolerant strategies, while others increased their rhizomatous components, rarely favouring competitive strategies. Strategy shifts were often associated with increased resilience of leaf tissues or rapid growth tendencies. The results suggest that grazing affects not only species composition but also functional diversity through strategic flexibility within the same species. These findings support the applicability of the CSR strategy framework at the microsite level for sustainable management of wetland grasslands.

Key words: CSR strategies, grassland ecosystems, plant functional traits, grazing stress

INTRODUCTION

Grazing is one of the most widespread forms of land use worldwide, directly affecting grassland and rangeland ecosystems, which cover approximately half of the Earth's land surface (Díaz et al., 2007; Gibson, 2009; Niu et al., 2025). Domestic livestock grazing not only reduces plant biomass but also physically destroys vegetation, compacts soil, alters microhabitat characteristics, and affects nutrient cycling, playing a decisive role in ecosystem function (Kauffman et al., 2004; Jones et al., 2011; Teuber et al., 2013). Such interactions lead to fundamental changes in the species composition, diversity, and functional structure of plant communities.

The CSR strategy theory developed by Grime (1977, 2006) to explain the strategies developed by plants in response to environmental stresses and disturbance pressures provides a powerful framework for understanding ecological responses. According to this model, plant species can be classified using three basic strategy spectra: competitive (C), stress-tolerant (S), and ruderal (R). Competitive species generally excel in areas where resources are abundant and disturbance is low, while stress tolerators are characterized by traits such as slow growth and longevity that adapt to resource limitations. Ruderal species gain an advantage when subjected to high disturbance, with short life cycles and high reproductive capacity (Grime and Pierce, 2012).

Although CSR theory has been widely used to understand the effects of continuous and selective disturbance regimes, such as grazing, on plant strategies, the existing literature has largely focused on community-level changes (Milchunas and Lauenroth, 1993; Díaz et al., 2007; Jones et al., 2011; Wang et al., 2018). However, some recent studies have shown that the same plant species can exhibit flexibility in their strategic responses to different disturbance intensities (Saatkamp, 2010; Wang et al., 2021). Stressors such as grazing can change not only the composition of the species but also the functional strategy position of the same species.

Indeed, shifts in the CSR strategy spectrum have been shown to shift from stress tolerance to ruderal strategies with increasing habitat degradation (Teuber et al., 2013; Zhou et al., 2021; Wang et al., 2018; Wala et al., 2023). However, these shifts are often based on interspecific comparisons, and empirical studies on strategy shifts within the same species are very limited. However, such analyses are critical for understanding plant plasticity and adaptive responses.

In this context, this study examines whether the same species exhibits a shift in the CSR strategy spectrum under grazing stress in the grasslands of the Kızılırmak Delta, located within the borders of Samsun province. The Kızılırmak Delta is one of the largest wetlands on the Black Sea coast and an ecosystem that has attracted attention due to its rich biodiversity and pasture utilisation. This study compared areas isolated from grazing pressure with areas under active grazing and analysed the differences in the strategic position of the species. This approach aims not only to test the dynamic nature of CSR theory but also to provide a functional tool for assessing the impacts of grazing management on ecosystem services.

1. MATERIALS and METHODS

1.1. Study Area

This study was conducted in Kızılırmak Delta Wetland and Bird Paradise Natural Protected Area, located within the borders of Ondokuzmayıs, Bafra, and Alaçam districts of Samsun province. The delta is listed on the UNESCO World Heritage Tentative List and is one of the largest and most biodiverse wetlands in Türkiye. The delta has a mosaic structure with lakes, marshes, reeds, pastures, dunes, forests, and meadows. The study area extends over a surface of approximately 23.686 hectares.

In the delta, grazing is carried out on a total area of approximately 15,680 decares, including permanently dry grazing areas (8,830 decares) and areas open for grazing due to seasonal water withdrawal (6,850 decares). The delta features grassland systems that support year-round grazing by animals such as buffalo, sheep, and horses.

