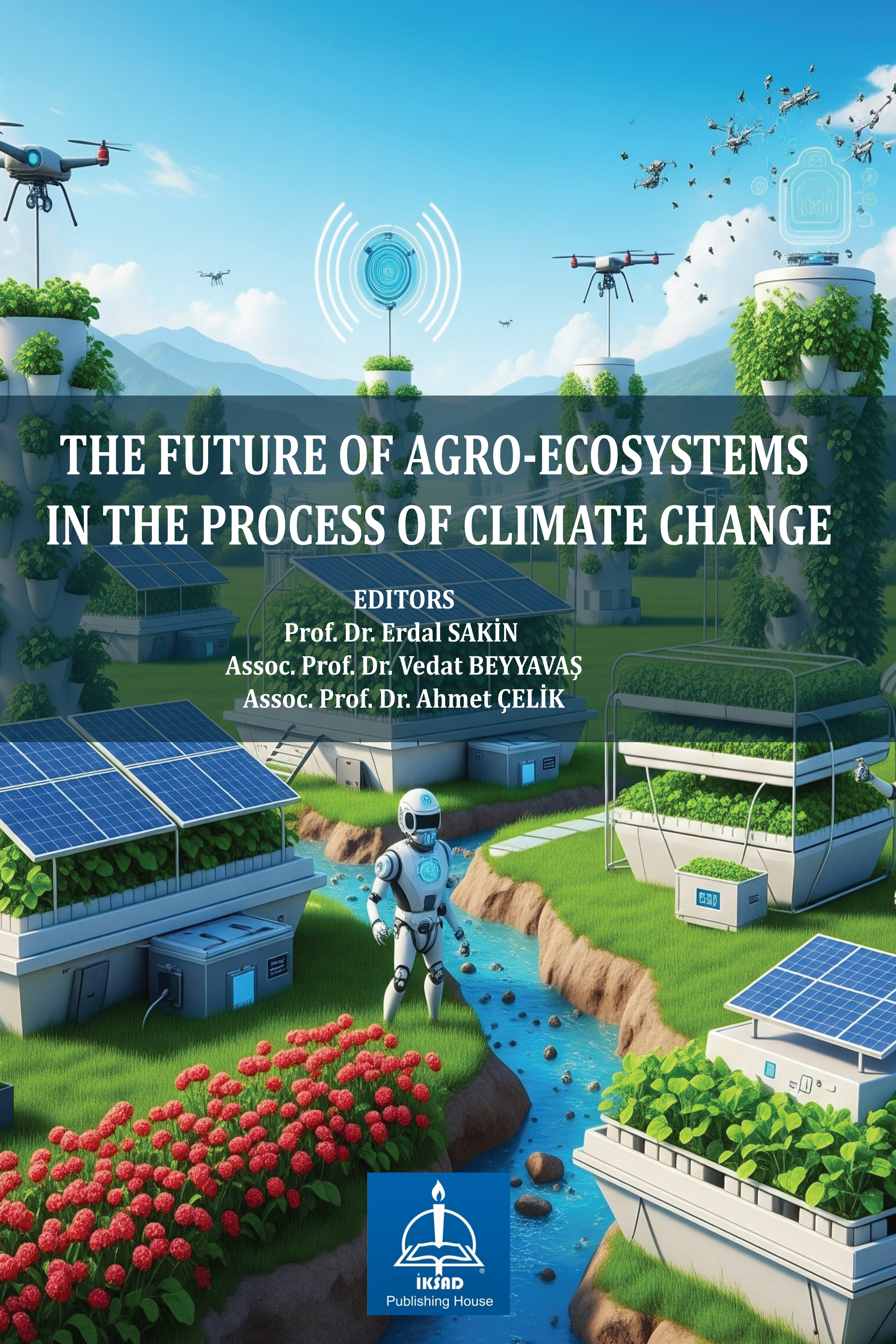

THE FUTURE OF AGRO-ECOSYSTEMS IN THE PROCESS OF CLIMATE CHANGE

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PREFACE

Agriculture is currently one of the sectors most affected by climate change. Due to its extensive area of activity and sensitivity to meteorological variability, the impacts of climatic change on agriculture can directly influence human life and other living organisms. The adverse environmental events that are occurring and are likely to occur in the future will especially affect human well-being in social and economic dimensions. Alongside a growing population, the shrinking availability of arable land and the increasing competition between food production and urbanization have brought food security into a critical and threatened position. This process directly influences the dynamics of agricultural ecosystems.

Identifying the direct risks posed by climate change to agricultural production and determining potential strategies to enhance the sustainability of agriculture have become imperative. The increase in agricultural risk factors can lead to reduced crop yields and productivity, decreased food production, increased incidences of diseases and pests, proliferation of invasive weeds, soil fatigue and contamination due to intensive use, and ultimately, a rise in production costs. For these reasons, climate change may adversely affect the provision and sustainability of ecosystem services and compromise food security for future generations in terms of both quantity and quality.

In contrast, agroecological approaches offer resilient and sustainable solutions to these changes. It is of great importance that agricultural policies are restructured to promote such systems.

In conclusion, the impacts of climate change on agriculture are inevitable; however, it is possible to build resilient, nature-compatible, and sustainable agro-ecosystems. The integration of scientific research with local practices will form the foundation of this transformation. When combined with agroecosystem principles, this transformation necessitates the implementation and support of new cultivation technologies and smart farming practices that can mitigate agricultural risks associated with climate change, such as drought, stress conditions, and inefficient water use.

We would like to thank the authors who contributed to the preparation of the book.

July, 2025

Prof. Dr. Erdal SAKİN
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CHAPTER 1

WHY IS SOIL pH SO IMPORTANT?

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INTRODUCTION

Soil pH is a critical factor in agriculture, horticulture, and environmental science. It is a measure of the acidity or alkalinity of the soil, expressed on a logarithmic scale from 0 to 14, where 7 is neutral, values below 7 are acidic, and values above 7 are alkaline. Soil pH influences numerous soil properties and processes, including nutrient availability, microbial activity, and plant growth. This review explores the significance of soil pH, its effects on soil-plant interactions, and its management for sustainable agriculture.

Soil pH is influenced by the mineral composition of the parent material and the weathering processes it undergoes. For example, in humid regions, prolonged soil acidification occurs as weathering products are leached away by water moving laterally or downward through the soil. In contrast, in arid environments, weathering and leaching are less pronounced, resulting in soils that are often neutral or alkaline in pH (Bloom et al., 2012).

For many, soil pH is primarily associated with soil chemistry and fertility. However, understanding soil's broader ecosystem functions beyond its role in plant nutrient supply and growth necessitates a multidisciplinary approach to studying soil and its properties. This perspective enables scientists to examine processes at various scales, from local landscapes to regional and global levels (Dahlgren, 2006). One such multidisciplinary field is soil biogeochemistry, which investigates the interconnected biological, chemical, and geological processes within soils. These biogeochemical processes are closely linked to the ecosystem functions of soil, highlighting its importance beyond agriculture. Soil is a vital component of life support systems, providing essential ecosystem goods and services such as carbon sequestration, water regulation, soil fertility, and food production, all of which significantly impact human well-being (FAO, 2015). These services are broadly classified into four categories: supporting, provisioning, regulating, and cultural services. According to the Millennium Ecosystem Assessment, provisioning and regulating services have the most substantial influence on human well-being, affecting safety, access to basic resources, health, and social relationships. Thus, soil's role extends far beyond plant growth, underpinning critical ecological and human systems (Neina, 2019).

Soil pH and Nutrient Availability

Soil pH directly affects the solubility and availability of essential plant nutrients. Soil pH significantly influences nutrient availability, impacting plant growth and agricultural productivity (Price, 2006). The pH scale ranges from 0 to 14. Soils with a pH below 7 are acidic, while those above 7 are alkaline. Most nutrients are optimally available to plants in slightly acidic to neutral soils (pH 6.0–7.0). In acidic soils (pH < 6.0), essential nutrients like phosphorus (P), calcium (Ca), and magnesium (Mg) become less available due to fixation or leaching, while toxic elements like aluminum (Al) and manganese (Mn) can reach harmful concentrations. Conversely, in alkaline soils (pH > 7.0), micronutrients such as iron (Fe), zinc (Zn), and copper (Cu) often form insoluble compounds, reducing their availability (Allen et al., 1994).

Phosphorus, a critical nutrient, is particularly sensitive to pH changes, with maximum availability occurring around pH 6.5. Nitrogen (N), primarily absorbed as nitrate (NO_3^-) or ammonium (NH_4^+), is also influenced by pH, as nitrification—the conversion of ammonium to nitrate—is hindered in highly acidic soils (White, 2005). Soil pH affects microbial activity, which plays a vital role in nutrient cycling. For instance, nitrogen-fixing bacteria and mycorrhizal fungi, essential for nutrient uptake, thrive in near-neutral pH conditions. Farmers often adjust soil pH using lime (to raise pH) or sulphur (to lower pH) to optimize nutrient availability. Regular soil testing is crucial to monitor pH levels and implement appropriate amendments. Understanding the relationship between soil pH and nutrient availability is essential for sustainable agriculture, ensuring efficient fertilizer use and minimizing environmental impacts such as nutrient runoff and soil degradation (Brady & Weil, 2008; Havlin et al., 2016). However, extreme pH levels can lead to nutrient deficiencies or toxicities

Acidic Soils (pH < 6.0)

In acidic soils, essential nutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg) become less available. Conversely, the solubility of toxic elements like aluminum (Al) and manganese (Mn) increases, which can inhibit root growth and nutrient uptake (Brady and Weil, 2008). Soil pH plays a critical role in regulating the solubility, mobility, and bioavailability of trace elements, which in turn affects their uptake and translocation in plants (Forstner, 1995). This regulation is primarily governed by the distribution of these elements between the solid and liquid phases of the soil, driven by precipitation-dissolution reactions (Rieuwerts et al., 1998) that are influenced by pH-dependent charges in both mineral and organic soil components. For example, at high pH levels, negative charges tend to dominate, while at low pH values, positive charges are more prevalent (Gillman, 2007). Furthermore, soil pH also controls the amount of dissolved organic carbon, which significantly impacts the availability of trace elements. At low pH, trace elements are usually soluble due to high desorption and low adsorption (Bradl, 2004).

Alkaline Soils (pH > 7.5)

In alkaline soils, micronutrients such as iron (Fe), zinc (Zn), and copper (Cu) become less available, leading to deficiencies in plants. Phosphorus also tends to form insoluble compounds with calcium, reducing its availability (Marschner, 2012). In calcareous soils, it is observed that at a certain pH level, the solubility of minerals reverses its trend as pH continues to rise; specifically, the solubility of calcium phosphate starts to increase with further pH elevation. This phenomenon occurs because carbonate competes effectively with phosphate for calcium, leading to the consumption of calcium by carbonate. As calcium carbonate (calcite) forms, the carbonate depletes the solution of Ca2+, which would otherwise have precipitated as calcium phosphate at lower pH levels (Penn and Camberato, 2019).

Soil pH and Microbial Activity

Soil microorganisms play a crucial role in nutrient cycling, organic matter decomposition, and soil structure formation. Soil pH is a key factor influencing microbial diversity, enzyme activity, and overall soil health. Microorganisms, including bacteria, fungi, and actinomycetes, thrive within specific pH ranges, with most preferring slightly acidic to neutral conditions (pH 6.0–7.5) (Khmelevtsova et al., 2022).

Effects of Acidic Soils (pH < 6.0) on Microbial Activity

In acidic soils, microbial diversity and activity often decline, as many beneficial bacteria, particularly those involved in nitrogen fixation and nitrification, are highly sensitive to low pH. For example, *Nitrosomonas* and *Nitrobacter*, which convert ammonium to nitrate, exhibit reduced activity in acidic environments, limiting nitrogen availability for plants. Similarly, the decreased activity of nitrogen-fixing bacteria such as *Rhizobium* negatively impacts legume crops, which rely on these bacteria for symbiotic nitrogen fixation.

Conversely, fungi generally tolerate a wider pH range and may dominate highly acidic soils, playing a significant role in organic matter decomposition and nutrient cycling (Sale et al., 2024). However, acidic soils can also foster the growth of pathogenic fungi, which may negatively impact plant health. Furthermore, the increased solubility of toxic elements like aluminum and manganese at low pH levels can further suppress microbial activity, leading to imbalances in nutrient cycling.

Effects of Alkaline Soils (pH > 7.5) on Microbial Activity

In alkaline soils, microbial activity can also be restricted due to the reduced solubility of essential nutrients such as iron and zinc, which are crucial for microbial metabolism. Soil pH influences enzyme function, as many enzymes involved in organic matter decomposition, such as cellulase and phosphatase, operate most efficiently at near-neutral pH. In highly alkaline conditions, phosphorus availability is also significantly reduced, hindering microbial growth since phosphorus is a vital component of nucleic acids and ATP.

Changes in soil pH can also shift microbial community composition, altering the balance between beneficial and pathogenic organisms. For example, mycorrhizal fungi, which enhance plant nutrient uptake, are less effective in highly acidic or alkaline soils. Additionally, the proliferation of alkaliphilic bacteria in alkaline soils may disrupt nutrient cycling, potentially leading to plant growth limitations.

Microbial Activity and Greenhouse Gas Emissions

Soil pH significantly influences microbial respiration rates and carbon cycling, impacting the release of greenhouse gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O). In neutral soils, microbial activity facilitates efficient organic matter decomposition, promoting carbon sequestration. However, in highly acidic or alkaline soils, microbial efficiency decreases, slowing decomposition and altering soil organic carbon dynamics. This can contribute to increased greenhouse gas emissions, particularly in disturbed agricultural soils.

Managing Soil pH for Optimal Microbial Activity

Maintaining optimal soil pH through targeted soil amendments is essential for promoting microbial diversity and sustaining healthy soil ecosystems. The application of lime to acidic soils helps neutralize pH and alleviate aluminum toxicity, enhancing bacterial diversity and function. Conversely, the addition of sulfur or acid-forming fertilizers to alkaline soils improves phosphorus and micronutrient availability, fostering a more balanced microbial community.

Regular soil pH monitoring is crucial for implementing appropriate corrective measures and ensuring long-term soil health. Sustainable soil management practices, including organic matter incorporation and crop rotation, can further stabilize soil pH and enhance microbial function, supporting overall soil fertility and agricultural productivity (Brady & Weil, 2008; Fierer & Jackson, 2006).

By understanding the relationship between soil pH and microbial activity, farmers and land managers can implement effective strategies to optimize soil health, improve nutrient cycling, and enhance crop productivity while minimizing environmental impacts.

Soil pH and Plant Growth

Soil pH plays a crucial role in plant growth by directly affecting root development and indirectly influencing nutrient availability and microbial activity. Plants rely on a sufficient supply of mineral nutrients, which are transported from the soil to the roots and then to the shoots. In many regions, especially in tropical areas, soil nutrient deficiencies significantly limit plant growth and crop productivity (Prescott et al., 1999). The rhizosphere, where microorganisms interact with root exudates, is the primary zone for nutrient absorption. However, soil pH is a key determinant of soil fertility and can be influenced by factors such as plant cultivation and fertilizer application (Yan et al., 1996).

Root Development

Soil pH strongly impacts root growth and nutrient uptake.

- Acidic Soils (pH < 5.5): Acidic soils often contain high levels of toxic aluminum (Al^{3+}) and manganese (Mn^{2+}), which can damage root tips, reducing their ability to absorb water and nutrients (Kochian et al., 2004). Acidification also displaces essential base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), leading to nutrient deficiencies (Goulding, 2016). Additionally, aluminum and iron minerals dissolve under acidic conditions, further altering soil chemistry. Among these effects, aluminum toxicity is the most detrimental to plant survival, as it inhibits root elongation and disrupts cell function (Bojórquez-Quintal et al., 2017).
- Alkaline Soils (pH > 7.5): In contrast, high soil pH can precipitate essential nutrients, making them less available to plants. Iron (Fe), phosphorus (P), and zinc (Zn) deficiencies are common in alkaline soils, leading to stunted root growth and reduced plant productivity. The reduced solubility of these nutrients affects root elongation and branching, ultimately hindering overall plant health.

These pH-related challenges highlight the importance of maintaining optimal pH levels to ensure effective root development and nutrient uptake.

Crop Yield and Quality

Soil pH has a direct impact on crop yield and quality by influencing nutrient uptake efficiency (Table 1).

- Acidic soils often lead to molybdenum (Mo) deficiency, which is critical for nitrogen metabolism in plants (Gupta, 1997). Additionally, aluminum toxicity and phosphorus fixation reduce the availability of essential nutrients, leading to poor crop growth.
- Alkaline soils cause micronutrient deficiencies, particularly of iron (Fe) and zinc (Zn), leading to problems such as chlorosis (leaf yellowing) and decreased fruit quality (Rengel, 1992).

Studies have demonstrated that maintaining soil pH within the optimal range (6.0–7.0) improves crop yield and nutritional quality (Fageria et al., 2015). Proper pH management strategies, such as liming acidic soil or applying sulfur to alkaline soils, are essential for sustainable agriculture and food security.

Table 1. pH Sensitivity of Different Crops

Crop Type	Common Crops	Optimal pH Range	Effects of Acidic Soils (pH < 5.5)	Effects of Alkaline Soils (pH > 7.5)	References
Cereals	Wheat, Rice, Maize	5.5 – 7.5	Al toxicity, P fixation	Fe, Zn deficiencies, reduced yields	Rengel (2003); Dobermann & Fairhurst (2000)
Legumes	Soybean, Peas	6.0 – 7.5	Poor rhizobia function, N fixation	P and Zn deficiencies	Zahran (1999); Tang et al. (2003)
Root Crops	Potatoes, Carrots	5.0 – 6.5	Al toxicity, stunted root growth	Ca accumulation affects development	Kochian et al. (2004)
Fruits	Citrus, Grapes	6.0 – 7.5	Root damage, Ca deficiency	Iron chlorosis, poor fruit quality	Marschner (2012)
Vegetables	Tomatoes, Lettuce	6.0 – 7.0	Growth inhibition, nutrient imbalance	Micronutrient deficiencies	Brady & Weil (2016)

Soil pH is a critical factor that influences nutrient availability, root development, and crop productivity. Acidic soils frequently suffer from aluminum toxicity and phosphorus deficiency, whereas alkaline soils lead to micronutrient imbalances. Proper pH management is essential for optimizing crop growth and maintaining sustainable agricultural practices.

Soil pH and Environmental Sustainability

Soil pH is a fundamental property that influences environmental sustainability through its effects on nutrient cycling, soil microbial communities, greenhouse gas emissions, and pollutant dynamics. It plays a critical role in ecosystem stability, as extreme pH conditions can lead to soil degradation, biodiversity loss, and increased greenhouse gas emissions (Jansson & Hofmockel, 2012). Additionally, fluctuations in soil pH impact water quality by altering the mobility of nutrients and contaminants, further influencing aquatic ecosystems and agricultural sustainability. Understanding and managing soil pH is essential for maintaining long-term soil health, enhancing carbon sequestration, and mitigating climate change impacts.

Soil pH and Greenhouse Gas Emissions

Soil pH regulates the activity of microbial communities responsible for the production and consumption of major greenhouse gases, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The influence of soil pH on microbial metabolism can accelerate or suppress greenhouse gas fluxes, contributing to variations in atmospheric composition and climate change dynamics.

Nitrous Oxide (N_2O) Emissions

Nitrous oxide (N_2O) is a potent greenhouse gas primarily produced through nitrification and denitrification processes. Soil pH affects denitrifying bacteria, which convert nitrate (NO_3^-) to nitrogen gas (N_2), thereby influencing N_2O emissions. Acidic soils ($pH < 5.5$) tend to have higher N_2O emissions due to incomplete denitrification, as low pH inhibits the last step of this process, causing N_2O accumulation (Simek & Cooper, 2002). In contrast, near-neutral soils (pH 6.5–7.5) promote complete denitrification, reducing N_2O release and enhancing N_2 production (Table 2).

Carbon Dioxide (CO_2) Emissions

Soil pH significantly affects microbial decomposition of organic matter, which is a primary source of CO_2 emissions. Neutral to slightly alkaline soils (pH 6.5–8.0) enhance microbial activity, accelerating organic matter breakdown and increasing CO_2 flux into the atmosphere. In contrast, acidic soils ($pH < 6.0$) suppress microbial respiration, reducing decomposition rates and CO_2 release (Lal, 2004). Extreme pH conditions also stress microbial populations, altering their respiratory efficiency and carbon turnover (Table 2).

Methane (CH_4) Emissions

Methane (CH_4) is produced by methanogenic bacteria under anaerobic conditions, such as those found in waterlogged soils and wetlands (Table 2). These bacteria are highly sensitive to pH fluctuations, with methane production being optimal between pH 6.5 and 8.5. Acidic conditions (pH < 5.5) suppress methanogenesis, leading to lower CH_4 emissions, whereas alkaline soils (pH > 8.5) create conditions unfavorable for methane oxidation, allowing more CH_4 to escape into the atmosphere (Brady & Weil, 2008).

Table 2. Influence of Soil pH on Greenhouse Gas Emissions

Greenhouse Gas	**Effect of Low pH (<6.0)**	**Effect of Neutral pH (6.0–7.5)**	**Effect of High pH (>7.5)**	**References**
N_2O (Nitrous Oxide)	Increased emissions due to incomplete denitrification	Reduced emissions due to complete denitrification	Lower emissions as denitrification efficiency increases	Simek & Cooper (2002)
CO_2 (Carbon Dioxide)	Lower emissions due to suppressed microbial respiration	Increased emissions due to enhanced organic matter decomposition	Very high emissions due to excessive microbial respiration	Lal (2004)
CH_4 (Methane)	Lower emissions due to suppressed methanogenesis	Optimal methane production in anaerobic soils	Reduced emissions due to inhibited methanotrophic activity	Brady & Weil (2008)

Strategies for Managing Soil pH

Maintaining an optimal soil pH range (6.0–7.5) is essential for ensuring efficient nutrient cycling, plant productivity, and environmental sustainability. Soil pH modifications involve lime application for acidic soils and sulfur amendments for alkaline soils.

Raising Soil pH (Managing Acidic Soils, pH < 5.5)

Acidic soils are often amended with lime ($CaCO_3$) to neutralize acidity and improve nutrient availability. The amount of lime required depends on soil texture, buffering capacity, and crop requirements (Havlin et al., 2016) (Table 3).

Lime Requirement Calculation Formula:

Lime Requirement= (Target pH−Initial pH)×Buffer Capacity×Soil Depth×2.0

Table 3. Lime Application Rates Based on Soil Texture

Soil Texture	Amount of Lime (tons/ha) to Raise pH by 1.0
Sand	1.0 – 2.0
Loam	2.0 – 4.0
Clay	4.0 – 6.0

Lowering Soil pH (Managing Alkaline Soils, pH > 7.5)

Alkaline soils require acidification using elemental sulfur, acid-forming fertilizers, or organic amendments (Tisdale et al., 1985) (Table 4).

Sulphur Requirement Calculation Formula:

Sulphur Requirement= (Initial pH−Target pH)×Soil Buffer Factor×Soil Depth×0.15

Table 4. Sulfur Application Rates Based on Soil Texture

Soil Texture	Amount of Elemental Sulfur (kg/ha) to Lower pH by 1.0
Sand	500 – 1,000
Loam	1,000 – 2,000
Clay	2,000 – 3,000

Soil pH is a key environmental factor that affects nutrient availability, microbial activity, and greenhouse gas emissions. Proper pH management is crucial for sustainable agriculture, carbon sequestration, and climate change mitigation. Future research should focus on eco-friendly soil pH management techniques, particularly in response to climate change and increasing global food demands.

REFERENCES

Allen, H. E., Huang, C. P., Bailey, G. W., & Bowers, A. R. (1994). *Metal speciation and contamination of soil*. Crc Press.

Assessment, M. E. (2005). Ecosystem and human well-being: Desertification synthesis. *World Resources Institute, Washington, DC*, *36*.

Bloom PR, Skyllberg U. Soil pH and pH buffering. In: Huang PM, Li Y, Sumner ME, editors. Handbook of Soil Sciences: Properties and Processes. 2nd ed. Boca Raton, FL: CRC Press; 2012. pp. 19-14. ISBN: 9781439803059.

Bojórquez-Quintal, E., Escalante-Magaña, C., Echevarría-Machado, I., & Martínez-Estévez, M. (2017). Aluminum, a Friend or Foe of Higher Plants in Acid Soils. *Frontiers in Plant Science, 8*, 1767.