1.2. Identifying CSR Strategies

This study was conducted in 10 different grazing areas in the Kızılırmak Delta Wetland and Bird Sanctuary in Samsun Province, Türkiye. A total of 41 wire cages were placed to analyse the effects of grazing on vegetative strategies. The area of each cage was 50x70 cm (0.35 m^2) and was mounted in a way to prevent the entry of animals. The identification of specimens taken from individuals of the same species inside and outside these cages was carried out using the 'Flora of Turkey and Eastern Aegean Islands' (Davis, 1965-1985; Davis et al., 1988;

Güner et al., 2000). To determine the ecological effects of grazing on plant species distributed in the area, measurements were made to determine whether there were differences in some functional characters of each species represented by at least 3 individuals in the cage area without grazing pressure and CSR (Competitive - Stress Tolerant - Ruderal) strategy types were determined.

The seven-feature CSR classification method developed by Hodgson et al. (1999) was used to determine the CSR strategies of plant individuals. In this method, basic functional traits, such as canopy height, leaf dry matter content (LDMC), specific leaf area (SLA), lateral spread, flowering time, and flowering onset time were measured in individuals of each species. Plant height was measured in situ with a tape measure in mature individuals, while leaf samples were collected in the field and transported to the laboratory, where turgor equilibration, drying, and weighing were used to calculate wet and dry weights (Pérez-Harguindeguy et al., 2013). The leaf area was determined using a CI-202 portable leaf area meter. The SLA was calculated as the leaf area divided by the dry leaf weight. Phenological data, such as flowering stage and onset times were determined using both field observations and literature sources.

2. RESULTS and DISCUSSION

Although a total of 115 plant taxa were identified in and around the cages placed in different areas during the study, only 19 plant species were found in sufficient density to determine the CSR strategy within the cage. This may indicate that empty niches created by grazing may have created opportunities for some species to settle, whereas in ungrazed areas, dominant species may have suppressed others and homogenized the community structure. When comparing areas isolated from grazing (inside the cage) with areas under active grazing pressure (outside the cage), a change in CSR strategies was observed in most of the 19 species (Tables 1 and 2).

Table 1: Comparison of functional traits and CSR strategy components of species observed in grazed and ungrazed areas*

Species name	Height		LA (cm^2)		FW (g)		DW (g)	
	U	G	U	G	U	G	U	G
Anagallis arvensis L.	5	3	0,82	0,36	0,01	0,005	0,002	0,0009
Briza minor L.	32,5	15,5	1,17	0,67	0,19	0,010	0,005	0,0023
Centaurea iberica Trey. ex Sprengel	30,33	30,5	12,5	7,68	0,47	0,34	0,08	0,048
Cynodon dactylon (L.) Pres.	6,5	4,5	0,51	0,45	0,006	0,007	0,002	0,002
Eryngium creticum Lam.	40	19	8,3	3,13	0,38	0,123	0,05	0,023
Euphorbia maculata L.	11	4,7	0,8	0,3	0,016	0,006	0,004	0,002
Hordeum murinum L.	6	6	0,61	0,25	0,009	0,003	0,002	0,001
Linum bienne Mill.	6,5	4,5	0,09	0,07	0,0005	0,0009	0,0003	0,0002
Lolium perenne L.	12,67	8,42	1,25	0,73	0,029	0,03	0,007	0,005
Lotus corniculatus L.	4	2,33	0,47	0,2	0,006	0,004	0,002	0,001
Medicago polymorpha L.	16	6,67	0,82	0,43	0,034	0,007	0,002	0,0013
Paspalum distichum L.	5,5	3,83	3,09	1,44	0,22	0,12	0,02	0,008
Plantago coronopus L.	7	4	0,94	0,44	0,11	0,05	0,01	0,005
Plantago lanceolata L.	24,33	10,78	10,9	2,24	0,56	0,09	0,078	0,017
Ranunculus repens L.	23,5	5	8,81	2,21	0,19	0,064	0,022	0,01
Spergularia media (L.) C. Presl	10	6,33	0,14	0,16	0,016	0,016	0,002	0,001
Trifolium campestre Schreb.	7,5	3,88	0,74	0,23	0,01	0,003	0,002	0,005
Trifolium resupinatum L.	15,2	7	1,32	0,43	0,02	0,011	0,004	0,002
Helminthotheca echioides (L.) Holub	22,5	14,5	6,28	1,32	0,33	0,07	0,038	0,01

*(LA: Leaf area, FW: Leaf fresh weight, DW: Leaf dry weight, G: Grazed, U: Ungrazed).

Some species showed a shift toward stress-tolerant strategies, whereas the ruderal component increased in some species, and competitiveness increased in only one species. These strategy shifts were supported by differences in leaf-level resource utilisation traits (SLA and LDMC) among the plants.

Table 2: Comparison of functional traits and CSR strategy components of species observed in grazed and ungrazed areas*

	LDMC (%)		SLA		Strategy types	
Species name	**U**	**G**	**U**	**G**	**U**	**G**
Anagallis arvensis	13,01	17,5	45,56	41,14	R	R/SR
Briza minor	2,34	21,95	26	29,78	CR	R/CR
Centaurea iberica	17,2	14,12	15,63	16	CR	CR
Cynodon dactylon	33,33	28,57	25,5	22,5	CSR	R/CSR
Eryngium creticum	12,15	18,65	18,04	13,61	R/CR	CR
Euphorbia maculata	23,75	28,74	21,05	18	R/CR	SR
Hordeum murinum	24,07	31,25	28,15	25	R/SR	R/SR
Linum bienne	60	25	30	32,67	S	SR
Lolium perenne	23,28	16,85	18,75	14,6	SR/CSR	S/CSR
Lotus corniculatus	33,33	26,09	23,5	20	S/CSR	SR/CSR
Medicago polymorpha	6,7	19,23	36,44	34,4	R/CR	SR
Paspalum distichum	8,97	6,87	15,45	17,28	S/CSR	S/CSR
Plantago coronopus	9,15	10,33	9,17	8,8	R	R
Plantago lanceolata	13,81	18,06	14,06	13,33	CR	CR
Ranunculus repens	11,49	15,89	40,66	21,74	CR	R/CR
Spergularia media	11,25	7,27	7,78	14	R/CR	R
Trifolium campestre	20,37	150	37	5,75	R/SR	S
Trifolium resupinatum	22,63	22,67	30,7	17,71	R/CR	SR
Helminthotheca echioides	11,54	14,29	16,75	13,2	R/CR	R/CR

*(LDMC: Leaf dry matter content, SLA: Specific leaf area; G: Grazed, U: Ungrazed).

Under grazing stress conditions, *Euphorbia maculata*, *Lolium perenne*, *Medicago polymorpha*, *Trifolium campestre*, and *Trifolium* *resupinatum* shifted to stress-tolerant strategies. In these species, a decrease in SLA values and an increase in LDMC values were generally observed. For example, in *Euphorbia maculata*, SLA decreased from 21.05 to 18.00 and LDMC increased from 23.75 to 28.74. These trends reflect a shift toward more durable, long-lasting, and conservative leaf traits. The dramatic increase in LDMC (from 20.37 to 150.00), especially in *Trifolium campestre*, can be considered an adaptive response to environmental stress after grazing. These data, together with the indirect effects of grazing (soil compaction, microclimate change, nutrient irregularities), indicate that protective strategies at the leaf level are prominent.

These observations suggest that the shift toward stress-tolerant strategies in the CSR strategy spectrum is shaped by the indirect effects of grazing. According to Grime's model, under high-stress and low-disturbance conditions, stress-tolerant species are more advantageous. These species are defined by traits such as slow growth, long leaf lifespan, and high leaf dry matter content (LDMC). Similarly, Wang et al. (2018), in their study on the Tibetan Plateau, reported that low levels of grazing favored S strategies; however, as grazing intensity increased, ruderal and competitive components increased. In this context, the shift toward stress tolerance in our study may be related to an increase in stressors in the microsite conditions rather than physical disturbance of the site. Furthermore, the fact that these strategic shifts can be functionally traced based on leaf traits such as SLA and LDMC reinforces the validity of CSR theory for field applications.