Bradl, H. B. (2004). Adsorption of heavy metal ions on soils and soils constituents. *Journal of colloid and interface science*, *277*(1), 1-18.

Brady, N. C., & Weil, R. R. (2008). *The Nature and Properties of Soils* (14th ed.). Pearson Education.

Brady, N.C., & Weil, R.R. (2016). *The Nature and Properties of Soils* (15th ed.). Pearson.

Dahlgren R. A., Biogeochemical processes in soils and ecosystems: from landscape to molecular scale, *Journal of Geochemical Exploration*. (2006) **88**, no. 1–3, 186–189, https://doi.org/10.1016/j.gexplo.2005.08.035, 2-s2.0-31744446232.

Fageria, N. K., Nascente, A. S., & Stone, L. F. (2015). Agronomic evaluation of coated and common urea in upland rice production. *Communications in Soil Science and Plant Analysis*, *46*(17), 2152-2161.

FAO, *Revised World Soil Charter*, 2015, Food and Agriculture Organization, Rome, Italy.

Fierer, N., & Jackson, R. B. (2006). The diversity and biogeography of soil bacterial communities. *Proceedings of the National Academy of Sciences*, 103(3), 626-631.

Forstner, U. (1995). Land contamination by metals: global scope and magnitude of problem. *Metal speciation and contamination of soil*, 1-33.

Gillman, G. P. (2007). An analytical tool for understanding the properties and behaviour of variable charge soils. *Soil Research*, *45*(2), 83-90.

Goulding, K.W.T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management, 32*(3), 390–399.

Gupta, U.C. (1997). Molybdenum and food production: A review of the literature and recommendations for research. *Soil Science and Plant Nutrition, 43*(2), 379–395.

Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2016). *Soil fertility and fertilizers*. Pearson Education India.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., & Nelson, W.L. (2016). *Soil Fertility and Fertilizers* (8th ed.). Pearson.

Jansson, J.K., & Hofmockel, K.S. (2012). The soil microbiome—role in climate change and sustainable agriculture. *Science, 338*(6110), 1407–1412.

Khmelevtsova, L. E., Sazykin, I. S., Azhogina, T. N., & Sazykina, M. A. (2022). Influence of agricultural practices on bacterial community of cultivated soils. *Agriculture*, *12*(3), 371.

Kochian, L.V., Piñeros, M.A., & Hoekenga, O.A. (2004). The physiology, genetics, and molecular biology of plant aluminum resistance and toxicity. *Plant and Soil, 274*(1-2), 175–195.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma, 123*(1-2), 1–22.

Marschner, H. (2012). *Mineral Nutrition of Higher Plants* (3rd ed.). Academic Press.

Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and environmental soil science*, *2019*(1), 5794869. https://doi.org/10.1155/2019/5794869

Penn, C. J., & Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*, *9*(6), 120.

Prescott, C.E., Grayston, S.J., & Helmisaari, H.S. (1999). Nutrient cycling in boreal forest ecosystems. *Soil Biology and Biochemistry, 31*(5), 677–687.

Price, G. (Ed.). (2006). *Australian soil fertility manual*. CSIRO publishing.

Rengel, Z. (1992). The role of micronutrients in crop response to acid soils. *Plant and Soil, 146*(1-2), 143–151.

Rengel, Z. (2003). Soil pH, soil health and climate change. In *Soil health and climate change* (pp. 69-85). Berlin, Heidelberg: Springer Berlin Heidelberg.

Rieuwerts, J. S., Thornton, I., Farago, M. E., & Ashmore, M. R. (1998). Factors influencing metal bioavailability in soils: preliminary investigations for the development of a critical loads approach for metals. *Chemical Speciation & Bioavailability*, *10*(2), 61-75.

Sale, S., Dobermann, A., Cerri, C. E., Svoray, T., van-Es, H., Amsili, J., & Katz, S. (2024). Towards a unified approach to prioritization of regenerative agricultural practices across cropping systems. *npj Sustainable Agriculture*, *2*(1), 24.

Simek, M., & Cooper, J. E. (2002). The influence of soil pH on denitrification: Progress towards the understanding of this interaction over the last 50 years. *European Journal of Soil Science, 53*(3), 345–354.

Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (1985). *Soil fertility and fertilizers* (pp. 754-pp). Macmillan Publishing.

White, R. E. (2006). *Principles and practice of soil science: the soil as a natural resource*. John Wiley & Sons.

Yan, F., Schubert, S., & Mengel, K. (1996). Soil pH increase due to biological decarboxylation of organic acids. *Soil Biology and Biochemistry, 28*(4-5), 617–624.

Zahran, H.H. (1999). Rhizobium-legume symbiosis and nitrogen fixation under severe conditions. *Applied Microbiology and Biotechnology, 52*, 27–37.

CHAPTER 2

ABIOTIC STRESS SENSING MECHANISMS IN LEGUMES

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1.Introduction

Legumes are one of the most significant food resources worldwide and are high in protein, fiber and various vitamins. These characteristics enhance the significance of legumes in human nutrition and make them essential for agricultural sustainability. Nevertheless, these crops are experiencing significant losses in production due to global climate change and environmental stress factors. In particular, abiotic stress factors are among the main threats to legume production. Abiotic stress is defined as the stress on plants caused by physical or chemical environmental factors such as water stress, salinity, heavy metal contamination and temperature extremes. Under these stress conditions, vital processes such as photosynthesis, protein synthesis and nutrient uptake in legumes can be adversely affected. Recent studies have investigated in detail the mechanisms of legume adaptation to abiotic stress conditions and provided important information on how these adaptations occur at the genetic level. For example, Farooq et al. (2017) investigated different adaptation strategies of legumes to drought stress. These strategies included increasing root depth, stomatal closure and osmotic adjustment. Furthermore, analyzing the genetic response of legumes under salt stress, Gupta et al. (2014) reported that overexpression of genes associated with salt tolerance in these plants can positively impact seedling development under stress.

The toxic effects of metals are also a serious source of abiotic stress on legumes. In particular, heavy metal accumulation can cause oxidative stress in plants, damaging cellular structure and inhibiting photosynthesis. In this context, a study by Sharma and Dietz (2016) focused on the role of protective enzymes against heavy metal stress in legumes. The study indicated that an increase in the activity of these enzymes may increase the survival rate of plants under stress conditions. Climate change, specifically with increases in temperature and CO2 concentration, affects legume production, which directly affects the growth and development processes of plants. Zhu et al. (2018) examined how increasing temperatures affect photosynthesis rates in legumes. The results show that temperature increase can increase photosynthesis rates up to a certain point, but beyond this limit, photosynthesis rates decrease.

2.Description and Importance of Abiotic Stress in Legumes

Abiotic stress is defined as stress caused by non-living environmental factors that affect the growth and productivity of plants. These stresses can be physical (temperature, light, wind, flooding, cold) or chemical (salinity, water stress, toxic metals) and negatively affect the vital functions of plants (Zhu, 2016). Abiotic stress affects the metabolic activities of plants, making it difficult to regulate basic biological processes such as photosynthesis, water and nutrient uptake, and protein synthesis. This can result in growth retardation, yield loss and even death in plants. (Osakabe et al., 2014).

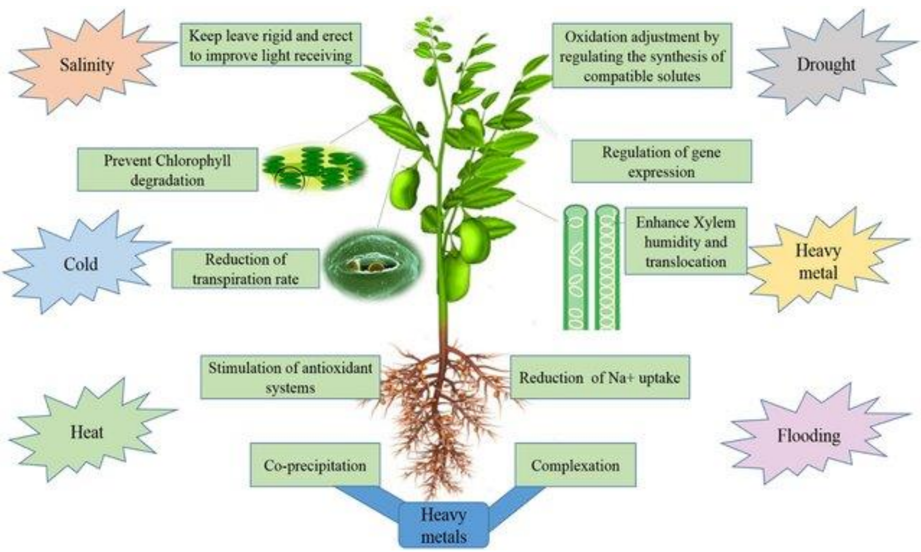

Figure.1. Effects of abiotic stresses on the growth of legume plants (Ali et al., 2022).

Abiotic stress is of major importance for global food security and agricultural sustainability. Climate change and increasing environmental variability increase the frequency and severity of abiotic stressors, putting pressure on agricultural production. In particular, the continuous increase in the world's population and the reduction of agricultural land have made the need to enhance the adaptation and tolerance of plants to abiotic stress conditions even more critical (Acquaah, 2012). Plants develop various mechanisms of defense against abiotic stress. These mechanisms include osmotic adjustment, enhancement of the antioxidant defense system, expression of stress-related proteins and morphological adaptations (Zhu, 2016). To understand abiotic stress conditions, it is essential to unravel these mechanisms in order to develop plant varieties that are more resistant to stress conditions. The definition of abiotic stresses and the in-depth study of their effects on plants are critical to optimize agricultural practices, guide plant breeding efforts and improve food security. Therefore, scientists and agricultural technologists are constantly researching and innovating to develop agricultural systems that are more resilient to abiotic stressors.

3. Types of Abiotic Stress: Salinity, Temperature and Drought

Abiotic stresses have various challenging effects on plants and the strategies developed to cope with these stresses are an area of significant research in plant biology and agricultural sciences. Salinity, temperature and drought are some of the most common and most effective abiotic stressors faced by plants. The effects of each of these factors and the responses of plants to these stresses have been widely discussed in literature.

3.1. Salinity Stress

Salinity is a stress that affects about 20 percent of agricultural land worldwide and causes significant reductions in agricultural productivity. In plants, salt stress reduces the osmotic potential of water, hindering water and nutrient uptake and leading to ionic imbalances. Under this stress, plants show various biochemical and physiological responses, such as the accumulation of osmoprotectants (such as proline) and activation of antioxidant defense systems. Research by Munns and Tester (2017) examined in detail how salt stress is perceived in plants and which signaling pathways are activated.

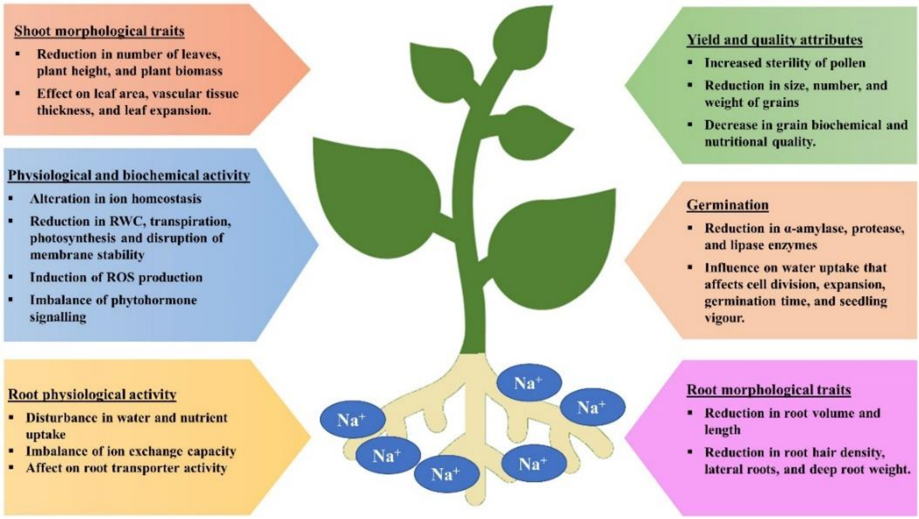

Figure.2. Detrimental effects of salinity stress on various plant parts at different growth stages (Atta et al., 2023).

Salinity makes it more difficult for plants to take up water and nutrients, inhibiting growth. Salinity stress disrupts the balance of cellular osmotic pressure, mainly due to high concentrations of sodium and chlorine ions. This restricts plants' water uptake and competes with nutrients, slowing photosynthesis processes and causing a reduction in growth. To cope with this stress, plants activate mechanisms such as ion separation, ion exclusion, and osmotic adjustment. Salinity stress is caused by high salt concentrations, especially in irrigation water, and interferes with water and nutrient uptake by plants. Under this stress, plants alter the expression of genes regulating ion pumps and channels to reduce the toxic effects of sodium and chlorine ions. Deinlein et al. (2014) examined the role of Na^+/H^+ antiporters in plants in response to salinity stress and showed that these proteins play critical roles in salt exclusion mechanisms. Furthermore, intensive studies have been conducted on specific transcription factors and signaling molecules associated with salt tolerance (Roy et al., 2014).

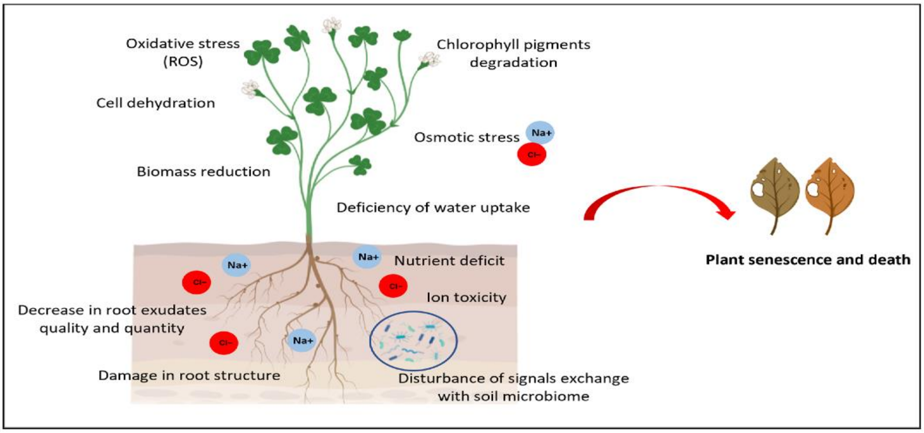

Figure.3. Effects of drought and salinity on legume growth and physiology (Ben Gaied et al.,2024).

3.2. Heat Stress

Heat stress is an environmental stress factor that limits the physiological and biochemical activities of plants. Generally, it occurs when plants are outside the optimum temperature range. High heat stress limits the growth and development of plants by negatively affecting basic biological processes such as photosynthesis, respiration and enzyme activities (Taiz & Zeiger, 2015). Such stress is becoming more frequent due to increasing greenhouse gas emissions and climate change and is particularly severe in arid and semi-arid regions.

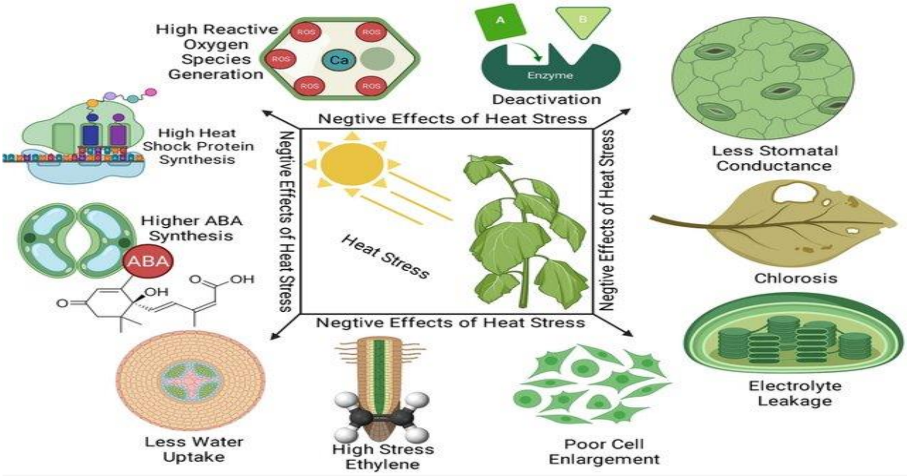

Figure.4. Effects of heat stress on plants (Ul Hassan et al.,2021).

Effects of Heat Stress and the Mechanisms Enhanced in Plants

Plants exposed to heat stress cause disruptions in metabolic processes, damage to cell membranes and accumulation of reactive oxygen species (ROS). This can result in cellular damage and denaturation of proteins. Plants have developed various adaptation mechanisms to mitigate these negative effects:

Heat Shock Proteins (HSPs): HSPs ensure correct folding of proteins and maintenance of cellular homeostasis (Wang et al., 2004).

Antioxidant Systems: Antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) reduce oxidative stress by controlling ROS levels (Mittler, 2006).

Osmoprotectants: Osmoprotectants such as proline and trehalose regulate water balance in cells and stabilize enzyme activities.

Stomatal Closure: Limits water loss by reducing transpiration and increases plant water use efficiency.

Heat Stress in Legumes

Legumes are a source of protein, minerals and fiber, which play an essential role in human nutrition and animal nutrition. In addition, they have an essential place in agriculture as they perform symbiotic nitrogen fixation in root nodules. Chickpeas (Cicer arietinum), lentils (Lens culinaris), beans (Phaseolus vulgaris), peas (Pisum sativum) and soybeans (Glycine max) are widely produced worldwide. Nevertheless, these crops are sensitive to environmental stresses and are particularly affected by high temperature stress. Several studies have shown that temperature increases negatively affect nodule formation, nitrogen fixation and root development (Aranjuelo et al., 2014).

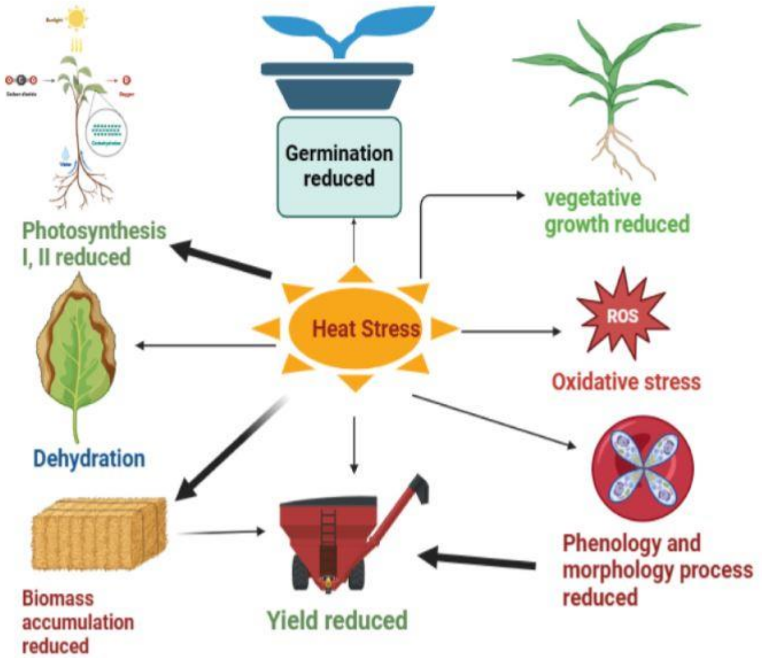

Figure.5. Effect of heat stress on legume crops (Sher et al.2024).

Nodule Performance: High temperatures reduce nitrogen fixation by reducing enzyme activities in nodules.

Photosynthesis: Since photosynthetic enzymes are temperature sensitive, temperature increase limits carbon assimilation (Chaves et al., 2009).

Reactive Oxygen Species: Increased ROS during heat stress cause lipid peroxidation of cell membranes and reduce the viability of bacteroids in nodules.Yavaş and Ünay (2018) examined the effects of temperature stress on nodule formation in legumes such as chickpea and bean. In the study, it was found that nodule formation decreased and nitrogen fixation decreased up to 50% at temperatures above 32°C. Another study revealed that heat shock proteins at the molecular level play an important role in developing temperature tolerance (Çirka et al., 2019).

Strategies to Reduce Heat Stress

Several agronomic and biotechnological approaches have been developed to mitigate the negative effects of heat stress on legumes;

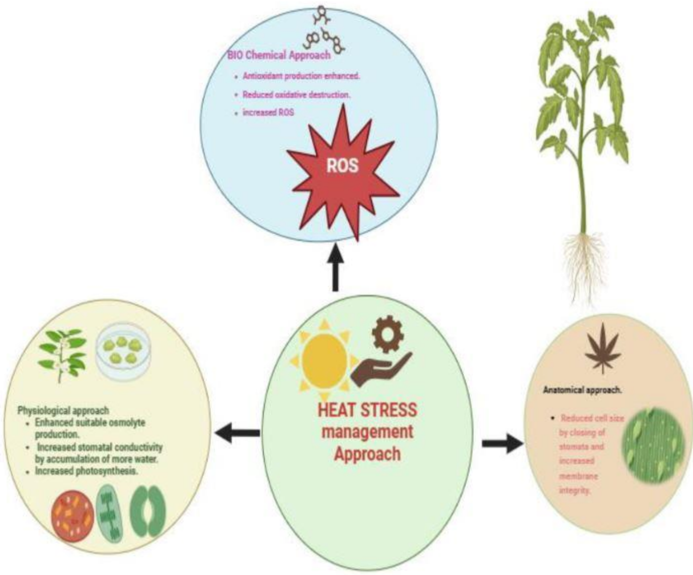

Figure.6. Approaches to heat stress management in legumes (Sher et al.2024).

Breeding Studies: The development of varieties that are tolerant to heat stress is possible through modern breeding techniques. These studies focus on selecting genotypes that provide tolerance to temperature stress using genetic variations (Çirka et al., 2019).

Molecular Genetics: Gene editing techniques such as CRISPR/Cas9 are used to identify and modify genes that increase tolerance to heat stress.

Agronomic Methods: Methods such as mulching, shading and drip irrigation can alleviate stress conditions by regulating plant microclimate.

Hormonal Regulations: Hormones such as abscisic acid (ABA) and salicylic acid (SA) used during abiotic stresses can increase the adaptive capacity of plants.

Heat stress poses a serious threat to agricultural production in the context of global warming and climate change. Understanding the effects of heat stress in legumes is important for sustainable agricultural production. In this context, the combination of genetic breeding, molecular biotechnology, and agronomic practices holds promise for the development of legume varieties resistant to heat stress. Future research will provide solutions to implement these strategies more effectively and to improve stress tolerance.

3.3. Drought Stress

Drought is a severe obstacle to agriculture, especially in regions where water resources are limited. Under drought stress, plants develop various physiological and morphological adaptations to reduce water loss and increase water use efficiency. Osakabe et al. (2014) investigated ABA (Abscisic Acid) mediated signaling pathways and gene expression regulation of plants under drought stress. This study revealed the genetic adaptations developed by plants against water stress and how such adaptations provided protection under stress conditions.

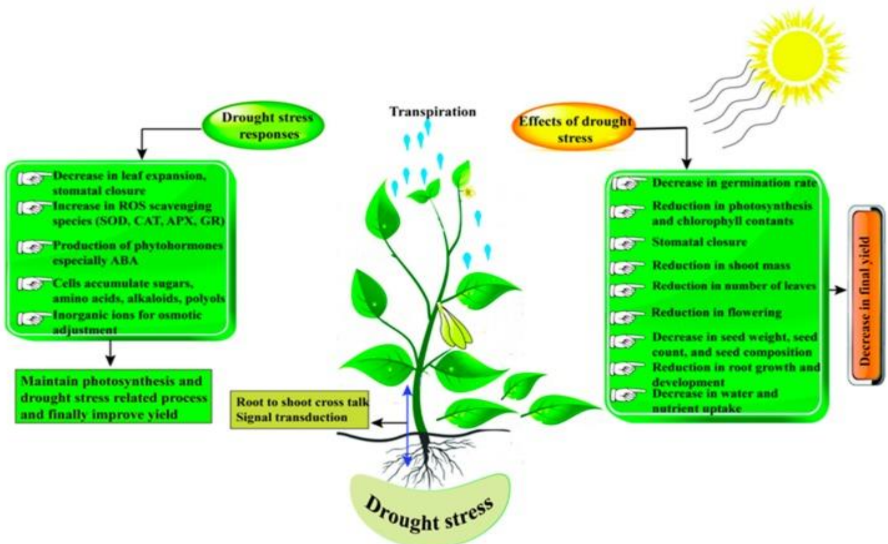

Figure.7. Impact of drought stress (DS) on plants and possible responses (Nadeem et al., 2019).