In contrast, the ruderal strategy component was found to be increased in *Briza minor*, *Cynodon dactylon*, *Linum bienne*, *Lotus* *corniculatus*, *Ranunculus* sp., and *Spergularia media*. Their short lifespan, rapid growth, and high reproductive capacity enable these species to quickly colonize open areas created by grazing. The structural characteristics also reflect this strategic shift. For example, in *Ranunculus repens*, SLA decreased from 40.66 to 21.74, and LDMC increased from 11.49 to 15.89. This suggests that fast-growing leaves are replaced by more robust and short-lived forms. In *Briza minor*, the increase in SLA (from 26.00 to 29.78) and the remarkable increase in LDMC (from 2.34 to 21.95) indicate the selective effect of grazing pressure together with ruderal characteristics. These species take advantage of their short life cycle and rapid reproduction strategies by rapidly filling the gaps left by grazing.

These findings reflect the ecological mechanism described by Grime in his C-S-R strategy theory, in which low stress but high disturbance pressure favors ruderal strategies. In particular, grazing-induced biomass removal and the creation of openings in the soil surface provide new areas of opportunity for establishing ruderal species. Zhou et al. (2021) found that in degraded alpine meadows, communities shifted from stress-tolerant (S) to ruderal (R) strategies, and these shifts were linked to changes in leaf traits, such as SLA, LA (leaf area), and LWC (leaf water content). Our findings show that grazing increases resource stress in some microhabitats and promotes a shift toward stress-tolerant strategies. Teuber et al. (2013) emphasized that under intense grazing pressure, ruderal species, especially short-lived ones with high SLA, become dominant. Similarly, Tölgyesi et al. (2015) reported that in a steppe-wetland mosaic in Hungary, increased grazing increased the abundance of ruderal species, resulting in a decrease in the relative abundance of stress-tolerant and competitive species.

Wala et al. (2023), on the example of *Ranunculus acris*, showed that under increasing stress conditions (e.g., salinity), the species shifted from competitive to ruderal strategies. This finding coincides with the strategy changes observed in *Ranunculus repens* in our study. Furthermore, studies by Wang et al. (2018) and Wirth et al. (2024) also showed that ruderal strategies become dominant in grasslands under intensive grazing and that this shift functionally affects CSR strategy composition.

Interestingly, an increase in the competitive (C) strategy component was observed only in *Eryngium creticum*. In this species, the decrease in SLA (from 18.04 to 13.61) and the increase in LDMC (from 12.15 to 18.65) indicate an increase in structural resilience, together with the ability to use resources more efficiently. The data obtained indicate that the morphological advantages of *E. creticum*, such as its spiny stem and deep root system, provide it with an advantage in competition under grazing conditions. However, this strategic shift may not be limited to the species' traits. The trampling effect due to grazing pressure may have reduced the competitiveness of tall dominant species, leading to niche openings and facilitating access by *E. creticum* to resources to which it previously had limited access. Grime and Pierce (2012) emphasized that plant strategies are contextual; strategic positions are shaped not only by the individual but also by the characteristics of neighboring species and community structure. Similarly, Pierce et al. (2014) showed that CSR strategies are influenced by both interspecific interactions and environmental factors.

In general, the findings reveal that CSR strategy shifts can change direction due to grazing pressure not only between species but also within the same species. Leaf-level functional traits, such as SLA and LDMC, are important indicators reflecting the ecological basis of these strategy shifts. In sensitive wetland ecosystems such as the Kızılırmak Delta, such strategic shifts provide effective tools for predicting the ecosystem-level impacts of grazing management decisions.

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