Drought is particularly problematic in water-limited environments and is the most common abiotic stress worldwide. In plants, drought stress restricts water uptake, reduces cellular turgor pressure, and slows plant growth and development. Studies show that under drought conditions, plants increase water access by deepening their root systems, reduce transpiration by promoting stomatal closure, and maintain cellular integrity by activating osmotic adjustment mechanisms (Hu and Xiong, 2014).

This research has contributed to understanding the effects of abiotic stresses on plants and developing new strategies to cope with these stresses. Such information can be used in plant breeding and genetic engineering studies, allowing the development of plant varieties that are more resistant to stress conditions.

To understand the biological effects of abiotic stresses, especially salinity, temperature and drought stresses, and their consequences on plants is an important area of research in plant sciences and agricultural applications. These stressors can profoundly affect plant life cycles, reproductive success and their role in the ecosystem. Below, the biological effects and reactions of these three main abiotic stresses are discussed in detail:

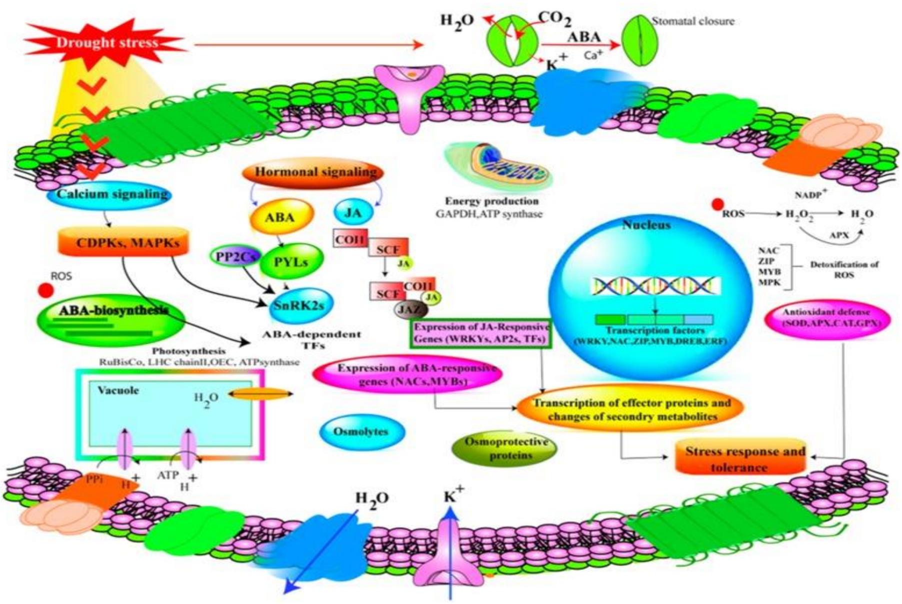

Figure.8. Schematic representation of drought tolerance mechanism in legumes (Nadem et al., 2019).

Drought is a form of stress experienced by plants when water is in short supply, severely limiting their water uptake, photosynthetic functions, and nutrient uptake. Drought stress leads to stomatal closure, reduced leaf area and reduced rates of photosynthesis. Long-term drought can reduce respiration rates and impair cellular integrity in plants. To cope with this stress, plants make morphological and physiological changes that reduce water loss, activate osmotic adjustment mechanisms and produce various stress-related proteins.

Abiotic stresses are environmental stressors that limit the growth, development, and productivity capacity of plants. In specific, salinity, temperature and drought are the main abiotic stresses that pose significant challenges to global agriculture and food security. These stresses lead to changes in plants at the morphological, physiological and molecular levels and understanding these changes is critical for the development of stress tolerant plant species.

4.Physiological Responses: Stress Sensing Mechanisms in Legumes

Legumes are a strategically important plant family in terms of global nutrition. While these crops serve as one of the main sources of protein worldwide, they can suffer severe production losses due to various abiotic stresses. Therefore, understanding the ability of legumes to respond to abiotic stresses is vital to improve their productivity and environmental adaptation. Abiotic stress sensing is the starting point of these responses and makes it possible to increase stress tolerance through genetic engineering.

4.1. Abiotic Stress Sensing Mechanisms

Legumes have specialized sensing mechanisms against various abiotic stresses. These mechanisms enable the plant to detect stress early and respond appropriately. Here are the sensing mechanisms in legumes against the most common abiotic stresses:

Salinity causes ionic imbalance and osmotic stress in plant cells. Legumes sense this stress mainly through ion channels and transporter proteins. These proteins are receptors and signaling molecules that enable the plant to sense salinity. For example, under salt stress, plants primarily sense sodium ions (Na^+). HKT transporters coded specifically for Na^+ ions sense high sodium concentrations intracellularly and transfer these ions out of the cell. Furthermore, NHX antiporters store sodium in vacuoles to maintain sodium and potassium (K^+) balance. These processes minimize the intracellular effects of salt stress and increase plant tolerance to salt stress (Blumwald, 2000).

High temperatures disrupt the natural structure of proteins and compromise cellular functions. Legumes produce heat shock proteins (HSPs) to sense this stress. HSPs are responsible for repairing damaged proteins and ensuring that new proteins fold correctly. Furthermore, heat shock factors (HSFs) trigger the transcription of HSP genes by sensing the temperature increase. These factors enable plants to respond quickly and efficiently to high temperature so that cellular integrity is maintained (Vierling, 1991). Drought stress occurs whenever water resources are limited. Legumes sense water stress through changes in the levels of the hormone abscisic acid (ABA). ABA levels rise rapidly under water limitation and this elevation reduces transpiration loss by closing the plant's stomata.

ABA also activates other molecular processes that respond to water stress by regulating gene expression under stress. It minimizes plant water loss and increases water use efficiency by making cellular osmotic adjustments during water stress (Zhu, 2002).To understand the abiotic stress sensing mechanisms of legumes is a fundamental step towards understanding the adaptation of these plants to environmental stress. With this knowledge, plant scientists and breeders can make genetic adjustments to increase productivity and expand adaptive capacity under stress conditions. In the future, technologies such as genetic engineering and CRISPR will make it possible to further improve these mechanisms.

5.Ecophysiological Effects: Effects on Growth, Development and Crop Yield

Legumes are noted for their high protein content and capacity for environmental adaptation as a major source of food worldwide. However, abiotic stressors on the growth, development and crop productivity of these plants are a major limiting factor. Stresses such as salinity, temperature and drought affect the ecophysiology of legumes and can reduce overall agricultural productivity. This chapter details the ecophysiological effects of these abiotic stresses on legumes, supported by various studies.

5.1. Effects on Growth and Development

Salinity causes toxicity and osmotic stress in plants, making water and nutrient uptake difficult. According to Munns and Tester (2008), salinity restricts root and leaf growth and reduces photosynthetic capacity. In legumes in particular, exposure to salinity can have adverse effects on seed germination and seedling growth (Shrivastava and Kumar, 2015). Temperature increases can cause reproductive failure in legumes, especially during pollen development and flowering periods. Studies by Hatfield and Prueger (2015) show that high temperature stress reduces pollen viability and impairs fertilization processes. Drought restricts water uptake by plants and reduces transpiration rates, which in turn reduces photosynthetic activity. Flexas et al. (2004) reported that drought stress is directly related to a decrease in photosynthesis. Furthermore, under prolonged drought conditions, legumes often develop deeper root systems, while vegetative growth at the surface remains limited (Ludlow and Muchow, 1990), which restricts plant access to water and nutrients.

5.2. Effects on Crop Yield

Abiotic stresses have direct effects on seed yield and quality of legumes. In particular, salinity and drought have negative effects during the reproductive period of the plant, reducing seed set and seed weight (Katerji et al., 2003). Under heat stress, the inhibitory effect of high temperatures on seed development can severely reduce overall yield (Barnabás et al., 2008). Abiotic stresses can cause significant losses in agricultural production by affecting growth, development and crop yield in legumes. The development of stress management strategies and the breeding of highly stress tolerant varieties play a critical role in alleviating these problems. Research in this area is enabling plant scientists and agronomists to develop legume varieties that are more resistant to stress conditions.

6.Biochemical Changes: Antioxidative Defense Systems

Legumes play an important role for global nutritional security and when exposed to various abiotic stresses, biochemical adaptation mechanisms kick in. These adaptations determine the capacity of plants to respond to stress conditions and increase their chances of survival. In particular, antioxidative defense systems to combat reactive oxygen species (ROS) are critical under stress conditions. In this chapter, the biochemical changes observed in plants in general and in legumes in particular, and the functions of antioxidative defense systems will be discussed in detail.Plants undergo various biochemical changes at the cellular and molecular levels in the face of environmental stressors. Under stress conditions, ROS production increases; these free radicals can cause oxidative damage to cellular structures. Increased ROS at the cellular level lead to lipid peroxidation, protein oxidation and DNA damage, which can cause cellular dysfunction and even cell death (Mittler et al., 2004). Legumes are particularly sensitive to abiotic stress conditions such as salinity, temperature and drought. Under these stresses, legumes activate biochemical defense mechanisms. For example, in legumes exposed to salinity stress, the activity of antioxidant enzymes increases and osmotic adjustment substances are synthesized to regulate intracellular salt concentration. Furthermore, legumes under stress produce secondary metabolites such as polyphenolic compounds and flavonoids, which serve as natural antioxidants and help protect cells from oxidative stress (Ahmad et al., 2010).

6.1. Antioxidative Defense Systems and Their Functions

Anti-oxidative defense systems are vital for plants to cope with oxidative stress. These systems include the following major enzymes and compounds:

Superoxide Dismutase (SOD) SOD functions as the primary line of defense against the damaging effects of ROS. Under oxidative stress, SOD enzymes dismutate superoxide radicals into the less harmful hydrogen peroxide and molecular oxygen. This conversion is a fundamental step in the protection of cells from oxidative damage (Alscher et al., 2002).

Catalase (CAT) CAT is responsible for the conversion of hydrogen peroxide to the harmless molecules water and oxygen. This enzyme is found in particularly high concentrations in peroxisomes and has a central role in ROS detoxication. In legumes, CAT activity increases especially under conditions of high salt and drought stress, which protects the plant from oxidative stress (Mittler, 2002). Ascorbate Peroxidase (APX) APX works within the ascorbate cycle and has a critical role in the reduction of hydrogen peroxide to water. This enzyme reduces the harmful effects of hydrogen peroxide by oxidizing intracellular ascorbate. APX can be induced in legumes, especially under drought and heat stress, and can increase the overall antioxidant defense capacity (Noctor and Foyer, 1998).

Glutathione Reductase (GR) GR maintains cellular redox balance by regenerating the reduced form of glutathione. This enzyme reduces the oxidized form of glutathione and maintains intracellular antioxidant capacity. The activity of GR is increased in legumes, especially under stress conditions where reactive oxygen species are high (Foyer and Noctor, 2005).

Understanding the antioxidative defense systems in legumes may provide better protection of these plants against various abiotic stress conditions. The efficiency of these systems directly affects the development of plants under stress conditions and crop yield. Therefore, plant breeding and genetic engineering efforts should aim to improve the stress tolerance of legumes by targeting these biochemical defense mechanisms

7.Management Strategies: Traditional and Biotechnological Approaches

Successful adaptation and tolerance of plants to abiotic stress is vital for the sustainability of agricultural production. In crops of high economic value, such as legumes, stress management strategies are realized through both traditional agricultural techniques and modern biotechnological approaches. These strategies aim to maintain yield and quality by increasing plant resilience to stress conditions. This chapter discusses traditional and biotechnological management strategies in detail and discusses the advantages and limitations of these approaches.

7.1. Traditional Management Strategies

Traditional management strategies mostly include techniques such as cultural practices, plant breeding and crop rotations. Such strategies have been part of agricultural practice for hundreds of years and are generally low-cost and easy to implement.

Cultural Practices: Cultural practices such as water management, tillage, fertilization, and timing of planting can improve plant resilience to stress conditions. For example, drip irrigation and mulching techniques provide effective management against drought stress by increasing water use efficiency (Kijne, 2006).

Plant Breeding and Selection: Traditional plant breeding methods involve selecting and developing varieties with high stress tolerance. Selective crossing and selection are used to increase resistance to abiotic stresses by maintaining and increasing the genetic diversity of plants (Acquaah, 2012).

Crop Rotations: The practice of rotating different crop species improves soil health and can increase tolerance to certain stressors. For example, rotation of legumes with other crops can reduce salinity stress by naturally increasing soil nitrogen levels (Cook et al., 2006).

7.3. Biotechnological Management Strategies

Biotechnology uses genetic engineering and molecular biology techniques to improve plant tolerance to stress. By directly altering the genetic makeup of plants, these modern approaches can accelerate their adaptation to specific stress conditions.

Genetic Engineering: Genetic engineering can increase stress tolerance by inserting foreign genes into the DNA of plants or modifying existing genes. For example, transgenic legume varieties with enhanced drought and salinity tolerance can show higher yield and growth under stress (Varshney et al., 2011).

Molecular Breeding: Using molecular markers and gene mapping techniques, genetic loci associated with stress tolerance can be identified. These techniques increase the efficiency of traditional breeding methods, allowing for faster and more accurate crosses (Collard and Mackill, 2008).

CRISPR/Cas9 and Other Gene Editing Technologies: Gene editing technologies such as CRISPR/Cas9 enable rapid and precise changes in the genetic material of plants. This technology can accelerate the adaptation of plants to abiotic stress conditions through direct regulation of stress-related genes (Bortesi and Fischer, 2015).

Traditional and biotechnological management strategies are complementary approaches to improve abiotic stress tolerance in legumes. Both strategies are of great importance for global food security and sustainability of agriculture. In the future, integrating these methods may offer innovative solutions to optimize crop yields under stress conditions while reducing environmental impacts.

8.Future Perspectives: Gene Editing Technologies and Sustainable Agricultural Practices

Modern agriculture aims at both environmental sustainability and meeting the food needs of a growing global population. This dual goal can be more effectively realized through the integration of gene editing technologies and sustainable agricultural practices. Such technologies promise to increase plant productivity and stress tolerance while reducing pressure on the ecosystem by optimizing resource use.

8.1. Gene Regulation Technologies

Gene regulation is a revolutionary technology that enables rapid and precise genetic modifications. Tools such as CRISPR/Cas9, TALENs and ZFNs are used to improve the traits of agricultural crops by intervening on specific genetic targets.

Disease and Pest Resistance: Gene regulation can enhance plant resistance to pathogens and pests, reducing the need for chemical control. For instance, the natural defense mechanisms of plants can be strengthened by adding pathogen-specific resistance genes or modifying existing genes using CRISPR technology. This approach enables plants to fight diseases more effectively and increases yields in large-scale agricultural applications (Jiang et al., 2013).

Abiotic Stress Tolerance: Abiotic stresses put enormous pressure on global agricultural productivity. Gene editing can be used to develop plant varieties that are more tolerant to stresses such as water, salt and temperature.

These plants perform better under harsh environmental conditions, enabling more efficient use of limited resources (Zhang et al., 2018).

Increasing Nutritional Content: Gene editing is a strategic tool for improving nutrient profiles in plants. For example, agricultural products enriched in essential amino acids, vitamins and minerals can be improved through gene editing. This can improve public health by enhancing nutritional quality, especially in developing countries (Ye et al., 2000).

8.2. Sustainable Agriculture Practices

Sustainable agriculture aims to maximize yields while minimizing environmental impact. These practices, combined with gene editing technologies, can enhance agricultural sustainability.

Ecological Diversity: Farming systems that promote ecological diversity can reduce the problems caused by monoculture. Varieties developed through gene editing can be used to conserve and increase biodiversity by making them more suitable for specific ecological niches. This can be both effective in biological control of pests and improve soil health (Altieri, 1999).

Soil Health: Practices that maintain soil health are key to long-term agricultural productivity. The use of organic matter improves soil water holding capacity and nutrient balance. Plants developed through gene editing can grow better in these conditions and reduce soil erosion (Lal, 2004).

Water Management: Conservation of water resources is critical for the sustainability of global agriculture. By developing plant varieties with high water use efficiency through gene editing, agriculture can be sustained in water-limited areas. These varieties show healthy growth even under arid conditions and save water (Postel et al., 2001).

Gene editing technologies and sustainable agricultural practices are the cornerstones of future agricultural strategies. Integration of these technologies will improve the environmental and economic sustainability of agriculture; help ensure food security and protect ecosystems. Strategic planning, policy development and effective use of these technologies will shape the future of global agriculture.

REFERENCES

Acquaah, G. (2012). *Principles of Plant Genetics and Breeding*, 2nd Edition. Wiley-Blackwell.

Ahmad, P., Jaleel, C. A., Salem, M. A., Nabi, G., & Sharma, S. (2010). Roles of enzymatic and nonenzymatic antioxidants in plants during abiotic stress. *Critical Reviews in Biotechnology, 30*(3), 161-175. doi: 10.3109/07388550903524243

Alscher, R. G., Erturk, N., & Heath, L. S. (2002). Role of superoxide dismutases (SODs) in controlling oxidative stress in plants. *Journal of Experimental Botany, 53*(372), 1331-1341. doi: 10.1093/jexbot/53.372.1331

Ali, A., Altaf, M. T., Nadeem, M. A., Karaköy, T., Shah, A. N., Azeem, H., ... & Chung, Y. S. (2022). Recent advancement in OMICS approaches to enhance abiotic stress tolerance in legumes. *Frontiers in Plant Science*, *13*, 952759.

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment, 74*(1-3), 19-31. doi: 10.1016/S0167-8809(99)00028-6

Apel, K., & Hirt, H. (2004). Reactive oxygen species: Metabolism, oxidative stress, and signal transduction. *Annual Review of Plant Biology, 55*, 373-399. doi: 10.1146/annurev.arplant.55.031903.141701

Atta, K., Mondal, S., Gorai, S., Singh, A. P., Kumari, A., Ghosh, T., ... & Jespersen, D. (2023). Impacts of salinity stress on crop plants: Improving salt tolerance through genetic and molecular dissection. *Frontiers in Plant Science*, *14*, 1241736.

Barnabás, B., Jäger, K., & Fehér, A. (2008). The effect of drought and heat stress on reproductive processes in cereals. *Plant, Cell & Environment, 31*(1), 11-38. doi: 10.1111/j.1365-3040.2007.01727.x

Ben Gaied, R., Brígido, C., Sbissi, I., & Tarhouni, M. (2024). Sustainable Strategy to Boost Legumes Growth under Salinity and Drought Stress in Semi-Arid and Arid Regions. *Soil Systems*, *8*(3), 84.

Blumwald, E. (2000). Sodium transport and salt tolerance in plants. *Current Opinion in Cell Biology, 12*(4), 431-434.

Bortesi, L., & Fischer, R. (2015). The CRISPR/Cas9 system for plant genome editing and beyond. *Biotechnology Advances, 33*(1), 41-52. doi: 10.1016/j.biotechadv.2014.12.006

Collard, B. C. Y., & Mackill, D. J. (2008). Marker-assisted selection: an approach for precision plant breeding in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1491), 557-572. doi: 10.1098/rstb.2007.2170

Cook, R. J., Veseth, R. J., (2006). Wheat health management. *Plant Health Instructor*. doi: 10.1094/PHI-A-2006-0414-01

Deinlein, U., Stephan, A. B., Horie, T., Luo, W., Xu, G., & Schroeder, J. I. (2014). Plant salt-tolerance mechanisms. *Trends in Plant Science, 19*(6), 371-379. doi: 10.1016/j.tplants.2014.02.001

Farooq, M., Gogoi, N., Hussain, M., Barthakur, S., Paul, S., Bharadwaj, N., ... & Siddique, K. H. M. (2017). Effects of drought stress on legumes. *Comprehensive Reviews in Food Science and Food Safety, 16*(2), 909-931. doi: 10.1111/1541-4337.12275

Flexas, J., Bota, J., Loreto, F., Cornic, G., & Sharkey, T. D. (2004). Diffusive and metabolic limitations to photosynthesis under drought and salinity in C3 plants. *Plant Biology, 6*(3), 269-279. doi: 10.1055/s-2004-820867

Foyer, C. H., & Noctor, G. (2005). Oxidant and antioxidant signalling in plants: A re-evaluation of the concept of oxidative stress in a physiological context. *Plant, Cell & Environment, 28*(8), 1056-1071. doi: 10.1111/j.1365-3040.2005.01327.x

Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry, 48*(12), 909-930. doi: 10.1016/j.plaphy.2010.08.016

Gupta, B., Huang, B., & Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. (2014). *International Journal of Genomics, 2014*, 701596. doi: 10.1155/2014/701596

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes, 10*(Part A), 4-10. doi: 10.1016/j.wace.2015.08.001

Hu, H., & Xiong, L. (2014). Genetic engineering and breeding of drought-resistant crops. *Annual Review of Plant Biology, 65*, 715-741. doi: 10.1146/annurev-arplant-050213-040000

Jiang, W., Zhou, H., Bi, H., Fromm, M., Yang, B., & Weeks, D. P. (2013). Demonstration of CRISPR/Cas9/sgRNA-mediated targeted gene modification in Arabidopsis, tobacco, sorghum and rice. *Nucleic Acids Research, 41*(20), e188. doi: 10.1093/nar/gkt780

Katerji, N., van Hoorn, J. W., Hamdy, A., & Mastrorilli, M. (2003). Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agricultural Water Management, 62*(1), 37-66. doi: 10.1016/S0378-3774(03)00005-2

Kijne, J. W. (2006). Water and salinity stress in agronomy. *Journal of Agronomy and Crop Science, 191*(6), 450-453. doi: 10.1111/j.1439-037X.2006.00213.x

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*(5677), 1623-1627. doi: 10.1126/science.1097396

Ludlow, M. M., & Muchow, R. C. (1990). A critical evaluation of traits for improving crop yields in water-limited environments. *Advances in Agronomy, 43*, 107-153. doi: 10.1016/S0065-2113(08)60477-0

Mittler, R. (2002). Oxidative stress, antioxidants and stress tolerance. *Trends in Plant Science, 7*(9), 405-410. doi: 10.1016/S1360-1385(02)02312-9

Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology, 59*, 651-681. doi: 10.1146/annurev.arplant.59.032607.092911

Munns, R., & Tester, M. (2017). Mechanisms of salinity tolerance. *Annual Review of Plant Biology, 59*, 651-681. doi: 10.1146/annurev.arplant.59.032607.092911

Nadeem, M., Li, J., Yahya, M., Sher, A., Ma, C., Wang, X., & Qiu, L. (2019). Research progress and perspective on drought stress in legumes: A review. *International journal of molecular sciences*, *20*(10), 2541.

Noctor, G., & Foyer, C. H. (1998). Ascorbate and glutathione: Keeping active oxygen under control. *Annual Review of Plant Physiology and Plant Molecular Biology, 49*, 249-279. doi: 10.1146/annurev.arplant.49.1.249

Osakabe, Y., Osakabe, K., Shinozaki, K., & Tran, L. S. P. (2014). Response of plants to water stress. *Frontiers in Plant Science, 5*, 86. doi: 10.3389/fpls.2014.00086

Postel, S. L., Daily, G. C., & Ehrlich, P. R. (2001). Human appropriation of renewable fresh water. *Science, 291*(5508), 785-788. doi: 10.1126/science.1055194

Roy, S. J., Negrão, S., & Tester, M. (2014). Salt resistant crop plants. *Current Opinion in Biotechnology, 26*, 115-124. doi: 10.1016/j.copbio.2013.12.004

Sharkey, T. D. (2016). Effects of moderate heat stress on photosynthesis: Importance of thylakoid reactions, Rubisco deactivation, reactive oxygen species, and thermotolerance provided by isoprene. *Plant, Cell & Environment, 39*(7), 1424-1430. doi: 10.1111/pce.12690

Sharkey, T. D., & Schrader, S. M. (2006). High temperature stress. *Physiologia Plantarum, 126*(1), 72-78. doi: 10.1111/j.1399-3054.2006.00607.x

Sharma, S. S., & Dietz, K. J. (2016). The significance of amino acids and amino acid-derived molecules in plant responses and adaptation to heavy metal stress. *Journal of Experimental Botany, 57*(4), 711-726. doi: 10.1093/jxb/erj073

Sher, A., Noor, M. A., Li, H. X., Nasir, B., Manzoor, M. A., Hussain, S., ... & Hussain, S. (2024). Heat stress effects on legumes: challenges, management strategies and future insights. *Plant Stress*, 100537

Shrivastava, P., & Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences, 22*(2), 123-131. doi: 10.1016/j.sjbs.2014.12.001

Ul Hassan, M., Rasool, T., Iqbal, C., Arshad, A., Abrar, M., Abrar, M. M., ... & Fahad, S. (2021). Linking plants functioning to adaptive responses under heat stress conditions: a mechanistic review. *Journal of Plant Growth Regulation*, 1-18.

Varshney, R. K., et al. (2011). Transgenic crop plants volume 1: Principles and development. Springer.

Vierling, E. (1991). The roles of heat shock proteins in plants. *Annual Review of Plant Biology, 42*, 579-620.

Ye, X., Al-Babili, S., Klöti, A., Zhang, J., Lucca, P., Beyer, P., & Potrykus, I. (2000). Engineering the provitamin A (beta-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science, 287*(5451), 303-305. doi: 10.1126/science.287.5451.303

Zhang, H., Zhang, J., Wei, P., Zhang, B., Gou, F., Feng, Z., ... & Zhou, J. (2018). The CRISPR/Cas9 system produces specific and homozygous targeted gene editing in rice in one generation. *Plant Biotechnology Journal, 12*(6), 797-807. doi: 10.1111/pbi.12200

Zhu, J. K. (2002). Salt and drought stress signal transduction in plants. *Annual Review of Plant Biology, 53*, 247-273.

Zhu, J. K. (2016). Abiotic stress signaling and responses in plants. *Cell, 167*(2), 313-324. doi: 10.1016/j.cell.2016.08.029

Zhu, X., Liu, S., Sun, L., Song, F., Liu, F., & Li, X. (2018). The impact of temperature on photosynthesis in different legume species. *Journal of Experimental Botany, 69*(15), 3563-3574. doi: 10.1093/jxb/ery121

CHAPTER 3

RESILIENT CITIES AGAINST CLIMATE CHANGE

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Introduction

As the global community confronts the escalating challenges posed by climate change, the imperative to build resilient cities has become more urgent than ever. Urban areas, which accommodate more than half of the world's population, are at the forefront of climate impacts, including rising temperatures, sea level rise, extreme weather events, and resource scarcity. The necessity for cities to both adapt to and mitigate these challenges has led to a growing emphasis on the concept of urban resilience. Urban resilience is defined as the capacity of cities to absorb shocks, adapt to changing conditions, and continue to function effectively under stress (Zhang and Li, 2018).

This section underscores the significance of resilient cities and their role in addressing climate change. The discussion is further strengthened by recognizing the critical contribution of cities to greenhouse gas emissions. Cities must not only adapt to the effects of climate change but also play an active role in global mitigation efforts through emission reduction.

In recent years, the substantial risks that climate change poses to urban areas have become increasingly evident. These risks include sea level rise, elevated temperatures, more intense precipitation and storms, droughts, and heatwaves. Furthermore, climate change presents serious threats to urban infrastructure, such as increased electricity demand and voltage fluctuations, stress on materials and equipment, transportation disruptions, and an elevated need for emergency management (IPCC, 2007; NPCC, 2009; Wardekker et al., 2003).

This section examines the concept of resilient cities, focusing on the principles and strategies that support their development. It also analyzes the roles of urban governance, policy, and technology in shaping urban resilience. Drawing on relevant literature, it presents case studies of cities that have successfully implemented resilience strategies and offers insights into the future of urban resilience in the context of escalating climate risks.

1. Defining Urban Resilience

Urban resilience refers to the capacity of cities and urban systems to anticipate, prepare for, and recover from a range of shocks and stresses, including those associated with climate change. This concept encompasses both resistance and adaptive capacities to extreme events (such as floods, heatwaves, and storms), with adaptive capacity defined as the ability of cities to adjust to long-term climatic changes—such as rising temperatures, sea level rise, and shifts in precipitation patterns (Zhang & Li, 2018).

Resilience is widely recognized as a multidimensional and interdisciplinary concept, whose definition and interpretation vary according to context, purpose, scale, system, discipline, and domain (Rana, 2020). For example, a city that demonstrates resilience to flood risks may not exhibit the same level of resilience when confronting challenges related to urban heat (Mehryar et al., 2022). According to the IPCC (2007), resilience is defined as "the ability of a social or ecological system to absorb disturbances while retaining its essential structure and functions, the capacity for self-organization, and the ability to adapt to stress and change." Climate resilience, in particular, refers to the ability of individuals and systems to sustain and enhance living standards, economic growth opportunities, and overall well-being in the face of environmental, economic, social, and political disruptions caused by climate change (Mehryar et al., 2022).

In a broader context, urban resilience is characterized by how cities or urban systems respond to a variety of shocks and stresses (Leichenko, 2011). It encompasses the capacity of cities to withstand external shocks, reduce vulnerability to disasters, promote technological innovation, and foster the development of sustainable infrastructure. Additionally, strengthening governmental institutions and addressing racial and political dynamics are essential components of this process.

1.1 Resilience Frameworks

To better understand urban resilience, scholars and practitioners have proposed various conceptual frameworks. One widely cited definition is provided by the Rockefeller Foundation through its 100 Resilient Cities initiative, which defines resilience as a city's ability to endure and recover from both chronic stresses and acute shocks (Rockefeller Foundation, 2014). The Resilience Alliance also offers a frequently referenced framework based on the concept of adaptive cycles, viewing cities as systems that must continually adapt, transform, and evolve in response to changing environmental and social conditions (Walker & Salt, 2006).

In the urban context, the notion of resilience is adapted from studies on how ecological systems respond to stress and disturbances caused by external forces (Davic & Welsh, 2004). From an ecological perspective, Holling (1973)—who first introduced the concept—and later Carpenter et al. (2001), argue that resilience refers to the "persistence of relationships within a system" and "the ability of these systems to absorb changes in state variables, driving variables, and parameters while continuing to function" (Holling, 1973). Put differently, resilience is "the capacity of a system to absorb disturbance and still retain its basic functions and controls" (Gunderson & Holling, 2001).

1.2 Components of Urban Resilience

Urban resilience comprises several key components:

Infrastructure Resilience:Infrastructure resilience involves ensuring that critical infrastructure systems can endure extreme weather events and long-term climate change impacts (Ahern, 2011). Climate change poses both acute threats—such as extreme weather events—and chronic risks resulting from gradual environmental shifts. These threats range from coastal and urban flooding to heatwaves, cold spells, droughts, and strong winds. Assessing the effects of climate change on transportation systems is inherently complex. While the body of knowledge regarding these impacts is growing, there remain significant gaps in understanding the vulnerabilities and adaptive strategies linked to behavioral responses, informational deficiencies, resource limitations, and the interdependence of physical systems. Given the long operational lifespans of many infrastructure systems, it is critical to integrate and assess the timing and magnitude of climate change and extreme weather events in planning processes (Markolf et al., 2019).

Social Resilience: Social resilience emphasizes strengthening the capacity of communities to respond to climate change, particularly among vulnerable groups disproportionately affected by climate-related risks (Adger, 2003). Current approaches to managing climate variability offer limited promise in addressing the increasing frequency and severity of climate extremes. Across various regions, shifts in rainfall and temperature patterns are already destabilizing agricultural productivity and food security (Molua, 2002). Studies examining how impoverished populations cope with climate-induced extremes—such as floods, droughts, and storms—highlight the substantial economic burdens and challenges they face, often with limited success (Kates, 2000). Climate-induced natural disasters frequently undermine development gains, destroying lives and livelihoods. As Sen (1981) noted, famines, climate-related risks, and food production declines often constitute human-made disasters resulting from failures in societal response.

Economic Resilience: Economic resilience refers to a city's ability to preserve economic stability amid climate-related disruptions (Simmie & Martin, 2010). Urban areas are frequently located in high-risk coastal zones, where both economic assets and populations are increasingly exposed to climate hazards. Understanding these risks requires assessing their influence on social and economic conditions and the core operational foundations of urban systems. Climate change's social ramifications include direct effects on residents' physical and mental health, food and water insecurity, disruptions to livelihoods, and displacement. A key aspect of the social dimension of climate change is its unequal impact, which has gained increased attention in contemporary discourse. Research increasingly demonstrates that climate change disproportionately affects marginalized individuals and groups, particularly those with limited resources or social isolation. Economically, climate change disrupts urban systems through the interruption of goods and services—such as the destruction of industrial infrastructure and the loss of commercial activity (Gasper et al., 2011).

Governance Resilience: Governance resilience entails the establishment of flexible, inclusive, and effective decision-making processes that enable cities to respond to climate change (Béné et al., 2012). Although governance concerns issue of authority and multi-actor engagement, it must also consider the rising uncertainty associated with climate change and its implications for urban planning and policy-making. Climate change presents novel and large-scale challenges in urban contexts, necessitating governance models capable of addressing uncertainty and complex, non-linear dynamics. The literature increasingly calls for flexible and adaptive urban strategies—for instance, enhancing resilience in urban drainage systems to better manage flood and water risks under uncertain climatic conditions (Gersonius et al., 2013). Adaptive governance, as an analytical framework, emphasizes the importance of collaborative networks and shared resource management to cope with global uncertainties (Folke et al., 2005). It is defined as a governance system comprising formal and informal institutions and social networks capable of learning and adapting in the face of change (Boyd & Folke, 2012).

Absorptive Capacity

Absorptive capacity refers to structural and non-structural measures such as flood barriers and stormwater management systems. The proliferation of impervious surfaces in urban areas significantly alters a city's hydrological structure and geomorphology, while also degrading stormwater quality and urban ecosystems. The loss of green spaces and coastal vegetation affects river water temperatures, flow regimes, and the distribution of aquatic plant and animal species (Anderson et al., 2010). The inherent vulnerability of urban areas contributes substantially to increased flood-related damages, highlighting the critical need to strengthen urban flood resilience (Li et al., 2024).

Adaptive Capacity

Adaptive capacity encompasses climate-resilient infrastructure and nature-based solutions, such as urban tree planting. Urban infrastructure plays a vital role in mitigating elevated temperatures within cities. Green-blue-grey infrastructure—which integrates vegetation-based, water-based, and engineering-based systems—has been widely advocated as a means to reduce urban heat and lower energy consumption (Zonato et al., 2021). These integrated systems offer substantial potential to enhance urban quality of life, support biodiversity, mitigate the impacts of climate change, and foster long-term sustainability.

2. Climate Change and Urban Vulnerability

The impacts of climate change are becoming increasingly evident in urban environments. Cities are particularly vulnerable due to high population densities and the concentration of infrastructure and economic activity. Social inequalities often exacerbate this vulnerability; as marginalized populations are more likely to reside in high-risk areas such as floodplains or informal settlements.

2.1 Major Climate Risks Facing Cities

Extreme Weather Events: Urban areas are frequently exposed to extreme weather conditions, including storms, heatwaves, heavy rainfall, and flooding. These events can severely damage infrastructure, disrupt daily activities, and result in substantial economic losses (IPCC, 2014).

Sea-Level Rise: Coastal cities are particularly at risk from rising sea levels, which may lead to urban inundation, population displacement, and significant infrastructure damage (Nicholls et al., 2007).

Temperature Extremes: Cities often experience elevated temperatures relative to surrounding rural areas due to the urban heat island effect. This phenomenon exacerbates the impacts of heatwaves and poses serious health risks, particularly for vulnerable groups (Oke, 1982).

Resource Scarcity: Climate change can intensify challenges related to water scarcity, rising energy demands, and food insecurity, as it disrupts supply chains and depletes local resources (Satterthwaite, 2008).

2.2 Social Inequalities and Vulnerability

The effects of climate change are disproportionately experienced by marginalized groups. Low-income communities, Indigenous peoples, the elderly, and persons with disabilities often face heightened risks due to substandard housing, limited access to essential resources, and reduced mobility. Addressing these inequalities is a crucial step toward fostering urban resilience (Füssel, 2007).

3. Building Resilient Cities: Strategies and Best Practices

Fostering urban resilience requires a dual approach: implementing adaptation strategies to reduce vulnerability and enacting mitigation measures to lower greenhouse gas emissions. Key strategies include:

3.1 Green Infrastructure

Green infrastructure involves leveraging natural and semi-natural systems—such as parks, green roofs, urban forests, and wetlands—to deliver environmental benefits and enhance urban resilience. These systems aid in stormwater management, reduce the urban heat island effect, and improve air quality. Initiatives such as New York City's MillionTrees program and Singapore's Gardens by the Bay illustrate how green infrastructure can effectively address climate risks (Demuzere et al., 2014).

3.2 Urban Planning and Zoning

Climate-resilient urban planning integrates future climate risks into city design, zoning regulations, and construction codes. Cities can mitigate vulnerability by avoiding development in high-risk areas, such as floodplains and coastal zones, and by promoting compact, walkable, mixed-use neighbourhoods. The "smart growth" model supports sustainable urban development while minimizing environmental impacts (Portney, 2003).

3.3 Disaster Risk Management and Early Warning Systems

An effective disaster risk management (DRM) framework is a cornerstone of urban resilience. Cities can enhance their preparedness by implementing early warning systems for extreme weather events, formulating evacuation plans, and strengthening emergency response capabilities. Examples from Tokyo's earthquake preparedness initiatives and Miami's flood resilience programs underscore the value of proactive planning in reducing disaster-related losses (Mimura et al., 2007).

3.4 Climate-Resilient Infrastructure

Strengthening infrastructure to withstand the impacts of climate change is a critical element of urban resilience. This includes fortifying buildings, bridges, and roads to endure extreme weather events, upgrading existing infrastructure, and investing in renewable energy sources such as solar and wind power. For example, Copenhagen has implemented comprehensive flood defense measures, including the world's largest stormwater management system, to address increasing rainfall (Skaarup et al., 2014).

3.5 Social Resilience and Community Engagement

Incorporating communities into climate resilience planning is essential. Involving local populations in decision-making processes, disaster preparedness efforts, and climate action initiatives can foster a culture of resilience. For instance, Portland, Oregon, has developed robust climate adaptation strategies that actively engage local communities in both decision-making and the implementation of resilience projects (Shaw & Deyle, 2013).

4. Conclusions

As cities confront the escalating challenges posed by climate change, building resilience has emerged as a critical objective for urban planners, policymakers, and residents. By integrating green infrastructure, adaptive urban planning, robust disaster risk management, and community engagement, cities can not only reduce the risks associated with climate change but also foster opportunities for sustainable development and improve the quality of life for all urban residents.

The path to resilience is complex and necessitates cooperation at local, national, and international levels. As more cities implement strategies for climate adaptation and mitigation, the global urban network can become better prepared, more equitable, and more resilient to the challenges of an uncertain future.

REFERENCES

Adger, W. N. (2003). Social resilience in the face of climatic change. *Global Environmental Change*, 13(3), 195-206.

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning*, 100(4), 341-343.

Alberti, M., et al. (2003). "Integrating Humans into Ecology." *Frontiers in Ecology*.

Anderson Jr, W. P., Anderson, J. L., Thaxton, C. S., & Babyak, C. M. (2010). Changes in stream temperatures in response to restoration of groundwater discharge and solar heating in a culverted, urban stream. *Journal of Hydrology*, *393*(3-4), 309-320.

Béné, C., et al. (2012). Resilience: New utopia or new tyranny? *Development Policy Review*, 30(1), 1-22.

Boyd, E., & Folke, C. (Eds.). (2011). *Adapting institutions: governance, complexity and social-ecological resilience*. Cambridge University Press.

Bulkeley, H. (2013). *Cities and Climate Change*.

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: resilience of what to what?. *Ecosystems*, *4*, 765-781.

Davic, R. D., & Welsh Jr, H. H. (2004). On the ecological roles of salamanders. *Annu. Rev. Ecol. Evol. Syst.*, *35*(1), 405-434.

Davis, M., & Lall, S. V. (2019). Cape Town's Water Crisis. *Journal of Urban Economics*, 112, 84-96.

Demuzere, M., et al. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green infrastructure. *Environmental Science & Policy*, 39, 58-68.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.*, *30*(1), 441-473.

Füssel, H. M. (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change*, 17(2), 155-167.

Gasper, R., Blohm, A., & Ruth, M. (2011). Social and economic impacts of climate change on the urban environment. *Current opinion in environmental sustainability*, *3*(3), 150-157.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2013). Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Climatic change*, *116*, 411-423.

Gunderson, L and CS. Holling, 2001. L. Gunderson, C.S. Holling (Eds.), Panarchy: Understanding transformations in human and natural systems, Island Press, Washington (DC) (2001)

Holling, C. S. (1973, November). *Resilience and stability of ecological systems*.

IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press.

IPCC, 2007. IPCC-Intergov. Panel Clim. Change (2007). *Climate change 2007: Fourth assessment report of the intergovernmental panel on climate change*. Cambridge, MA: Cambridge Univ. Press

IPCC. (2007). Climate change 2007: Appendix to synthesis report. Climate change *2007*: Synthesis report. Contribution of working groups I, II, and III to the fourth assessment report of the intergovernmental panel on climate change, 76–89.

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability*.

Kates, R. W. (2000). Cautionary tales: adaptation and the global poor. *Climatic change*, *45*, 5-17.

Leichenko, R. (2011). Climate change and urban resilience. *Current opinion in environmental sustainability*, *3*(3), 164-168.

Li, J., Zou, Y., Li, J., & Si, S. (2024). Urban spatial, engineering and management resilience capacity enhancement from a flood safety perspective. *Water-Energy Nexus* 7;213-226.

Markolf, S. A., Hoehne, C., Fraser, A., Chester, M. V., & Underwood, B. S. (2019). Transportation resilience to climate change and extreme weather events–Beyond risk and robustness. *Transport policy*, *74*, 174-186.

Meerow, S., et al. (2016). "Defining Urban Resilience." *Landscape and Urban Planning*.

Mehryar, S., Sasson, I., & Surminski, S. (2022). Supporting urban adaptation to climate change: What role can resilience measurement tools play?. *Urban Climate*, *41*, 101047.

Mimura, N., et al. (2007). Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. IPCC.

Molua, E. L. (2002). Climate variability, vulnerability and effectiveness of farm-level adaptation options: the challenges and implications for food security in Southwestern Cameroon. *Environment and Development Economics*, *7*(3), 529-545.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1-24.

Portney, K. E. (2003). Taking sustainable cities seriously: Economic development, the environment, and quality of life in American cities. MIT Press.

Rana, I. A. (2020). Disaster and climate change resilience: A bibliometric analysis. *International journal of disaster risk reduction*, *50*, 101839.

Rockefeller Foundation. (2014). 100 Resilient Cities: Pioneering a New Urban Agenda.

Rosenzweig, C., Solecki, W., Blake, R., Bowman, M., Castaldi, A., Faris, C., ... & Zimmerman, R. (2009). Climate risk information. *New York, NY: New York Panel on Climate Change*.

Satterthwaite, D. (2008). Climate change and urbanization: Effects and implications for urban governance. *In: Urbanization and Development*. Earthscan.

Sen, A. (1982). *Poverty and famines: an essay on entitlement and deprivation*. Oxford university press.

Shaw, D., & Deyle, R. E. (2013). Local governments and the challenge of climate resilience. *Journal of Environmental Planning and Management*, 56(3), 1-18.

Walker, B., & Salt, D. (2006). Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press.

Wardekker, J. A., De Jong, A., Knoop, J. M., & Van Der Sluijs, J. P. (2010). Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. *Technological Forecasting and Social Change*, *77*(6), 987-998.

Zonato, A., Martilli, A., Gutierrez, E., Chen, F., He, C., Barlage, M., ... & Giovannini, L. (2021). Exploring the effects of rooftop mitigation strategies on urban temperatures and energy consumption. *Journal of Geophysical Research: Atmospheres*, *126*(21), e2021JD035002.

Zhang, X., & Li, H. (2018). Urban resilience and urban sustainability: What we know and what do not know?. *Cities*, *72*, 141-148.

CHAPTER 4

ADAPTATION OF FRUIT CULTIVATION TO CLIMATE CHANGE THE ROLE OF *IN VITRO* TISSUE CULTURE TECHNIQUES

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1. Introduction

The widespread use of fossil fuels as the primary energy source poses serious threats to global ecological sustainability. The combustion of fossil fuels releases carbon dioxide (CO_2) and other greenhouse gases into the atmosphere, where they accumulate and accelerate the process of global warming, leading to structural changes in the climate system that are increasingly difficult to reverse. CO_2, the principal driver of global warming, has become one of the most critical components of climate change due to its current atmospheric concentration. Indeed, since the Industrial Revolution, approximately 2,590 gigatons of CO_2[3] have been emitted into the atmosphere between 1850 and 2024 (Our World in Data, 2025). This accumulation has had lasting effects on global climate dynamics, impacting many sectors, particularly agriculture. Among agricultural systems, fruit cultivation is especially sensitive to climatic conditions and is directly and significantly affected by these changes.

As of 2023, global greenhouse gas emissions vary significantly across countries. As illustrated in Figure 1, nations such as China, the United States, and India account for a substantial share of global emissions. In contrast, low-income countries contribute much less. In contrast, regions like the African continent, Central Asia, and several small island states make relatively minor contributions to total global emissions. This spatial disparity highlights the severe geographic injustices between the causes and consequences of the climate crisis.

3 This data represents the total carbon dioxide emissions caused by human activities since 1850; changes in the natural carbon cycle are not included.

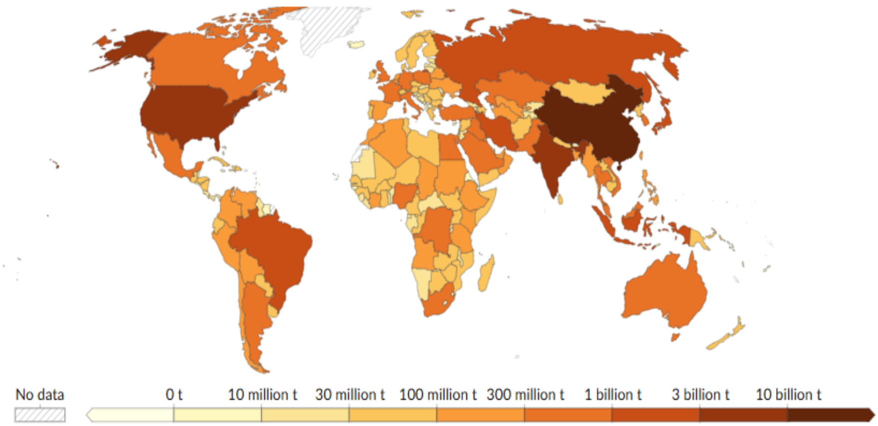

Figure 1. Global Greenhouse Gas Emission Levels: 2023[4]
Source: Our World in Data (2025)

In this context, countries contributing the least to emissions are often the regions most affected by climate change. Therefore, the impacts of climate change on agricultural pests and diseases vary depending on the crop type and geographical region (Beckford & Norman, 2016: 195). The global consequences of this increase are being felt in a multifaceted manner, particularly across the agricultural sector, including fruit cultivation.

On the other hand, agricultural activities are both a cause and a victim of climate change. According to FAO (2024), the agricultural sector is responsible for approximately 20.4% of global greenhouse gas emissions, with a total of 10.9 gigatons of CO_2 equivalent emissions stemming from on-farm crop and livestock production (7.8 Gt CO^2)[5] and agricultural land use (3.1 Gt CO^2). However, when considering emissions from all stages of the food system, the total greenhouse gas contribution was calculated to be 29.7% as of 2022. This share was 38% in 2000 but has declined over time (FAO, 2024). The decrease is attributed not to a reduction in agricultural emissions, which have remained relatively stable, but rather to a relative increase in emissions from the energy and industrial sectors. Thus, although emissions from agricultural production may appear to have declined proportionally, the sector's contribution to

4 Figure 1 is based on country-level CO_2-equivalent data from the year 2023, derived from the Global Greenhouse Gas Emissions database provided by Our World in Data.
5 It covers emissions directly resulting from crop production (e.g., wheat, maize) and livestock activities (e.g., cattle, sheep).

greenhouse gas emissions remains substantial and continues to play a critical role in climate change.

Rising temperatures, irregular precipitation, drought, floods, and storms—*extreme weather events triggered by climate change*—negatively affect agricultural productivity and efficiency (IPCC, 2019; FAO, 2015: 36). Temperature increases during critical stages of plant development led to yield losses, while reductions in water resources limit irrigation potential (Hatfield & Prueger, 2015: 4). Simultaneously, the expansion of the geographical range of pests and diseases increases production risks (Porter et al., 1991; Gullino et al., 2022: 12), thereby deepening the vulnerability of smallholder farmers, particularly those engaged in subsistence agriculture (Beckford & Norman, 2016: 189; Gregory et al., 2005: 2145).

When explicitly examined in the context of fruit cultivation, the adverse effects are even more pronounced due to the perennial[6] and climate-sensitive nature of fruit production systems (Russos, 2024: 558). Tree species possess limited adaptive capacity to environmental stresses because of their long lifespan. This limitation affects many critical physiological processes such as flowering timing, fruit set, yield, and quality (Russos, 2024; Osorio Marín et al., 2024).

Accordingly, climate change poses serious threats to the agricultural sector in terms of production levels, food security, and the stability of rural livelihoods (Abbas et al., 2023). Therefore, it is important to develop practical solutions to the challenges faced, particularly in fruit cultivation, during the climate change adaptation process. One such solution is tissue culture techniques, a modern biotechnological tool that enables the rapid, reliable, and disease-free propagation of stress-tolerant genotypes, especially in fruit species (Beckford & Norman, 2016). In other words, tissue culture is a technique that allows plants to be rapidly produced in sterile, artificial nutrient media and containers, free from bacterial and fungal contamination. Thus, tissue culture becomes a apparatus to enhance production efficiency and a strategic method that supports the development of climate-resilient fruit production systems.

6 Perennial plants refer to species that remain alive across multiple growing seasons and produce yield each year.

In particular, methods such as *in vitro* micropropagation[7] make it possible to select and introduce genotypes that are tolerant to various abiotic stress factors[8], including drought (*water stress*), salinity, extreme temperatures (*heat stress*), nutrient deficiencies or toxicities, and heavy metal contamination (Al-Khateeb et al., 2020: 2; Rezaei et al., 2023: 1475). Furthermore, tissue culture plays a strategic role in areas such as the conservation of endangered plant varieties under environmental pressure caused by climate change (IUCN, 2023), the long-term preservation of genetic resources, and the development of new lines (Kulak et al., 2022; Benelli et al., 2022; Tarraf & De Carlo, 2024). This crucial role is fulfilled through *in vitro* techniques, which allow for rapid and continuous testing of plant material under laboratory conditions without dependency on external environmental factors (Kantoğlu et al., 2021: 713). In this respect, tissue culture supports sustainable fruit production practices and provides a scientific foundation for climate-resilient agricultural transformation (Benelli et al., 2022).

This study aims to comprehensively evaluate the potential role of tissue culture in adapting fruit cultivation to climate change. The first section outlines a general framework of climate change, with an introductory focus on its impacts, particularly on the agricultural sector and fruit cultivation. The second section addresses the specific effects of climate change on fruit production. The third section explores the potential of tissue culture applications in fruit growing to adapt to climate change. At the same time, subsection 3.1 presents concrete examples of current scientific applications in this field. The fourth section includes discussion and future-oriented evaluations. Finally, the fifth and last sections offer a general assessment of the study and presents its conclusions.

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7 Micropropagation is the process of propagating plants from tissue fragments under sterile conditions in a laboratory environment. It generally aims to produce healthy and genetically uniform seedlings in culture media.

8 Abiotic stress refers to the pressure exerted on plants by non-living environmental factors such as drought, salinity, and extreme temperatures. Unlike biotic stress, it does not involve living agents.

2. Effects of Climate Change on Fruit Cultivation

2.1. Climate Change and Agriculture

The growth and development of agricultural products depend on fundamental environmental components such as soil, water, sunlight, and temperature. Climate is a dynamic factor that directly influences all of these components. Climate-related risks and inherent uncertainties pose significant challenges for the agricultural sector. Agriculture is a dual-impact sector—it contributes to and is strongly affected by climate change. Figure 2 schematically presents the impacts of climate change on agriculture. This general framework calls for more specific and in-depth analyses, particularly for sub-sectors like fruit cultivation, which are highly sensitive to environmental variability.

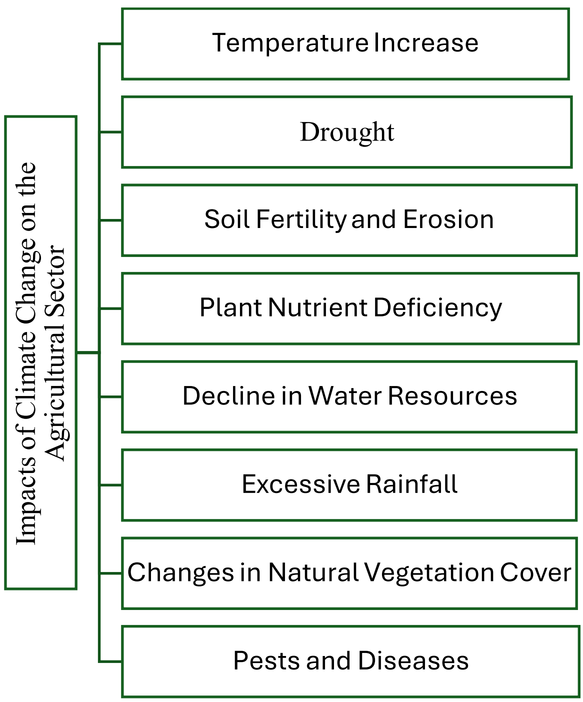

Figure 2. Impacts of Climate Change on the Agricultural Sector
Source. Created by the authors based on data from the Republic of Türkiye Ministry of Agriculture and Forestry (2021).

Rising temperatures, changes in precipitation patterns, drought, floods, desertification, and extreme weather events directly challenge agricultural production systems. The impacts of these changes are felt across multiple dimensions, including food security, water resource management, agricultural economics, and rural development. Climate change also leads to significant disruptions in natural cycles (water, carbon, and nutrient cycles) and ecosystem services, threatening the sustainability of agricultural production.

In countries like Türkiye, which are located in the Mediterranean climate zone, rising temperatures and decreasing rainfall are increasing the risk of drought, resulting in yield reductions, shifts in crop patterns, and greater vulnerability of rural livelihoods (Republic of Türkiye Ministry of Agriculture and Forestry, 2021). Therefore, the agricultural sector must be addressed as a priority in both climate adaptation and mitigation strategies. In this context, the 13th United Nations Sustainable Development Goal, "*Climate Action*," aims to enhance the resilience of the agricultural sector through greenhouse gas reduction, climate adaptation, early warning systems, and awareness-raising initiatives.

However, the effects of climate change on agriculture are not felt equally across all sub-production systems. Fruit cultivation, characterized by perennial production structures and high sensitivity to environmental conditions, presents more complex and long-term risks in this regard. Compared to field crops, fruit trees have a more limited capacity to adapt to climatic stressors and cannot respond rapidly to changing environmental conditions. This creates significant vulnerabilities in productivity, product quality, and continuity of production. Moreover, the high fixed investment and long return period inherent in fruit growing expose producers to biophysical limitations and economic vulnerabilities such as investment recovery delays and market uncertainties.

2.2. Effects of Climate Change on Fruit Cultivation

The climate-induced vulnerabilities observed across the broader agricultural sector manifest as more complex and multidimensional risk areas in the context of fruit production. One of the primary reasons for this is the perennial nature of fruit production systems, whose biological cycles operate within specific agroclimatic thresholds and are implemented in spatially fixed growing areas. These characteristics limit the plasticity[9] of fruit production systems in adapting to environmental variability (Rimpika et al., 2021: 191; Guy & Dufour, 2014: 2).

As a result of global climate change, deviations in key climatic parameters—*such as temperature, humidity, photoperiod, and radiation*—disrupt fundamental phenological stages, including flowering synchronization, bud break, fruit set, and ripening. These disruptions cause asynchronies[10], reduce reproductive success and trigger yield losses (Pertille et al., 2022: 111353; Mo et al., 2023: 2; Wyer et al., 2023: 109281).

Additionally, abiotic stress factors such as extreme heat, drought, salinity, and excessive radiation lead to physiological disturbances in plants (dos Santos et al., 2022: 113–115). These disturbances negatively affect fruit quality through responses such as reduced photosynthetic capacity, stomatal closure[11] (Ak et al., 2023), and decreased water potential (dos Santos et al., 2022: 113–115; Li et al., 2023: 3).

Moreover, the high fixed investment requirements and long return on investment periods characteristic of fruit production systems render these systems biophysically vulnerable. The seasonal shifts and the increasing frequency and intensity of extreme weather events caused by global climate change expose agricultural production to high uncertainty and volatility. In fruit cultivation—*where phenological timing[12] is critical*—this situation transforms unpredictability into a structural risk factor.

In this context, developing genetically superior, stress-tolerant plant varieties and their rapid, reliable, and disease-free propagation under controlled conditions make *in vitro* tissue culture techniques one of the most effective biotechnological tools for climate adaptation in fruit growing.

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9 Plasticity is the ability of an organism to adapt phenotypically to environmental changes.

10 Phenological stages are developmental phases such as budding, flowering, and fruit set. Asynchrony refers to the lack of synchronization in the timing of these stages.

11 It is the closure of pores (stomata) on the surface of plant leaves to prevent water loss. This condition also limits gas exchange, thereby reducing the efficiency of photosynthesis.

12 Phenological timing refers to the seasonal schedule of key developmental events in plants, such as budburst, flowering, fruit set, and leaf fall, which are often sensitive to climatic conditions.

2.2.1. Disruption of Phenological Synchrony and Developmental Deviations

In fruit trees, productivity and quality largely depend on the alignment of successive phenological events—s*uch as flowering, fruit set, bud break, and ripening*—with environmental cues like temperature, photoperiod, and humidity (Mo et al., 2023: 2). In other words, the phenological phases of fruit trees (*dormancy release, flowering, fruit set, ripening, etc.*) are triggered based on specific temperature and light thresholds (Clark et al., 2014: 1344). Suppose there is insufficient chilling accumulation during winter or inadequate warming in spring. In that case, these stages fail to initiate in synchrony (Fraga & Santos, 2021: 1), leading the tree to exhibit irregular and scattered flowering rather than a uniform bloom. This mismatch also disrupts pollen viability, fertilization, and fruit set, resulting in yield losses (Tominaga et al., 2022: 2).

Due to global warming, rising winter temperatures—especially in temperate fruit species—prevent proper dormancy release, leading to delays, irregularities, and phenological asynchrony in flowering timing (Inouye, 2022; Tominaga et al., 2022: 2; Roussos, 2024: 4). Inadequate dormancy release hinders both vegetative and reproductive development, reducing flowering intensity, which in turn compromises flower and pollen viability, pollination success, and ultimately fruit set rates (Pertille et al., 2022).

Another critical risk is the temporal mismatch between flowering and pollinator activity, which weakens integrated pollination mechanisms and further reduces reproductive success (Hegland et al., 2009; Memmott, 2007). These phenological mismatches lead to heterogeneity in fruit quality, staggered ripening, and significant losses in commercial yield. Therefore, climate change alters the pace of fruit trees' developmental processes and disrupts the synchrony between these processes, structurally destabilizing fruit production systems.

2.2.2. Abiotic Stress Factors: Drought, Salinity, and Heat

Common abiotic stress factors such as drought, salinity, and extreme heat exert multifaceted and suppressive effects on fruit trees' physiological, biochemical, and morphological processes. These stressors disrupt the plant’s osmotic balance, alter cell membrane permeability, and lead to the accumulation of reactive oxygen species[13] (ROS), thereby impairing normal metabolic functions (Rao et al., 2016: 6). In particular, physiological responses such as reduced photosynthetic activity, decreased water potential, and stomatal closure diminish carbon assimilation and turgor pressure, resulting in significant declines in key fruit quality parameters (Farooq et al., 2009).

Abiotic stress not only causes short-term quality losses but also leads to long-term structural damage. Under drought conditions, xylem water transport is severely impaired, suppressing photosynthetic efficiency and fruit development. Excessive heat stress, on the other hand, results in protein denaturation, membrane degradation, and disruptions in hormonal balance, particularly in abscisic acid (ABA)[14] and ethylene levels, negatively affecting reproductive development processes (Ahmad et al., 2022; Sehar et al., 2022). In conclusion, these stress factors represent significant environmental constraints that threaten fruit production systems' stability in terms of yield and quality.

2.2.3. Pests, Diseases, and Emerging Risk Areas

Global warming is transforming not only climatic parameters but also the dynamics of plant–pathogen–vector interactions. Rising average temperatures and longer and warmer growing seasons are increasing the number of generations many pest species can complete and altering their geographical distribution (Bebber et al., 2013: 985; Garrett et al., 2006: 495). In particular, under simultaneous increases in temperature and humidity, the sporulation capacity of fungal pathogens rises, and the transmission potential of vector-borne viruses also intensifies (Gregory et al., 2009: 2827). As a result, agricultural production systems are increasingly confronted with a more complex web of threats (Beckford & Norman, 2016: 189).

For example, pests such as the olive fruit fly *(Bactrocera oleae*) (Daane & Johnson, 2010: 160) and the Mediterranean fruit fly (*Ceratitis capitata*) (Gilioli et al., 2021: 261) are not only emerging earlier under higher temperature and humidity conditions, but also producing more generations per

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13 High-energy oxygen derivatives that accumulate in plants under stress conditions and can damage cell membranes.

14 ABA (Abscisic Acid) is a plant hormone that triggers stomatal closure under stress conditions such as drought.

year, exceeding traditional intervention thresholds and becoming harder to control. Consequently, dependence on chemical control methods increases, leading to more frequent and intensive pesticide use, threatening environmental sustainability.

Moreover, pest species previously limited to specific microclimatic conditions are now observed at higher altitudes and northerly latitudes. This ecological expansion puts pressure on local biodiversity. The growing pest burden necessitates a re-evaluation of integrated pest management (IPM)[15] strategies, as the adaptation capacity and effectiveness of biological control agents are also directly affected by climate variability (Bebber et al., 2013: 985; Gullino et al., 2022: 1–2).

In conclusion, global climate change is creating a multilayered risk structure that threatens productivity and the long-term sustainability of agricultural production. Beyond biophysical and environmental impacts, climate change significantly affects fruit production systems at the socioeconomic level, creating new areas of vulnerability, particularly for smallholder farmers (Zenda, 2024: 2).

3. The Role of Tissue Culture in Fruit Cultivation within the Climate Change Adaptation Process

Despite the significant advancements and increasing mechanization in fruit cultivation, the sector continues to experience the multifaceted adverse effects of climate change. The growing challenges posed by air, water, and soil pollution—*exacerbated by climate change*—make sustaining fruit production under natural conditions increasingly difficult. Additionally, low productivity, seasonal dependency, high susceptibility to diseases, and limited genetic diversity are critical issues in fruit cultivation. Furthermore, the development of climate-resilient plant varieties is becoming increasingly essential to address the projected impacts of global warming in the near future.

In this context, plant tissue culture technology effectively produces high-quality planting material and develops superior genotypes. While traditional breeding methods require long-term and high-cost processes, micropropagation

15 Integrated Pest Management

offers a more rapid and cost-effective strategy for achieving genetic gains (Rai et al., 2011: 89; Sahu et al., 2013: 39).

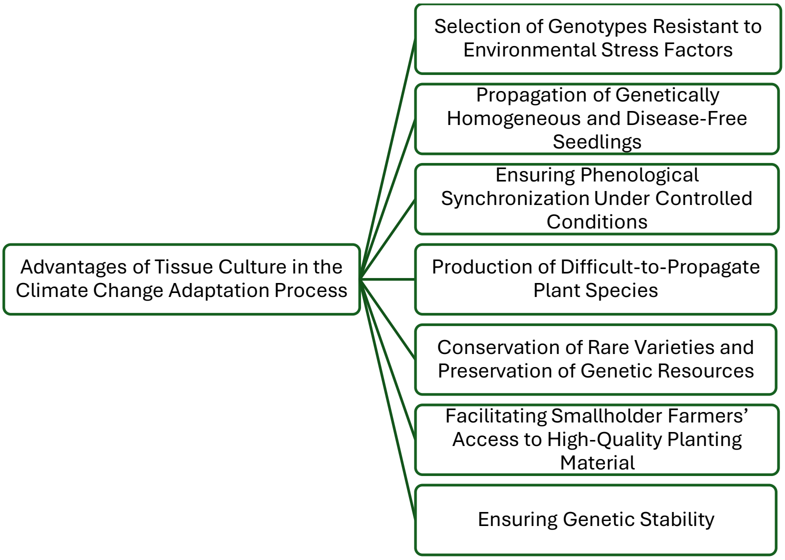

Figure 3: Advantages of Tissue Culture in the Climate Change Adaptation Process

These multidimensional impacts necessitate a biophysical response and the enhancement of the adaptive capacity of fruit production systems in the face of climate change. Therefore, supporting local producers, strengthening knowledge and technology transfer, and widespread adoption of biotechnological methods (such as tissue culture and the development of stress-tolerant genotypes) have become critical requirements for establishing climate-resilient fruit production models.

In other words, considering all the challenges of global climate change, tissue culture applications emerge as a strategic tool in developing fruit production systems resistant to the climate crisis. This technique offers significant advantages in the selection of genotypes tolerant to environmental stress conditions and the propagation of disease-free and genetically homogeneous plant material (Eckard et al., 2023: 25). For these reasons, tissue culture is a fundamental biotechnological solution that both enhances production security and supports the transition to sustainable fruit production systems.

In *in vitro* selection methods based on tissue culture, cells or tissues that exhibit resistance or tolerance are identified and multiplied within culture media enriched with selective agents that simulate stress conditions. This approach enables the early-stage identification and multiplication of stress-tolerant variants. The success of plant regeneration from planting material in this technique is highly dependent on factors such as the type of explant used, culture conditions, and the composition of the culture medium. Various climate-stress-resistant plants have been successfully regenerated through tissue culture techniques by adjusting medium components and using explants suitable for the targeted stress.

As the effects of climate change on agricultural production intensify, fruit cultivation has become one of the most severely affected sectors. Perennial plants, in particular, demonstrate high sensitivity to sudden temperature fluctuations, frost events, hailstorms, and out-of-season climatic conditions during their development stages. These stressors cause severe losses not only in yield quantity but also in fruit quality. In addition, global climate change disrupts chilling requirements, budburst and flowering timing, and pollination mechanisms. It increases the risks of sunburn, frost, hail, and disturbances in the ecological balance of pests and diseases. These biotic and abiotic stress factors reduce productivity in fruit cultivation and create a complex risk environment that undermines sustainability for producers (Oğuz, 2023: 218).

Before evaluating the effectiveness of tissue culture techniques, it would be useful to present several examples related to the phenological impacts of climate change on fruit production.

Table 1: Findings on Climate Change-Induced Phenological Shifts in Fruit Cultivation

Author(s)	Year	Study Area (Species/Scope)	Key Finding
Campoy et al.	2011	Temperate fruit species – Yield impact	Climate change negatively affects fruit yield depending on species and region.
Romanovskaja & Bakšiene	2009	Lithuania – Apple flowering	Apple trees are flowering 4–5 days earlier.
Legave et al.	2013	Europe – Bud break in various regions	Blooming occurs approximately 10 days earlier in northern continental Europe, 6–7 days earlier in western oceanic regions such as France, and slightly earlier along the Mediterranean coastline.
Miller-Rushing et al.	2007	Japan – Cherry species	On average, flowering occurred 5.5 days earlier over the 25-year period. Most species flowered 3–5 days earlier per 1°C increase, while early-flowering taxa advanced by as much as 9 days per 1°C.
Cosmulescu et al.	2010	Romania – Plum	Flowering has shifted 12–20 days earlier.
Chmielewski et al.	2004	Phenological response to temperature	Winter and early spring are the most sensitive periods.
Türkoğlu et al.	2014	Türkiye – Apple, cherry, wheat	Harvest dates have advanced; phenological phases shift earlier with temperature rise.

As shown in Table 1, climate change can lead to a wide range of adverse effects on fruit productivity, depending on the species and region. In this context, plant tissue culture technology emerges as a powerful and effective solution to the environmental challenges faced by modern agriculture. This technology, which finds application in numerous fields—from plant cell biology and genetic engineering to secondary metabolite production and stress tolerance enhancement—enables a deeper understanding of cellular processes, the improvement of genetic structure, and the development of plant lines resistant to environmental stress factors.

In particular, the mass production of healthy and genetically homogeneous planting material, free from viruses and pathogens, within a short period significantly reduces risks that threaten productivity. Furthermore, plant species that are difficult to propagate through conventional methods can also be introduced into agricultural production through tissue culture techniques (Nhut, 2022: 5–10). Indeed, Beckford and Norman (2016) state that tissue culture improves the health of planting materials and supports genetic diversity, thereby contributing to sustainable agricultural production. In this regard, tissue culture has become a strategic tool in developing climate-resilient fruit production systems (Chadipiralla et al., 2020: 393).

3.1. Tissue Culture Research in Fruit Cultivation within the Climate Change Adaptation Process

Due to climate change, rising temperatures, and irregular rainfall patterns in agricultural lands are leading to increased salinity levels (notably involving Na^+ and Cl^- ions), triggering osmotic and ionic stress in plants. When the salt concentration in the root zone exceeds a certain threshold, an initial rapid osmotic phase slows shoot growth, followed by a slower ionic phase, during which salt accumulation in older leaves causes leaf abscission (Munns & Tester, 2008). In recent years, *in vitro* tissue culture techniques have become a promising approach for developing plants resistant to such abiotic stress conditions.

In this context, various *in vitro* applications aimed at enhancing tolerance to salinity and drought have demonstrated significant success:

Al-Khateeb et al. (2020) conducted embryogenic callus culture experiments on *Phoenix dactylifera* cv. *Khalas*, exposing regenerants to 0–300 mM NaCl. Under 200 and 300 mM NaCl conditions, the regenerated plants exhibited significantly lower Na^+ accumulation in the leaves and a higher K^+/Na^+ ratio. These salt-adapted regenerants maintained photosynthetic rates and showed improved stomatal conductance, clearly outperforming the control and non-adapted regenerants. The findings suggest that tissue culture-derived lines could serve as a critical adaptation strategy in agricultural production against increasing salinity stress caused by climate change.

Alyousif et al. (2023) tested salinity stress levels (0–5000 ppm NaCl) in an in vitro culture study involving Simmondsia chinensis (jojoba). Seedlings exposed to 2000 ppm showed the highest shoot length, leaf number, and multiplication capacity. Although performance declined at 3000 ppm, physiological tolerance was still observed. At 5000 ppm, overall growth was significantly reduced. These results suggest that tissue culture can support the propagation of salt-tolerant jojoba clones, providing a promising tool for biotechnological adaptation to soil salinity under climate change.

Molnar et al. (2024) tested seven different blueberry (*Vaccinium* spp.) cultivars in an *in vitro* environment containing 10–150 mM NaCl and reported that the cultivar 'Goldtraube' exhibited the highest salt tolerance index, while 'Brigitta Blue' and 'Blueray' showed the lowest shoot development under 150 mM NaCl conditions. This study demonstrates that tissue culture techniques are practical tools for identifying variety-specific adaptation strategies against salinity stress induced by climate change.

Similarly, Aras and Eşitken (2017) conducted a comparative evaluation of the short-term physiological responses of cherry rootstocks to salinity stress, observing more pronounced decreases in stomatal conductance, leaf relative water content, and chlorophyll (SPAD) values in MaxMa 14 and CAB-6P rootstocks compared to Mazzard. These findings underscore the significance of genotype-specific physiological responses as key indicators of salt tolerance.

Mahmoud et al. (2023) evaluated a tetraploid somatic hybrid, produced by the protoplast fusion of salt-sensitive *Carrizo citrange* and salt-tolerant *Cleopatra mandarin*, in *in vitro* media containing 0, 50, and 100 mM NaCl. Under 100 mM NaCl, the hybrid exhibited lower malondialdehyde (MDA) accumulation, reduced electrolyte leakage, and higher total phenolic content. In addition, its chlorophyll levels and antioxidant capacity (DPPH) were superior to those of the diploid parents. These results suggest that the tetraploid hybrid demonstrated enhanced tolerance to salinity stress compared to its diploid progenitors and that tissue culture-derived lines can serve as critical adaptation strategies in fruit cultivation under increasing salinity conditions driven by climate change.

Elloumi et al. (2024) conducted *in vitro* experiments on two newly developed Tunisian olive cultivars, '*Zeitoun Ennour*' and '*Zeitoun Ennwader*', using a modified Hoagland nutrient medium supplemented with 0, 75, 150, and 225 mM NaCl. The results revealed that both new cultivars could maintain a high K^+/Na^+ ratio even under 150 mM NaCl, without significantly reducing shoot elongation or stem diameter. In contrast, the traditional cultivar '*Chemlali Sfax*' experienced 40–80% reductions in shoot growth and stem diameter under the same salinity level. These findings suggest that, while not derived from tetraploid or hybrid backgrounds, newly selected salt-tolerant cultivars can offer enhanced resilience under salt-stress conditions caused by climate change.

In addition, earlier classical studies have also contributed to this field. *In vitro* salinity and drought tolerance experiments have been conducted in several fruit and crop species, including Citrus spp. (*C. aurantium, C. limon, C. sinensis*), strawberry *(Fragaria × ananassa*), mulberry (*Morus* sp.), coconut (*Cocos nucifera*), and cherry (*Prunus avium*)—forming a foundational body of literature (Koç et al., 2009; Piqueras et al., 1996; Ben-Hayyim & Goffer, 1989; Dziadczyk et al., 2003).

On the other hand, studies focusing on drought stress have also yielded noteworthy insights:

Vuksanović et al. (2022) applied PEG 6000 (1, 10, 20, and 50 g/L) in their study on Populus alba clones to simulate *in vitro* drought stress and perform tolerance screening. Under 50 g/L PEG conditions, the '*Villafranca'* clone demonstrated superior performance compared to other clones in terms of shoot length, number of roots, and rooting percentage. The study showed that drought-tolerant genotypes can be selected under *in vitro* conditions and that PEG application is an effective biotechnological tool in this process. These findings represent a strategic approach to developing genotype-specific drought-resilient individuals under climate-induced water scarcity.

Bidabadi and Mahmood (2012) simulated water stress using PEG 6000 in *Musa* spp. (banana) variants and identified drought-tolerant lines. Under 30 g/L PEG, EMS-mutagenized variants L2-5 and L1-5 outperformed control plants regarding leaf number, fresh weight, and chlorophyll content. These variants also exhibited increased proline accumulation and reduced H_2O_2 and MDA levels. Genetic differences were confirmed through RAPD analyses. This study highlighted the effectiveness of *in vitro* PEG stress testing in selecting and identifying drought-tolerant genotypes under laboratory conditions.

Rezai et al. (2023) developed *in vitro* micropropagation protocols for five superior almond genotypes (P. *elaeagnifolia, P. scoparia* × *P. elaeagnifolia, P. eburnea, P. scoparia*, and '*Garnem'*). They found that the MS medium supplemented with 3 mg/L BA, 3 mg/L GA_3, and 0.1 mg/L IBA yielded the highest shoot induction and proliferation rates, while for rooting, ½ MS medium with 0.5–1 mg/L IBA gave optimal results. This study emphasized that such protocols can be effectively used in biotechnological adaptation strategies for the commercial propagation of drought-tolerant genotypes under climate change conditions.

Tissue culture has also proven effective for biosafety and virus elimination.

Hu et al. (2012) tested a combination of meristem-tip culture, thermotherapy at 35 °C for 40 days, and ribavirin application (15–25 mg/L) to eliminate Apple chlorotic leaf spot virus (ACLSV) and apple stem grooving virus (ASGV) from *Pyrus pyrifolia in vitro*. Results showed 100% elimination of both viruses under combined treatment conditions. This highlights the effectiveness of *in vitro* biosafety protocols as strategic tools for virus-free seedling production, especially under increasing viral threats driven by climate change.

Szabó et al. (2023) reviewed *in vitro* virus elimination techniques in the *Prunus* genus fruit trees (e.g., peach, cherry, apricot). The study compared the effectiveness of meristem culture, thermotherapy, cryotherapy, chemotherapy (e.g., *ribavirin*), and their combinations. It concluded that combined approaches significantly enhance viral cleaning success rates, reaffirming the importance and applicability of tissue culture-based strategies for producing virus-free planting material in an era of increasing vector-borne disease pressure due to climate instability.

Advanced molecular research is also gaining attention in terms of enhancing genetic resilience.

Yang et al. (2025) demonstrated that the MdHB7L–MdICE1L–MdHOS1 gene module in apple responds to cold stress through both CBF-dependent and CBF-independent pathways, explaining the molecular regulation of low-temperature tolerance. These findings offer a crucial biotechnological basis for selecting cold-tolerant genotypes in *in vitro* culture conditions. The study further emphasizes that understanding gene regulatory networks in developing cold-resistant lines holds strategic value for sustainable fruit production systems in the context of climate change. In this regard, integrating molecular biotechnology with tissue culture is a tangible contribution to climate adaptation.

These examples demonstrate that tissue culture techniques are essential for the propagation of planting material and play a critical role in developing stress-tolerant lines, conserving genetic resources, and restoring phenological balance in fruit production.

Indeed, the tetraploid individuals obtained through in vivo colchicine applications in grape varieties demonstrate that polyploidization can be an effective strategy for developing new genotypes through mutation breeding and introducing new cultivars with adaptive traits to cope with climate change-induced stress conditions (Kara & Yazar, 2020).

4. Discussion and Recommendations

Global climate change profoundly and multidimensionally affects perennial production systems such as fruit cultivation, which have limited adaptive capacity to environmental stressors (Russos, 2024: 558; Osorio Marín et al., 2024). Rising temperatures, irregular precipitation patterns, extreme weather events, and imbalances in soil–salinity–water dynamics threaten fruit production's physiological processes and economic sustainability (FAO, 2024; IPCC, 2019). Under such conditions, it is evident that traditional agricultural techniques alone are insufficient, and the integration of innovative tools provided by plant biotechnology has become necessary.

In this context, *in vitro* tissue culture techniques stand out as a strategic tool in climate adaptation efforts due to their applications in the development of stress-tolerant genotypes, the production of healthy and genetically uniform seedlings, virus and pathogen elimination, and the conservation of genetic resources (Beckford & Norman, 2016; Benelli et al., 2022; Kulak et al., 2022; Szabó et al., 2023).

Recent studies show that tissue culture offers theoretical benefits and tangible production outcomes. For example, Al-Khateeb et al. (2020) demonstrated that salt-adapted regenerants of *Phoenix dactylifera* cv. *Khalas* maintained a high K^+/Na^+ ratio, optimized photosynthetic rate, and stomatal conductance even under 300 mM NaCl, showcasing a successful biotechnological adaptation to salt stress. Similarly, Alyousif et al. (2023) reported that *in vitro* propagated jojoba cultivars remained viable and developed healthy shoots even under 3000 ppm NaCl, indicating high adaptability.

Beyond salinity, studies on drought stress have also yielded promising results. In Populus alba clones, PEG 6000 application enabled the selection of the '*Villafranca*' clone for superior shoot and root development (Vuksanović et al., 2022). In *Musa* spp., the EMS-mutagenized lines L1-5 and L2-5 showed higher chlorophyll content and lower H_2O_2 and MDA accumulation under PEG-simulated drought, highlighting the effectiveness of tissue culture-based drought tolerance screening (Bidabadi & Mahmood, 2012).

Tissue culture has also proven effective in virus elimination and biosafety. Hu et al. (2012) reported 100% elimination of ASPV and 67% of ASGV in *Pyrus pyrifolia* using a combination of meristem culture, thermotherapy, and ribavirin. Szabó et al. (2023) emphasized that combined techniques yield higher success rates in virus removal for Prunus species, indicating a strategic role for tissue culture in combating climate-induced vector-borne diseases.

Furthermore, integrating molecular biotechnology with tissue culture strengthens the adaptation capacity. Yang et al. (2025) revealed that the MdHB7L–MdICE1L–MdHOS1 gene module regulates cold stress responses via CBF-dependent and independent pathways, providing a genetic foundation for selecting cold-tolerant lines under *in vitro* conditions. This highlights the strategic value of understanding gene regulatory networks in building sustainable fruit production systems under climate change.

Key Advantages of Tissue Culture in Climate Adaptation

1. Rapid selection and multiplication of plants resistant to drought, salinity, and heat stress
2. Production of virus- and pathogen-free, healthy, and clonal planting material
3. Conservation of genetic resources and preservation of rare species
4. Ability to simulate stress conditions independently of environmental variables

Development of phenologically synchronized genotypes in response to developmental asynchronies

Policy Recommendations

- Regional expansion of tissue culture infrastructure and its application to local genetic resources
- Increased public R&D investment and strengthened partnerships between the private sector and universities
- Inclusion of biotechnological strategies in national climate adaptation policies and their integration into national agricultural development plans

In conclusion, the multifunctional solutions offered by tissue culture techniques to the threats posed by the global climate crisis represent a sustainable model that enhances resilience at the biological level and across economic, environmental, and social dimensions. In light of current scientific evidence, it is clear that tissue culture has become a cornerstone of climate adaptation in the fruit production sector.

5. Conclusion

Climate change imposes multifaceted and lasting effects on agricultural production systems that are long-lived and highly sensitive to environmental conditions, such as fruit cultivation. Phenomena such as rising temperatures, irregular rainfall patterns, increasing soil salinity, and declining water resources directly affect trees' physiological development, productivity, and fruit quality. Simultaneously, the increased pressure from pests and diseases threatens production continuity, rendering fruit cultivation a biologically and environmentally vulnerable sector.

There is a pressing need for innovative and science-based solutions beyond conventional agricultural practices in this context. Among modern biotechnological tools, tissue culture techniques directly and effectively respond to this need. Conducted under *in vitro* conditions, these techniques offer significant advantages in diverse areas, including selecting and propagating stress-tolerant genotypes, producing healthy and uniform seedlings, conserving genetic resources, and eliminating viruses.

Through tissue culture, it becomes possible to identify and rapidly multiply stress-resilient plant lines at early stages under controlled conditions, enabling the development of fruit production systems better equipped to cope with the uncertainties of climate change. Thus, this technique serves as a comprehensive adaptation strategy that supports production efficiency, food security, rural livelihoods, and environmental sustainability.

In conclusion, tissue culture applications strategically build climate-resilient fruit production systems and provide a robust scientific foundation for establishing a safer, more productive, and more sustainable agricultural future. Therefore, greater support and dissemination of tissue culture-based strategies—both in research and practice—is crucial for the success of climate change adaptation efforts in the agricultural sector.

REFERENCES

Abbas, G., Ahmed, M., Fatima, Z., Hussain, S., Kheir, A. M., Ercişli, S., & Ahmad, S. (2023). Modeling the potential impact of climate change on maize-maize cropping system in semi-arid environment and designing of adaptation options. Agricultural and Forest Meteorology, 341, 109674. https://doi.org/10.1016/j.agrformet.2023.109674

Ahmad, M., Imtiaz, M., Shoib Nawaz, M., Mubeen, F., & Imran, A. (2022). What Did We Learn From Current Progress in Heat Stress Tolerance in Plants? Can Microbes Be a Solution? *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.794782

Ak, B. E., Can, M., Açar, İ., Hatipoglu, I. H., et al. (2023). Determination of Leaf and Stomata Characteristics of Some Late Blooming Almond (Amygladus communis L.) Cultivars and Their Hybrids Grown in Semi-arid Climate Conditions. Journal of Agricultural Faculty of Gaziosmanpaşa University, 40(1), 1-10. https://doi.org/10.55507/gopzfd.1139252

Al-Khateeb, S. A., Al-Khateeb, A. A., Sattar, M. N., & Mohmand, A. S. (2020). Induced in vitro adaptation for salt tolerance in date palm (Phoenix dactylifera L.) cultivar Khalas. *Biological Research*, *53*(1), 37. https://doi.org/10.1186/s40659-020-00305-3

Alyousif, N. A., El Sherif, F., Yap, Y.-K., & Khattab, S. (2023). Selection of Salt-Tolerant Jojoba (Simmondisa chinensis L.) Cultivars via In Vitro Culture. *Horticulturae*, *9*(6), 675. https://doi.org/10.3390/horticulturae9060675

Aras, S., & Eşitken, A. (2018). Physiological responses of cherry rootstocks to short term salinity. Erwerbs-Obstbau, 60(2), 161-164. https://doi.org/10.1007/s10341-017-0350-x

Bebber, D. P., Ramotowski, M. A. T., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, *3*(11), 985–988. https://doi.org/10.1038/nclimate1990

Beckford, C. L., & Norman, A. (2016). Climate Change and Quality of Planting Materials for Domestic Food Production: Tissue Culture and Protected Agriculture. In C. L. Beckford & K. Rhiney (Eds.), *Globalization, Agriculture and Food in the Caribbean: Climate Change, Gender and*

Geography (pp. 189–215). London: Palgrave Macmillan UK. https://doi.org/10.1057/978-1-137-53837-6_8

Benelli, C., Tarraf, W., Izgu, T., & De Carlo, A. (2022). In Vitro Conservation through Slow Growth Storage Technique of Fruit Species: An Overview of the Last 10 Years. *Plants*, *11*(23), 3188. https://doi.org/10.3390/plants11233188

Ben-Hayyim, G., & Goffer, Y. (1989). Plantlet regeneration from a NaCl-selected salt-tolerant callus culture of Shamouti orange (Citrus sinensis L. Osbeck). *Plant Cell Reports*, *7*(8), 680–683. https://doi.org/10.1007/BF00272060

Bidabadi, S. S., Mahmood, M., Meon, S., Wahab, Z., & Ghobadi, C. (2011). Evaluation of in vitro water stress tolerance among EMS — Induced variants of banana (Musa spp., AAA), using “morphological, physiological and molecular” traits. *Journal of Crop Science and Biotechnology*, *14*(4), 255–263. https://doi.org/10.1007/s12892-011-0073-8

Campoy, J. A., Ruiz, D., & Egea, J. (2011). Dormancy in temperate fruit trees in a global warming context: A review. *Scientia Horticulturae*, *130*(2), 357–372. https://doi.org/10.1016/j.scienta.2011.07.011

Chadipiralla, K., Gayathri, P., Rajani, V., & Reddy, P. V. B. (2020). Plant Tissue Culture and Crop Improvement. In R. Roychowdhury, S. Choudhury, M. Hasanuzzaman, & S. Srivastava (Eds.), *Sustainable Agriculture in the Era of Climate Change* (pp. 391–412). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-45669-6_18

Chmielewski, F.-M., Müller, A., & Bruns, E. (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology*, *121*(1), 69–78. https://doi.org/10.1016/S0168-1923(03)00161-8

Clark, J. S., Salk, C., Melillo, J., & Mohan, J. (2014). Tree phenology responses to winter chilling, spring warming, at north and south range limits. *Functional Ecology*, *28*(6), 1344–1355. https://doi.org/10.1111/1365-2435.12309

Cosmulescu, S., Baciu, A., CICHI, M., & Marius, G. (2010). The effect of clımate changes on phenologıcal phases ın plum tree (prunus domestica l.) In south-western romanıa. *South-Western Journal of Horticulture,* *Biology & Environment*, *1*, 9–20.

Daane, K. M., & Johnson, M. W. (2010). Olive Fruit Fly: Managing an Ancient Pest in Modern Times. *Annual Review of Entomology*, *55*(1), 151–169. https://doi.org/10.1146/annurev.ento.54.110807.090553

dos Santos, T. B., Ribas, A. F., de Souza, S. G. H., Budzinski, I. G. F., & Domingues, D. S. (2022). Physiological Responses to Drought, Salinity, and Heat Stress in Plants: A Review. *Stresses*, *2*(1), 113–135. https://doi.org/10.3390/stresses2010009

Dziadczyk, P., Bolibok-Bragoszewska, H., Tryka, M., & Hortyñski, J. A. (2003). (PDF) In vitro selection of strawberry (Fragaria × ananassa Duch.) clones tolerant to salt stress. *ResearchGate*, *132*(1), 49–55. https://doi.org/10.1023/A:1024647600516

Eckardt, N. A., Ainsworth, E. A., Bahuguna, R. N., Broadley, M. R., Busch, W., Carpita, N. C., … Zhang, X. (2022). Climate change challenges, plant science solutions. *The Plant Cell*. https://doi.org/10.1093/plcell/koac303

Elloumi, O., Amar, F. B., Trigui, A., Gargouri, K., & Ghrab, M. (2024). Early evaluation of salt-stress tolerance of new released olive cultivars based on physiological and biomass allocation indicators. *Journal of Agriculture and Food Research*, *18*, 101503. https://doi.org/10.1016/j.jafr.2024.101503

FAO. (2015). *Climate change and food security: Risks and responses*. Food And Agrıculture Organızatıon Of The Unıted Natıons.

FAO. (2024). *Greenhouse gas emissions from agrifood systems*. Retrieved from https://openknowledge.fao.org/handle/20.500.14283/cd3167en

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant Drought Stress: Effects, Mechanisms and Management. In E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, & C. Alberola (Eds.), *Sustainable Agriculture* (pp. 153–188). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-90-481-2666-8_12

Fraga, H., & Santos, J. A. (2021). Assessment of Climate Change Impacts on Chilling and Forcing for the Main Fresh Fruit Regions in Portugal. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.689121

Garrett, K. A., Dendy, S. P., Frank, E. E., Rouse, M. N., & Travers, S. E. (2006). Climate Change Effects on Plant Disease: Genomes to Ecosystems.

Annual Review of Phytopathology, *44*(1), 489–509. https://doi.org/10.1146/annurev.phyto.44.070505.143420

Gilioli, G., Sperandio, G., Colturato, M., Pasquali, S., Gervasio, P., Wilstermann, A., … Schrader, G. (2022). Non-linear physiological responses to climate change: The case of Ceratitis capitata distribution and abundance in Europe. *Biological Invasions*, *24*(1), 261–279. https://doi.org/10.1007/s10530-021-02639-9

Gregory, P. j, Ingram, J. s. i, & Brklacich, M. (2005). Climate change and food security. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2139–2148. https://doi.org/10.1098/rstb.2005.1745

Gregory, P. J., Johnson, S. N., Newton, A. C., & Ingram, J. S. I. (2009). Integrating pests and pathogens into the climate change/food security debate. *Journal of Experimental Botany*, *60*(10), 2827–2838. https://doi.org/10.1093/jxb/erp080

Gullino, M. L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K. A., … Stephenson, T. (2022). Climate Change and Pathways Used by Pests as Challenges to Plant Health in Agriculture and Forestry. *Sustainability*, *14*(19), 12421. https://doi.org/10.3390/su141912421

Guy, K. A., & Dufour, R. (2014). *Climate Change and Perennial Fruit and Nut Production: Investing in Resilience in Uncertain Times*. ATTRA Sustainable Agriculture.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A.-L., & Totland, Ø. (2009). How does climate warming affect plant-pollinator interactions? *Ecology Letters*, *12*(2), 184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x

Hu, G. J., Hong, N., Wang, L. P., Hu, H. J., & Wang, G. P. (2012). Efficacy of virus elimination from *in vitro*-cultured sand pear (*Pyrus pyrifolia*) by chemotherapy combined with thermotherapy. *Crop Protection*, *37*, 20–25. https://doi.org/10.1016/j.cropro.2012.02.017

Inouye, D. W. (2022). Climate change and phenology. *WIREs Climate Change*, *13*(3), e764. https://doi.org/10.1002/wcc.764

IPCC. (2019). *Summary for Policymakers—Special Report on Climate Change and Land*. Retrieved from https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

IUCN. (2023). Plant Species in the World and Its Annual Increase [Veri Tabanı]. Retrieved May 18, 2025, from https://nc.iucnredlist.org/redlist/content/attachment_files/2024-1_RL_Table_1a_v2.pdf

Kantoğlu, K. Y., Kuşvuran, Ş., & Ellialtoğlu, Ş. Ş. (2021). Doku Kültürü Yöntemlerinin Islah Çalışmalarında Kullanımı. In Ş. Ş. Ellialtoğlu, H. Y. Daşgan, & Ş. Kuşvuran (Eds.), *Sebzelerde Stres Toleransı ve Islah Stratejileri* (pp. 708–741). Ankara: Gece Kitaplığı.

Kara, Z., & Yazar, K. (2022). Induction of polyploidy in grapevine (Vitis vinifera L.) seedlings by in vivo colchicineapplications. *Turkish Journal of Agriculture and Forestry*: 46(2),152-159. https://doi.org/10.55730/1300-011X.2967

Koç, N. K., Bas, B., Koç, M., & Küsek, M. (2009). Investigations of in vitro Selection for Salt Tolerant Lines in Sour Orange (Citrus aurantium L.). *Biotechnology(Faisalabad)*, *8*(1), 155–159.

Kulak, V., Longboat, S., Brunet, N. D., Shukla, M., & Saxena, P. (2022). In Vitro Technology in Plant Conservation: Relevance to Biocultural Diversity. *Plants*, *11*(4), 503. https://doi.org/10.3390/plants11040503

Legave, J. M., Blanke, M., Christen, D., Giovannini, D., Mathieu, V., & Oger, R. (2013). A comprehensive overview of the spatial and temporal variability of apple bud dormancy release and blooming phenology in Western Europe. *International Journal of Biometeorology*, *57*(2), 317–331. https://doi.org/10.1007/s00484-012-0551-9

Li, Q., Gao, Y., Hamani, A. K. M., Fu, Y., Liu, J., Wang, H., & Wang, X. (2023). Effects of Warming and Drought Stress on the Coupling of Photosynthesis and Transpiration in Winter Wheat (Triticum aestivum L.). *Applied Sciences*, *13*(5), 2759. https://doi.org/10.3390/app13052759

Mahmoud, L. M., Killiny, N., Holden, P., Gmitter, F. G., Grosser, J. W., & Dutt, M. (2023). Physiological and Biochemical Evaluation of Salt Stress Tolerance in a Citrus Tetraploid Somatic Hybrid. *Horticulturae*, *9*(11), 1215. https://doi.org/10.3390/horticulturae9111215

Memmott, J., Craze, P. G., Waser, N. M., & Price, M. V. (2007). Global warming and the disruption of plant–pollinator interactions. *Ecology Letters*, *10*(8), 710–717. https://doi.org/10.1111/j.1461-0248.2007.01061.x

Miller-Rushing, A. J., Katsuki, T., Primack, R. B., Ishii, Y., Lee, S. D., & Higuchi, H. (2007). Impact of global warming on a group of related species and their hybrids: Cherry tree (Rosaceae) flowering at Mt. Takao, Japan. *American Journal of Botany*, *94*(9), 1470–1478. https://doi.org/10.3732/ajb.94.9.1470

Mo, Y., Li, X., Guo, Y., & Fu, Y. (2023). Warming increases the differences among spring phenology models under future climate change. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1266801

Molnar, S., Clapa, D., Pop, V. C., Hârța, M., Andrecan, F. A., & Bunea, C. I. (2024). Investigation of salinity tolerance to different cultivars of highbush blueberry (Vaccinium corymbosum L.) grown in vitro. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *52*(1), 13691–13691. https://doi.org/10.15835/nbha52113691

Munns, R., & Tester, M. (2008). Mechanisms of Salinity Tolerance. *Annual Review of Plant Biology*, *59*(Volume 59, 2008), 651–681. https://doi.org/10.1146/annurev.arplant.59.032607.092911

Nhut, D. T. (2022). General Information: Some Aspects of Plant Tissue Culture. In D. T. Nhut, H. T. Tung, & E. C.-T. Yueng (Eds.), *Plant Tissue Culture: New Techniques and Application in Horticultural Species of Tropical Region* (pp. 1–23). Singapore: Springer. https://doi.org/10.1007/978-981-16-6498-4_1

Oğuz, H. İ. (2023). İklim değişikliği ve meyvecilik. In M. Avan (ed.), *Tarım Bilimlerinde Yenilikçi Multidisipliner Yaklaşımlar* (pp. 215–254). Ankara: İksad Yayınevi.

Osorio-Marín, J., Fernandez, E., Vieli, L., Ribera, A., Luedeling, E., & Cobo, N. (2024). Climate change impacts on temperate fruit and nut production: A systematic review. *Frontiers in Plant Science*, *15*. https://doi.org/10.3389/fpls.2024.1352169

Our World In Data. (2025). Greenhouse gas emissions. Retrieved May 17, 2025, from Our World in Data website: https://ourworldindata.org/grapher/total-ghg-emissions

Pertille, R. H., Citadin, I., Oliveira, L. de S. de, Broch, J. de C., Kvitschal, M.

V., & Araujo, L. (2022). The influence of temperature on the phenology of apple trees grown in mild winter regions of Brazil, based on long-term records. *Scientia Horticulturae*, *305*, 111354. https://doi.org/10.1016/j.scienta.2022.111354

Piqueras, A., Hernández, J. A., Olmos, E., Hellín, E., & Sevilla, F. (1996). Changes in antioxidant enzymes and organic solutes associated with adaptation of citrus cells to salt stress. *Plant Cell, Tissue and Organ Culture*, *45*(1), 53–60. https://doi.org/10.1007/BF00043428

Porter, J. H., Parry, M. L., & Carter, T. R. (1991). The potential effects of climatic change on agricultural insect pests. *Agricultural and Forest Meteorology*, *57*(1), 221–240. https://doi.org/10.1016/0168-1923(91)90088-8

Rai, M. K., Kalia, R. K., Singh, R., Gangola, M. P., & Dhawan, A. K. (2011). Developing stress tolerant plants through *in vitro* selection—An overview of the recent progress. *Environmental and Experimental Botany*, *71*(1), 89–98. https://doi.org/10.1016/j.envexpbot.2010.10.021

Rao, N. K. S., Laxman, R. H., & Shivashankara, K. S. (2016). Physiological and Morphological Responses of Horticultural Crops to Abiotic Stresses. In N. K. S. Rao, K. S. Shivashankara, & R. H. Laxman (Eds.), *Abiotic Stress Physiology of Horticultural Crops* (pp. 3–17). New Delhi: Springer India. https://doi.org/10.1007/978-81-322-2725-0_1

Rezaei, A., Gharaghani, A., Shekafandeh, A., & Eshghi, S. (2023). Developing a Promising Micropropagation Method for Several Drought Tolerant and Hard-to-Root Wild and Domesticated Almond Genotypes by Shoot Tips Culture. *Erwerbs-Obstbau*, *65*(5), 1463–1477. https://doi.org/10.1007/s10341-023-00866-z

Rimpika, Sharma, D. P., & Ajender. (2021). Vulnerability of Temperate Fruit Production to Climate Change: Adaptation and Mitigation Measures: A Review. *Agricultural Reviews*. Retrieved from https://arccjournals.com/journal/agricultural-reviews/R-2016

Romanovskaja, D., & Baksıene, E. (2009). Influence of climate warming on beginning of flowering of apple tree (Malus domestica Borkh.) in Lithuania. *Influence of Climate Warming on Beginning of Flowering of Apple Tree (Malus Domestica Borkh.) in Lithuania*, *7*(1), 87–96.

Roussos, P. A. (2024). Climate Change Challenges in Temperate and Sub-

Tropical Fruit Tree Cultivation. *Encyclopedia*, *4*(1), 558–582. https://doi.org/10.3390/encyclopedia4010036

Sahu, J., & Sahu, R. K. (2013). A Review on Low Cost Methods for In Vitro Micropropagation of Plant Through Tissue Culture Technique. *Pharmaceutical and Biosciences Journal*, 38–41. https://doi.org/10.20510/ukjpb/1/i1/91115

Sehar, Z., Gautam, H., Iqbal, N., Alvi, A. F., Jahan, B., Fatma, M., … Khan, N. A. (2022). The Functional Interplay between Ethylene, Hydrogen Sulfide, and Sulfur in Plant Heat Stress Tolerance. *Biomolecules*, *12*(5), 678. https://doi.org/10.3390/biom12050678

Szabó, L. K., Desiderio, F., Kirilla, Z., Hegedűs, A., Várallyay, É., & Preininger, É. (2023). A mini-review on in vitro methods for virus elimination from Prunus sp. Fruit trees. *Plant Cell, Tissue and Organ Culture (PCTOC)*, *156*(2), 42. https://doi.org/10.1007/s11240-023-02670-9

Tarraf, W., & De Carlo, A. (2024). In Vitro Biotechnology for Conservation and Sustainable Use of Plant Genetic Resources. *Plants*, *13*(14), 1897. https://doi.org/10.3390/plants13141897

T.C. Tarım Ve Orman Bakanlığı. (2021). *İklim Değişikliği Ve Tarım Değerlendirme Raporu*. Ankara: T.C. Tarım Ve Orman Bakanlığı Tarım Reformu Genel Müdürlüğü.

Tominaga, A., Ito, A., Sugiura, T., & Yamane, H. (2022). How Is Global Warming Affecting Fruit Tree Blooming? “Flowering (Dormancy) Disorder” in Japanese Pear (Pyrus pyrifolia) as a Case Study. *Frontiers in Plant Science*, *12*, 787638. https://doi.org/10.3389/fpls.2021.787638

Vuksanović, V., Kovačević, B., Orlović, S., Kebert, M., & Kovač, M. (2019). The influence of drought on growth and development of white poplar shoots in vitro. *Topola*, (203), 13–18.

Wyver, C., Potts, S. G., Edwards, R., Edwards, M., & Senapathi, D. (2023). Climate driven shifts in the synchrony of apple *(Malus x domestica Borkh.)* flowering and pollinating bee flight phenology. *Agricultural and Forest Meteorology*, *329*, 109281. https://doi.org/10.1016/j.agrformet.2022.109281

Yang, J., Li, N., Li, M., Yi, R., Qiu, L., Wang, K., … Mao, K. (n.d.). The MdHB7L–MdICE1L–MdHOS1 Module Fine-Tunes Apple Cold

Response via CBF-Dependent and CBF-Independent Pathways. *Advanced Science*, *n/a*(n/a), 2501524. https://doi.org/10.1002/advs.202501524

Zenda, M. (2024). A systematic literature review on the impact of climate change on the livelihoods of smallholder farmers in South Africa. *Heliyon*, *10*(18). https://doi.org/10.1016/j.heliyon.2024.e38162

CHAPTER 5

CLIMATE CHANGE AND INSECT PEST MANAGEMENT: CHALLENGES AND ADAPTATION STRATEGIES

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Introduction

Climate change is a global environmental crisis that exerts substantial influence on natural and agricultural ecosystems (Thayer et al. 2020). Among the most vulnerable and responsive biological groups to these changes are insect pests, which pose a significant threat to global food security (Sharma and Prabhakar, 2014). Insects are ectothermic organisms whose biological processes, such as development, reproduction, and dispersal, are highly temperature-dependent (Mutlu and Sertkaya, 2016). Consequently, even modest changes in climate variables such as increased average temperatures, altered precipitation patterns, and elevated atmospheric CO_2 can have profound effects on their population dynamics and interactions with crops and natural enemies (Cammell and Knight, 1992; Živković et al, 2021). In these context, Agricultural pests, which already cause substantial yield losses in crops worldwide, are expected to become even more problematic under shifting climatic conditions (Deutsch et al., 2018). Such ecological changes also disrupt the balance between pests and their natural enemies, thus challenging existing Integrated Pest Management (IPM) practices.

The implications of climate change are particularly relevant for countries like Turkey, which straddles multiple agro-ecological zones and is highly vulnerable to climatic variability. Some studies have documented shifts in the population dynamics and phenology of major pests, such as *Eurygaster integriceps* (Hemiptera; Scutelleridae), *Tuta absoluta* (Lepidoptera; Gelechiidae) and *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), along with reduced efficacy of chemical and biological control agents (Aljaryian et al, 2016; Pomari-Fernandes et al, 2015; Islamoğlu, 2022). Therefore, understanding the interplay between climate change and insect pest behavior is crucial to safeguard national and global food security (Sharma and Prabhakar, 2014; Subedi et al., 2023). Recent research has increasingly focused on the multifaceted impacts of climate change on insect pest dynamics, highlighting significant alterations in their biology, distribution, outbreak potential, and management complexity (Deka et al., 2010; Bajwa et al., 2020; Subedi et al., 2023). One of the most widely observed effects is the influence of rising temperatures on insect physiology. Elevated thermal conditions are known to accelerate metabolic rates and shorten developmental durations, ultimately increasing the number of generations per season for many pest species (Neven, 2000; Mutlu and Sertkaya, 2015; Dubois et al. 2022). These phenological changes often result in greater pest pressure and more frequent infestations, especially in temperate agroecosystems. In addition to temperature, climate-induced variations in precipitation and atmospheric CO_2 levels also play a crucial role in shaping insect-plant interactions. Altered rainfall patterns and elevated CO_2 can affect host plant quality, pest feeding behavior, and survival rates, potentially leading to localized outbreaks and the expansion of pests into previously unsuitable habitats (Ziska and McConnell, 2016; Živković et al., 2021;). Such shifts are particularly concerning for polyphagous pests, whose adaptability makes them more likely to exploit new environments under changing conditions (Hill and Braschler, 2007). Furthermore, warmer winters and milder seasonal extremes enhance the overwintering success of many insect pests, increasing their capacity for establishment and damage in new geographic regions (Rozsypal, 2023). These range expansions not only threaten local biodiversity but also complicate existing pest management frameworks. In forest and perennial crop systems, the situation is even more complex. Trophic interactions among herbivores, host plants, and natural enemies are being altered in unpredictable ways, making it increasingly difficult to anticipate pest dynamics or implement effective biological control strategies (Lorenz and Jeyapragasan, 2020; Kistner-Thomas, 2022). This ecological uncertainty underlines the urgent need for climate-adaptive pest forecasting and integrative management approaches across diverse agro-ecological contexts.

The implications for pest management are significant. Integrated Pest Management (IPM) systems, which rely on a combination of biological, chemical, and cultural control strategies, are being challenged by the increasing unpredictability and adaptability of pest populations (Živković et al., 2021; Reddy et al., 2024;. Innovative approaches that incorporate climate data, remote sensing, and modeling tools are now essential to adapt pest management frameworks to changing environmental conditions (Kriticos et al., 2024; Chaturvedi et al., 2025). This paper aims to synthesize current scientific understanding of how climate change is altering insect pest dynamics and to explore adaptive strategies that can enhance resilience in pest management systems globally.

1. Population Growth and Distribution

One of the most consistent biological responses of insect pests to climate change is the acceleration of population growth and shifts in geographic distribution (Sharma, 2013). As ambient temperatures rise and critical thermal thresholds for development are more frequently exceeded, many pest species exhibit increased voltinism producing more generations per year than previously observed (Mutlu and Sertkaya, 2016). This trend has been documented across a range of agro-ecological zones, including both temperate and tropical regions (Sampaio et al., 2021). Warmer climates not only enhance the metabolic rate and developmental speed of insects but also extend the length of the growing season, allowing pests to exploit host plants over a longer period (Mutlu and Sertkaya, 2015; 2016). Consequently, some species that were historically regarded as secondary or occasional pests have now emerged as economically important threats. For example, *Spodoptera frugiperda* (fall armyworm), traditionally confined to the Americas, has rapidly expanded its range across sub-Saharan Africa and South Asia under favorable climatic conditions (Goergen et al., 2016; Early et al., 2018). Similarly, *T. absoluta*, a major pest of tomato crops, has increased its generation number and spread widely across the Mediterranean Basin and the Middle East (Bayram et al., 2017, Desneux et al., 2021).

In the European context, warming has facilitated northward expansions of pests such as *Leptinotarsa decemlineata* (Colorado potato beetle), now established in regions that were once climatically unsuitable (Izzo et al., 2014). In Turkey, increases in the abundance and temporal activity of *H. armigera* and *E. integriceps* have also been reported, with direct implications for wheat, cotton, and horticultural crop production (Öztemiz et al., 2009; Duman and Sertkaya, 2015). These shifts in population dynamics not only heighten the intensity and frequency of pest outbreaks but also present new challenges for timely monitoring and control, particularly in regions where pest forecasting systems are not yet climate-adaptive.

2. Challenges in Chemical and Biological Control under Changing Climates

The intensification of climate change not only accelerates pest population dynamics but also poses significant challenges to the efficacy of both chemical and biological pest control strategies. These approaches are fundamentally dependent on environmental conditions such as temperature, humidity, and atmospheric CO_2 levels variables that are increasingly unstable and unpredictable under climate change scenarios (Sharma, 2013; Skendžić et al., 2021; Chidawanyika et al., 2022; Nitta et al., 2024).

For chemical control methods, temperature fluctuations can alter pesticide degradation rates, reduce residual efficacy, and shift the timing of optimal application. Warmer temperatures often increase the volatility and photodegradation of insecticides, thereby decreasing their persistence in the environment and necessitating more frequent applications (Delcour et al., 2015; Matzrafi, 2018). This not only increases economic costs but also raises the risk of resistance development and environmental contamination. Furthermore, changes in pest feeding behavior and physiology under elevated CO_2 levels may reduce the susceptibility of target pests to certain active ingredients (Martin and Johnson, 2011; Matzrafi, 2018).

Biological control, often considered a cornerstone of Integrated Pest Management (IPM), is likewise vulnerable to climate-driven disruptions. Natural enemies such as parasitoids, predators, and entomopathogenic fungi are particularly sensitive to environmental variables. For instance, parasitoids generally exhibit narrower thermal tolerances compared to their hosts, making them more susceptible to heat stress and phenological mismatches (Aqueel and Leather, 2013; Jensen et. Al 2020). Similarly, the efficacy of microbial control agents like Beauveria bassiana and Metarhizium anisopliae declines under elevated temperatures and reduced humidity levels conditions expected to become more frequent in many regions (Doberski, 1981; El-Mukhlef et al., 2023). These challenges are further exacerbated in regions like the Middle East and Mediterranean Basin, where prolonged droughts and heatwaves already limit the effectiveness of traditional pest control options. In Turkey, for example, recent studies have shown a decrease in the performance of biological agents against pests such as Tuta absoluta and Eurygaster integriceps, especially during prolonged hot and dry summers (Bayram et al., 2017; Duman and Sertkaya, 2015; Islamoğlu, 2022).

To address these emerging constraints, pest management strategies must incorporate climate-resilient approaches such as the selection of heat-tolerant biocontrol strains, microclimate-based spray scheduling, and the development of predictive models that account for abiotic stressors. Failing to adapt control measures to climate realities may not only reduce control success but also undermine long-term agricultural sustainability.

3. Resistance and Outbreak Frequency

Climate change not only intensifies pest pressures but also indirectly contributes to the development of pesticide resistance and the frequency of pest outbreaks. One major driver of this phenomenon is the acceleration of insect life cycles under elevated temperatures, which allows for more generations per season and thus more opportunities for resistance alleles to be selected and fixed within populations (Rao et al., 2010; Musolin and Saulich, 2012; Tiwari, 2022). In parallel, extreme climatic events such as droughts and heatwaves can reduce the efficacy of biological control agents, compelling growers to rely more heavily on chemical insecticides often with increased frequency and dose (Pérez-Lucas et al., 2024; Vázquez, 2019). This overreliance on pesticides, particularly under climate-induced crop stress, creates ideal conditions for resistance evolution. For instance, in cotton-growing regions of Asia and Africa, pests such as Helicoverpa armigera and *Bemisia tabaci* (Hemiptera: Aleyrodidae) have developed widespread resistance to pyrethroids, neonicotinoids, and Bt toxins in response to both intense insecticide use and longer pest activity seasons (Houndété et al., 2010; Ahmad et al., 2019). In addition to resistance concerns, climate change is facilitating the expansion and outbreak potential of migratory pest species. The fall armyworm (*Spodoptera frugiperda*), originally endemic to the Americas, has rapidly spread across Africa, Asia, and Oceania in less than a decade enabled by increasingly suitable climatic conditions in these new territories (Liu et al., 2019; Szanyi et al., 2025). In newly colonized regions, this pest has caused significant economic damage, often overwhelming local monitoring and response capabilities.

Outbreak frequency is also rising among native pests due to warmer winters and extended growing seasons. For example, increased outbreak reports of *Locusta migratoria* (Orthoptera: Acrididae) and *Grapholita molesta* (Lepidoptera: Tortricidae) in parts of Central Asia and the Mediterranean are closely associated with temperature anomalies and reduced overwintering mortality (Yu et al, 2009; Tiring et al., 2023). These climate-driven changes not only destabilize pest control systems but also demand urgent rethinking of regional Integrated Pest Management (IPM) frameworks to incorporate adaptive, resistance-aware approaches.

4. Adaptation of Integrated Pest Management (IPM) Strategies

Integrated Pest Management (IPM) is widely regarded as an ecologically sound and economically viable approach to pest control. It seeks to balance the use of biological, cultural, physical, and chemical methods while minimizing harm to human health, non-target organisms, and the environment (Ünlü et al., 2012). However, the effectiveness of traditional IPM strategies is increasingly threatened by the dynamic and unpredictable nature of climate change. Shifting pest phenologies, expanded geographic ranges, and altered interactions between pests and their natural enemies necessitate a re-evaluation of current IPM frameworks (Thomson et al., 2010; Sharma, 2013). To remain effective under future climate conditions, IPM must become more flexible, anticipatory, and region-specific. One key area of adaptation involves improving pest surveillance systems. Traditional monitoring tools such as pheromone traps and degree-day models must now integrate climate forecasting data, remote sensing technologies, and real-time pest movement analytics to better predict outbreaks (Acharya and Thapa, 2015; Akman et al., 2017). Such predictive capabilities are especially critical for migratory and invasive pests like *S. frugiperda* or *T. absoluta*, whose rapid spread has outpaced conventional monitoring networks. Another vital adaptation is the selection and deployment of climate-resilient biological control agents. Strains of parasitoids and entomopathogenic fungi that maintain efficacy under heat and moisture stress are being identified through advanced screening and molecular tools (Kidanud, ,2020; Yadav et al., 2025).

Cultural practices such as crop rotation, intercropping, and planting dates must also be re-optimized in light of new pest-crop-climate interactions. For instance, in parts of southern Europe and Türkiye, adjustments in sowing time and crop sequencing have been shown to delay infestation by heat-accelerated pests such as *H. armigera* and *Eurygaster* spp. (Gürsoy et al., 2012; Huang et al., 2021; Randhawa et al. 2023). Perhaps most importantly, the success of adaptive IPM depends on capacity building and farmer engagement. Educational outreach, participatory pest scouting, and access to localized advisory systems will be essential to ensure timely responses and knowledge diffusion. Without integrating climate awareness into IPM extension services, the potential of even the best scientific innovations may go unrealized.

5. IPM Under Climate Stress

Integrated Pest Management (IPM) systems, long promoted as sustainable and ecologically sound frameworks for pest control, are increasingly being tested under the weight of climate change. Traditional components of IPM such as crop rotation, conservation of natural enemies, and the use of biological control agents are facing significant performance limitations in the context of shifting weather patterns, temperature extremes, and irregular precipitation (Skendžić et al., 2021). One of the most critical vulnerabilities lies in the climate sensitivity of beneficial arthropods, particularly pollinators, parasitoids, and predators. These organisms often have narrower ecological tolerances than their pest counterparts, making them highly susceptible to extreme climatic events such as heatwaves, droughts, and unseasonal cold snaps (Sharma, 2013; Sharma and Prabhakar, 2014; Kazenel et al., 2024). For instance, elevated temperatures can disrupt the synchrony between natural enemies and their hosts, undermining the stability of trophic interactions essential for biological control. In addition, extreme climate events can compromise soil health, reduce microbial biodiversity, and impair the effectiveness of soil-based biocontrol organisms such as entomopathogenic fungi and nematodes (Frankenstein, 2024; Weir, 2024). In turn, these disruptions weaken the ecological balance that IPM systems depend upon and force greater reliance on chemical inputs, thus eroding the sustainability of IPM.

To remain viable, modern IPM strategies must evolve into climate-resilient systems that integrate real-time monitoring, predictive modeling, and digital technologies. Advances in remote sensing, automated pest detection, and artificial intelligence (AI)-based forecasting tools are now enabling early detection and site-specific responses, which can significantly improve decision-making under uncertainty (Aziz et al., 2025; Sharada et al., 2025). Furthermore, participatory surveillance networks and climate-smart extension services can empower farmers to implement dynamic, data-driven IPM plans that respond effectively to localized risks. Overall, IPM must be reconceptualized as a dynamic and data-integrated platform rather than a fixed set of practices, with flexibility to adapt to rapidly evolving climatic and ecological contexts.

6. Policy and Research Priorities for Climate-Resilient Pest Management

Adapting pest management systems to the challenges posed by climate change demands a dual response scientific innovation and robust policy integration. While technological advances in pest forecasting, biological control, and climate-resilient cropping systems are critical, their impact will remain limited without supportive institutional frameworks and coordinated policy action. Governments, academic institutions, and international organizations must treat climate-resilient pest control as a central component of food security, biodiversity conservation, and climate adaptation strategies (Sekabira et al., 2023; Zhou et al., 2024). Policy-level interventions are essential to mainstream Integrated Pest Management (IPM) within national climate action plans. This includes developing and funding regional early warning systems, supporting farmer-led surveillance networks, and promoting policies that reduce the overuse of synthetic pesticides. Subsidies and incentives should prioritize low-risk pest control methods such as pheromone traps, biological agents, and precision agriculture technologies (Adamson et al., 2014; Lefebvre et al., 2015). Moreover, regulatory frameworks must adapt to facilitate the registration and deployment of novel biocontrol products that meet climate-resilient criteria.

Capacity building and education must also be a central focus of policy agendas. Extension services need targeted training to help farmers and pest managers interpret climate data and apply adaptive decision-making tools. This is particularly relevant for smallholder systems in vulnerable regions, where knowledge gaps and limited access to adaptive technologies amplify the risks of climate-driven pest outbreaks (Asare-Nuamah et al., 2019; Kumbhar et al., 2025). In this context, public-private partnerships can play a catalytic role in scaling up climate-smart pest solutions. From a research perspective, multidisciplinary studies are needed to better understand how climate variables interact with pest ecology, resistance development, and ecosystem services (Sharma, 2013; Skendžić, 2021). Emphasis should be placed on developing predictive models that integrate pest biology, climate projections, cropping systems, and socio-economic data. Investment in molecular biology and genomics can also enhance the development of pest-resistant crop varieties and stress-tolerant biocontrol agents. At the international level, organizations such as FAO, CGIAR, and EPPO are well-positioned to coordinate cross-border pest risk assessments, harmonize phytosanitary standards, and disseminate best practices. Regional cooperation will be particularly vital as migratory pests expand their ranges across political boundaries due to climate suitability.

Ultimately, climate-resilient pest management will require a systems-thinking approach, where policies, research, and practice are integrated across sectors and scales. Without this alignment, pest-related threats to food production and environmental integrity are likely to escalate in the coming decades.

Conclusion

Climate change is reshaping the landscape of pest management, challenging long-standing practices and necessitating urgent adaptation at multiple level from field implementation to policy design. The acceleration of pest life cycles, increased outbreak frequencies, pesticide resistance, and shifting geographic distributions are symptoms of a broader ecological disequilibrium driven by global warming. Integrated Pest Management (IPM), though historically effective, must be reengineered to withstand these pressures. This entails not only enhancing biological and chemical control strategies but also embedding digital tools, climate modeling, and ecological resilience into the very fabric of pest management systems. The incorporation of AI-driven forecasting, climate-resilient biocontrol agents, and real-time monitoring technologies offers promising avenues for adaptation. At the same time, a successful transformation requires supportive policy environments, increased investment in interdisciplinary research, and robust farmer education. Regional cooperation and international frameworks must also evolve to address the transboundary nature of climate-driven pest threats.

Ultimately, the path forward lies in proactive, adaptive, and evidence-based pest management systems that are flexible enough to respond to climatic volatility, yet robust enough to protect crop productivity, ecosystem integrity, and food security in a rapidly changing world.

REFERENCES

Acharya, M., & Thapa, R. (2015). Remote sensing and its application in agricultural pest management. *Journal of Agriculture and Environment*, 16, 43–61.

Adamson, D., Zalucki, M., & Furlong, M. (2014). Pesticides and Integrated Pest Management: Practice, Practicality and Policy in Australia. In R. Peshin & D. Pimentel (Eds.), Integrated Pest Management: Pesticide Problems, Vol. 3 (pp. 387–411). Dordrecht: Springer. https://doi.org/10.1007/978-94-007-7802-3_16

Ahmad, M., Rasool, B., Ahmad, M., & Russell, D. (2019). Resistance and synergism of novel insecticides in field populations of cotton bollworm Helicoverpa armigera in Pakistan. *Journal of Economic Entomology*, 112(2), 859–871. https://doi.org/10.1093/jee/toy409

Akman, O., Comar, T. D., & Hrozencik, D. (2017). Model selection for integrated pest management with stochasticity. *Journal of Theoretical Biology*, 442, 110–122

Aljaryian, R., Kumar, L., & Taylor, S. (2016). Modelling the current and potential future distributions of the sunn pest *Eurygaster integriceps* (Hemiptera: Scutelleridae) using CLIMEX. *Pest Management Science*, 72 10, 1989-2000. https://doi.org/10.1002/ps.4247.

Aqueel, M. A., & Leather, S. (2013). Virulence of *Verticillium lecanii* (Z.) against cereal aphids; does timing of infection affect the performance of parasitoids and predators? *Pest Management Science*, 69(4), 493–498. https://doi.org/10.1002/ps.3398.

Asare-Nuamah, P., Botchway, E., & Onumah, J. A. (2019). Helping the helpless: Contribution of rural extension services to smallholder farmers' climate change adaptive capacity and adaptation in rural Ghana. *International Journal of Rural Management*, 15(2), 244–268. https://doi.org/10.1177/0973005219876211

Aziz, D., Rafiq, S., Saini, P., Ahad, I., Gonal, B., Rehman, S. A., Rashid, S., Saini, P., Rohela, G. K., Aalum, K., Singh, G., Gnanesh, B. N., & Iliya, M. N. (2025). Remote sensing and artificial intelligence: Revolutionizing pest management in agriculture. *Frontiers in Sustainable Food Systems*. Article 1551460. https://doi.org/10.3389/fsufs.2025.1551460

Bajwa, A. A., Farooq, M., Al-Sadi, A. M., Nawaz, A., Jabran, K., & Siddique, K. H. (2020). Impact of climate change on biology and management of wheat pests. *Crop Protection*, 137, 105304.

Bayram, Y., Duman, M., Buyuk, M., & Mutlu, C. (2017). Efficiency of pheromone water traps and life cycle of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Diyarbakir province, Turkey. Fresenius Environmental Bulletin, 26(12A), 8146-8153.

Cammell, M., & Knight, J. (1992). Effects of climatic change on the population dynamics of crop pests. *Advances in Ecological Research*, 22, 117-162. https://doi.org/10.1016/S0065-2504(08)60135-X.

Chidawanyika, F., Mudavanhu, P., & Nyamukondiwa, C. (2012). Biologically based methods for pest management in agriculture under changing climates: challenges and future directions. *Insects*, 3(4), 1171-1189.

Deka, S., Byjesh, K., Kumar, U., & Choudhary, R. (2010). Climate change and impacts on crop pests-a critique. *ISPRS archives*, 48(8), W3.

Delcour, I., Spanoghe, P., & Uyttendaele, M. (2015). Literature review: Impact of climate change on pesticide use. *Food Research International*, 68, 7-15.

Desneux, N., Han, P., Mansour, R., Arnó, J., Brévault, T., Campos, M. R., ... & Biondi, A. (2022). Integrated pest management of Tuta absoluta: practical implementations across different world regions. *Journal of Pest Science*, 1-23.

Doberski, J. (1981). Comparative laboratory studies on three fungal pathogens of the elm bark beetle *Scolytus scolytus*: Effect of temperature and humidity on infection by *Beauveria bassiana*, *Metarhizium anisopliae*, and *Paecilomyces farinosus*. *Journal of Invertebrate Pathology*, 37, 195–200. https://doi.org/10.1016/0022-2011(81)90075-6

Dubois, T., Tonnang, H., Sokame, B., & Abdel-Rahman, E. (2022). Measuring and modelling crop yield losses due to invasive insect pests under climate change. *Current Opinion In Insect Science*, 100873 . https://doi.org/10.1016/j.cois.2022.100873.

Duman, M., & Sertkaya, E. (2015). Adult parasitoid species and parasitization rates of Sunn pest *Eurygaster integriceps* Puton (Hemiptera: Scutelleridae) in Karacadağ overwintering region and Diyarbakır cereal fields. *Türkiye Entomoloji Bülteni*, 5(2), 85-94.

El-Mukhlef, A. A., Kharouf, S. A., & Al-Khalaf, A. (2023). Effect of temperature on efficacy of the entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* against the Sunn pest, *Eurygaster integriceps*. Arab Journal for Plant Protection, 41(2), 134–139. https://doi.org/10.22268/ajpp-41.2.134139

Early, R., González-Moreno, P., Murphy, S. T., & Day, R. K. (2018). Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm. *bioRxiv*. https://doi.org/10.1101/391847.

Frankenstein, D., Luu, M. S., Luna-Ayala, J., Willett, D. S., & Filgueiras, C. S. (2024). Soil moisture conditions alter behavior of entomopathogenic nematodes. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.13326

Goergen, G., Kumar, P. L., Sankung, S. B., Togola, A., & Tamò, M. (2016). First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PLoS ONE*, 11(10), e0165632. https://doi.org/10.1371/journal.pone.0165632

Gürsoy, S., Mutlu, Ç., Urğun, M., Kolay, B., Karaca, V., & Duman, M. (2012). The effect of ridge planting and earliness of durum wheat varieties on sunn pest (Eurygaster spp.) damage and grain yield. *Crop Protection*, 38, 103–107. https://doi.org/10.1016/J.CROPRO.2012.03.004

Hill, J., & Braschler, B. (2007). Role of larval host plants in the climate-driven range expansion of the butterfly *Polygonia c-album*.. The *Journal of Animal Ecology*, 76 3, 415-23 . https://doi.org/10.1111/J.1365-2656.2007.01217.X.

Huang, J. (2021). Effects of climate change on different geographical populations of the cotton bollworm *Helicoverpa armigera* (Lepidoptera, Noctuidae). *Ecology and Evolution*, 11, 18357–18368. https://doi.org/10.1002/ece3.8426 (Huang, 2021)

Houndété, T., Ketoh, G., Héma, O., Brévault, T., Glitho, I., & Martin, T. (2010). Insecticide resistance in field populations of *Bemisia tabaci* (Hemiptera: Aleyrodidae) in West Africa. *Pest Management Science*, 66(11), 1181–1185. https://doi.org/10.1002/ps.2008

Islamoğlu, M. (2022). Effect of Some Abiotic Factors on Migration of Sunn Pest (*Eurygaster integriceps* Put.) (Hemiptera: Scutelleridae) from

Aestivation Sites to Overwintering Sites. *Pakistan Journal of Zoology*,55(1);379. https://doi.org/10.17582/journal.pjz/20181212191237.

Izzo, V. M., Hawthorne, D., & Chen, Y. H. (2014). Geographic variation in winter hardiness of a common agricultural pest, *Leptinotarsa decemlineata*, the Colorado potato beetle. *Evolutionary Ecology*, 28, 505–520. https://doi.org/10.1007/s10682-013-9681-8

Jensen, R. E., Cabral, C., Enkegaard, A., & Steenberg, T. (2020). Influence of the plant-interacting entomopathogenic fungus *Beauveria bassiana* on parasitoid host choice-behavior, development, and plant defense pathways. *PLoS ONE*, 15(10), e0238943. https://doi.org/10.1371/journal.pone.0238943

Kazenel, M. R., Wright, K. W., Griswold, T., Whitney, K. D., & Rudgers, J. A. (2024). Heat and desiccation tolerances predict bee abundance under climate change. *Nature*. https://doi.org/10.1038/s41586-024-07241-2

Kidanud, S. (2020).Research and application of entomopathogenic fungi as pest management option: A review. *Journal of Environment and Earth Science*, 10(3), 31–39 https://doi.org/10.7176/jees/10-3-03

Kistner-Thomas, E., Adhikari, S., Neven, L., & Eigenbrode, S. (2022). Introduction to the Collection: Climate Change, Insect Pests, and Beneficial Arthropods in Production Systems. *Journal of Economic Entomology,* 115, 1315 - 1319. https://doi.org/10.1093/jee/toac107.

Kriticos, D., Szyniszewska, A., Bradshaw, C., Li, C., Verykouki, E., Yonow, T., & Duffy, C. (2024). Modelling tools for including climate change in pest risk assessments. *EPPO Bulletin*, 54, 38-51.

Kumbhar, M. I., Khan, M. H. N., Khooharo, A., Mari, F. M., Magsi, H., Mirani, Z., Riaz, A., Masood, A., Naseem, A., & Shah, S. T. (2025). Building extension agents' capacity for sustainable development to promote climate resilience in Pakistani agriculture: A case study of South Punjab. *Social Science Review Archives*, 3 (1); 1468-1483.

Lefebvre, M., Langrell, S., & Gomez-y-Paloma, S. (2015). Incentives and policies for integrated pest management in Europe: A review. Agronomy for Sustainable Development, 35, 27–45. https://doi.org/10.1007/s13593-014-0237-2

Liu, T., Wang, J., Hu, X., & Feng, J. (2019). Land-use change drives present and future distributions of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae). *Science of the Total Environment*, 706, 135872. https://doi.org/10.1016/j.scitotenv.2019.135872

Lorenz, F., & Jeyapragasan, G. (2020). The impact of climate change on tri-trophic interactions and crop production. *The iScientist*, 5(1), 4-12.

Martin, P., & Johnson, S. N. (2011). Evidence that elevated CO2 reduces resistance to the European large raspberry aphid in some raspberry cultivars. *Journal of Applied Entomology*, 135(3), 237-240.

Matzrafi, M. (2019). Climate change exacerbates pest damage through reduced pesticide efficacy. *Pest Management Science*, 75(1), 9-13.

Mishra, A., Chaturvedi, G., Mishra, S., S, A., Naveen, G., Khokhar, C., K, T., & Jan, U. (2025). Predicting Insect Pest Outbreaks Using Climate Models and Remote Sensing. *Uttar Pradesh Journal Of Zoology*. https://doi.org/10.56557/upjoz/2025/v46i54827.

Musolin, D., & Saulich, A. (2012). Responses of insects to the current climate changes: from physiology and behavior to range shifts. *Entomological Review*, 92, 715–740. https://doi.org/10.1134/S0013873812070019

Mutlu, Ç., & Sertkaya, E. (2015). Studies on Bio-ecology of Zyginidia sohrab Zachvatkin (Hemiptera: Cicadellidae), harmful leafhopper on maize plant in Diyarbakir Province. *Plant Protection Bulletin*, 55(1): 15-30.

Mutlu, Ç., & Sertkaya, E. (2016). Biology of the leafhopper, Zyginidia sohrab Zachvatkin, on corn under laboratory conditions. *Journal of Entomology and Zoology Studies*, 4(4), 401-406.

Neven, L. (2000). Physiological responses of insects to heat. *Postharvest Biology and Technology*, 21, 103-111. https://doi.org/10.1016/S0925-5214(00)00169-1.

Nitta, A., Natarajan, V., Reddy, A. J., & Rakesh, T. (2024). Impact of climate change on pest biology, behaviour and their distributions. International *Journal of Environment and Climate Change*, 14(4), 46-56.

Oztemiz, S., Karacaoğlu, M., & Yarpuzlu, F. (2009). Parasitization rate of *Helicoverpa armigera* Hübner eggs after field releases of *Trichogramma evanescens* in cotton in Çukurova Region of Turkey. *Journal of the Kansas Entomological Society*, 82(2), 183–193. https://doi.org/10.2317/JKES607.15.1 (Oztemiz et al., 2009)

Pérez-Lucas, G., Navarro, G., & Navarro, S. (2024). Adapting agriculture and pesticide use in Mediterranean regions under climate change scenarios: A comprehensive review. *European Journal of Agronomy*. https://doi.org/10.1016/j.eja.2024.127337

Pomari-Fernandes, A., de Freitas Bueno, A., & Sosa-Gómez, D. R. (2015). Helicoverpa armigera: current status and future perspectives in Brazil. *Current Agricultural Science and Technology*, 21(1).

Randhawa, H., Kaur, C., Singh, G., & Taggar, G. K. (2023). Impact of chickpea varieties and sowing dates on pod borer Helicoverpa armigera (Hubner). *Legume Research - An International Journal*, 4895; 1-6. https://doi.org/10.18805/lr-4895

Rao, M. S., Rao, G. R., & Venkateswarlu, B. (2010). Impact of climate change on insect pests. National Symposium on Climate Change and Rainfed Agriculture, February, 18-20, 2010, CRIDA, Hyderabad, India, pp 43-53.

Reddy, A., Natarajan, V., Rakesh, T., & Nitta, A. (2024). Impact of Climate Change on Pest Biology, Behaviour and Their Distributions. *International Journal of Environment and Climate Change*. https://doi.org/10.9734/ijecc/2024/v14i44094.

Rozsypal, J. (2023). Estimating the Potential of Insects from Warmer Regions to Overwinter in Colder Regions under a Warming Winter Scenario Using Simulation Experiments: A Case Study in *Sesamia nonagrioides*. *Insects*, 14. https://doi.org/10.3390/insects14120957.

Sampaio, F., Krechemer, F., & Marchioro, C. A. (2021). The hotter the better? Climate change and voltinism of *Spodoptera eridania* estimated with different methods. *Journal of Thermal Biology*, 98, Article 102946. https://doi.org/10.1016/j.jtherbio.2021.102946

Sekabira, H., Tepa-Yotto, G., Kaweesa, Y., Simbeko, G., Tamò, M., Agboton, C., Tahidu, O., & Abdoulaye, T. (2023). Impact of CS-IPM on key social welfare aspects of smallholder farmers' livelihoods. *Climate*, 11(5), Article 97. https://doi.org/10.3390/cli11050097

Sharada, K., Choudhary, S. L., Harikrishna, T., Dixit, R. S., Suman, S. K., Ayyappa Chakravarthi, M., & Bhagyalakshmi, L. (2025). GeoAgriGuard: AI-Driven Pest and Disease Management with Remote

Sensing for Global Food Security. *Remote Sensing in Earth Systems Sciences*, 1-14.

Sharma, H. C. (2013). Biological Consequences of Climate Change on Arthropod Biodiversity and Pest Management. In: International Conference on Insect Science, 14-17 February 2013, Bangalore, India.

Sharma, H. C., & Prabhakar, C. S. (2014). Impact of climate change on pest management and food security. In Integrated pest management (pp. 23-36). Academic Press.

Yu, G., Shen, H., & Liu, J. (2009). Impacts of climate change on historical locust outbreaks in China. Journal of Geophysical Research: *Atmospheres*, 114(D18).

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., & Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects*, 12(5), 440.

Subedi, B., Poudel, A., & Aryal, S. (2023). The impact of climate change on insect pest biology and ecology: Implications for pest management strategies, crop production, and food security. *Journal of Agriculture and Food Research*, 14, 100733.

Szanyi, S., Barta, M., Velchev, D., Beshkov, S., Mumford, S., Todorov, I., Nagy, A., Varga, Z., Tóth, M., & Toshova, T. (2025). First report of a migratory pest, the fall armyworm, *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae) from Bulgaria. *Insects*. https://doi.org/10.3390/insects16020134

Thayer, A. W., Vargas, A., Castellanos, A. A., Lafon, C. W., McCarl, B. A., Roelke, D. L., & Lacher, T. E. (2020). Integrating agriculture and ecosystems to find suitable adaptations to climate change. *Climate*, 8(10), 1-19.

Thomson, L., Macfadyen, S., & Hoffmann, A. (2010). Predicting the effects of climate change on natural enemies of agricultural pests. *Biological Control*, 52(3), 296–306. https://doi.org/10.1016/J.BIOCONTROL.2009.01.022

Tiring, G., Ada, M., Ada, M., Dona, R., & Satar, S. (2023). The effect of climate on the population of *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) in Mersin, Türkiye. Erwerbs-Obstbau, 65, 2289–2297. https://doi.org/10.1007/s10341-023-00943-3

Tiwari, A. K. (2022). Impacts of climate change on insect pests and crop protection strategies. *Chemical Engineering*. https://doi.org/10.51470/che.2022.03.02.01

Ünlü, L., Ögür, E., & Çelik, Y. (2012). The importance of integrated pest management for sustainable agriculture. *Journal of Selcuk University Natural and Applied Science*, 1, 54–59.

Vázquez, L. L. (2019). Climate change and biological control of pests in agriculture. Natural Enemies of Insect Pests in Neotropical Agroecosystems: *Biological Control and Functional Biodiversity*, 63-69.

Weir, J. C. (2024). Trophic generalism in the winter moth: a model species for phenological mismatch. *Oecologia*, 206, 225–239. https://doi.org/10.1007/s00442-024-05629-5

Yadav, S., Thodusu, M., Shankar, U., Nautiyal, A., Khajuria, M., Sarangi, S., Maheshwari, S., & Pandey, K. (2025). Entomopathogenic fungi: Dual role in insect control and plant disease management. *Uttar Pradesh Journal of Zoology*, 46(2), 172-184. https://doi.org/10.56557/upjoz/2025/v46i24772

Zhou, W., Arcot, Y., Medina, R. F., Bernal, J., Cisneros-Zevallos, L., & Akbulut, M. E. S. (2024). Integrated pest management: An update on the sustainability approach to crop protection. *ACS Omega*, 9, 41130–41147. https://doi.org/10.1021/acsomega.4c06628

Ziska, L., & McConnell, L. (2016). Climate Change, Carbon Dioxide, and Pest Biology: Monitor, Mitigate, Manage. *Journal of Agricultural and Food Chemistry*, 64 1, 6-12 . https://doi.org/10.1021/jf506101h.

Živković, I., Lešić, V., Skendžić, S., Zovko, M., & Lemić, D. (2021). The Impact of Climate Change on Agricultural Insect Pests. *Insects*, 12. https://doi.org/10.3390/insects12050440.

CHAPTER 6

EFFECTS OF CLIMATE CHANGE ON HARMFUL AND BENEFICIAL INSECT SPECIES IN AGRICULTURAL ECOSYSTEMS

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1. INTRODUCTION

Climate change, as one of the most important global environmental problems of the 21st century, has profound effects on ecosystem dynamics. Biotic factors are among the most important factors limiting the quantity and quality of agricultural products (Avan, 2022a). Insects, on the other hand, have dual effects with both beneficial and harmful roles in agricultural ecosystems. Insects are also critical organisms that provide a wide range of ecosystem services in agricultural ecosystems. While pollinator species increase productivity in the production of many fruit and vegetable species, some species stand out as pests that cause significant losses in agricultural products (Altieri, 1999; Tscharntke et al., 2012; Avan, 2022b). At the same time, natural enemy insect species play an important role in biological control and keep harmful insect populations under control. It is reported that climate change causes significant changes in the life cycle, distribution area, physiological tolerance limits and feeding behavior of these organisms, thus creating new risks for the sustainability of agricultural production (Lehmann et al., 2020; Avan and Kotan 2021; FAO-IPPC, 2024).

Climate change brings about both positive and negative effects by changing the life cycles, distribution areas, population densities and interspecific relationships of insects. This situation brings about problems such as the expansion of the distribution areas of harmful insects, the increase of invasive species, phenological incompatibilities and the decrease in the effectiveness of biological control agents (Parmesan, 2006; Tylianakis et al., 2008).

Increasing greenhouse gas concentrations in the atmosphere cause average temperatures to rise, precipitation patterns to change, and extreme climate events to increase in frequency. These effects significantly affect the structure and functioning of natural and agricultural ecosystems (IPCC, 2021). Agricultural production systems are highly sensitive to the direct and indirect effects of climate change; changes in the activities of insect communities, especially plant pests and pollinators, have been reported to pose significant risks to the sustainability of these systems (Deutsch et al., 2018).

Climate change causes some pest species to expand their geographical distribution areas, produce more offspring during the year, and adapt to new habitats. This situation has been reported to disrupt the phenological harmony between natural enemies and pest species, reduce the effectiveness of biological control systems, and increase pest pressure (Frontiers in Ecology and Evolution, 2019). Similarly, the shrinkage of pollinator insect habitats, disruption of their timing with plants, and decreases in their populations have been found to pose significant threats to both ecosystem activities and agricultural productivity (Potts et al., 2010).

However, climate change causes the rapid spread of invasive insect species through global trade and climate change, disrupting local ecosystem balances and increasing economic losses (Liebhold et al., 2011). In addition, climate change has been reported to reduce pollination efficiency by causing deviations in the timing of plant-insect interactions and weakening natural enemy-pest relationships (Memmott et al., 2007). Therefore, it is considered vital to comprehensively understand the effects of climate change on insect communities in agricultural ecosystems and to develop integrated management strategies accordingly.

In this study, the effects of climate change on insects in agricultural ecosystems were examined in light of scientific literature. In addition, the effects on harmful insect population activities, the increase in invasive species, phenological incompatibilities and biodiversity were focused on. In this context, this study aims to better understand the effects of ecological processes related to climate change on agricultural production and to develop adaptation policies as a result.

2. Activities of Insects in the Ecosystem

Insects are the most diverse and widespread organisms in the world. Insects undertake a wide variety of ecological tasks in both natural and agricultural ecosystems. The activities carried out by insects include vital activities such as pollination, pest control, decomposition, maintenance of the nutrient cycle, soil processing and sustainability of the food chain (Losey & Vaughan, 2006). The protection and support of these activities in agricultural ecosystems is very important for sustainable food production. However, climate change directly and indirectly affects the capacity of insects to perform these activities. These activities of insects in the ecosystem are briefly examined below.

Pollination

Pollination is one of the main factors that ensure the reproduction of flowering plants in particular. Approximately 75% of agricultural products in the world depend on pollination provided by insects (Klein et al., 2007). Pollination is provided by bees (Apidae), butterflies (Lepidoptera), flies (Diptera) and some insect families. Bumblebees and bumblebees, especially honeybees (Apis mellifera), directly contribute to the increase in yield in many agricultural products.

The increase in temperature that occurs as a natural result of climate change is decreasing the duration of the flowering period in plants. This situation causes bees and other pollinator insects to have a hard time finding food. In addition, the temperature changes that occur with global warming cause producers to make more effort to search for flowering plants for food. This situation both increases production costs and causes labor loss (Topal et al., 2016). As a result of food shortages, it causes significant decreases in the populations of pollinator insects or their mass extinction. Another result of global warming is that floods caused by excessive rainfall cause bee colony losses, while serious decreases in water resources due to drought cause more suitable environments for the natural enemies of bees (Klein et al., 2007; Tirado et al., 2013).

For example, products with high economic value such as almonds, apples, strawberries, melons and cocoa depend on pollinator insect pollination. A study has shown that when pollinators decrease in strawberry plants, both the number and size of their fruits decrease by more than 30% (Garibaldi et al., 2013).

It has also been determined that climate change disrupts the distribution areas of pollinator insects and their compatibility with plants. For example, it has been determined that as a result of increasing early spring temperatures, the activity period of bees does not coincide with the flowering periods of plants, reducing the pollination rate (Bartomeus et al., 2011).

2.2. Natural Enemies

Natural enemies are beneficial organisms that provide natural control of pests in agriculture. They play a key role in integrated pest management (IPM) strategies, limiting the use of chemicals. Natural enemies are predatory or parasitoid insect species, and they suppress the populations of many pest species. For example, members of the Coccinellidae family provide natural control by feeding on pests such as aphids (Aphididae). Another example is Trissolcus spp., which parasitizes the eggs of the sunn pest and suppresses their populations (İslamoglu, 2012).

Climate change can shorten the period during which natural enemies are effective or weaken their populations by exceeding their thermal tolerance limits. For example, temperatures above 35 °C have been reported to negatively affect the development of Trichogramma species and reduce parasitism rates by up to 40% (Roitberg & Mangel, 2010). This suggests that the use of chemical pesticides may increase and cause a loss of natural balance.

2.3. Decomposition

Decomposer insects (e.g., some Coleoptera and Diptera species) play a key role in the breakdown of organic waste and its incorporation into the soil. This process allows the recovery of nutrients that are essential for soil health and fertility. In particular, the release of nitrogen, phosphorus and other minerals is accelerated by the decomposition of straw and animal waste.

For example, species belonging to the Scarabaeidae family (dung beetles) bury animal manure, providing both aeration of plant roots and supporting the nitrogen cycle. However, drought and increased soil temperature can restrict the activity of these species and slow down decomposition processes (Nichols et al., 2008).

2.4. Soil Processing and Aeration

Some insect species, especially ants (Formicidae) and termites (Isoptera), are effective in physically regulating soil structure. These species increase soil water permeability, provide aeration and support root development through their tunneling and soil moving behaviors. For example, tunnels created by termites in tropical regions facilitate the passage of water underground, reducing the risk of erosion (Jouquet et al., 2011).

However, rising soil temperatures or drought conditions due to climate change may cause a decrease in the colonies of such insects and a slowdown in their activities. This may negatively affect soil fertility.

3. The Effect of Climate Change on Insects

3.1. The Effect of Temperature Increase on Insects

The temperature increase in the ecosystem due to global warming and climate change will cause insects' development periods to be much shorter than normal and their reproductive capabilities to increase. While it will destroy some of the existing insect species on earth, it will also affect the habitats of a significant portion of them and cause an increase in migration behavior in populations. This will cause economic losses in agricultural products due to the increase in the number of pests due to the emergence of insect species that have not been seen in the region before in agricultural lands in addition to existing pests. In addition to all these effects, it is predicted that significant negative effects will occur in the habitats of bees, which are of great importance especially for agricultural production and biodiversity. The possible effects of the effects of global warming and climate change on the ecosystem on insects, which are the main elements of biodiversity and agricultural production, have been evaluated.

a- The effect of temperature increase on insect biology

It is expected that increasing temperatures due to climate change will accelerate insect biological processes and extend their activity periods. Since insects are ectotherms that are dependent on external environmental temperature, their developmental speed is directly related to temperature (Harrington et al., 2001). Increasing temperature causes the developmental period to shorten, especially in spring and summer, and accordingly, species to become adults earlier. However, in order to fully utilize this advantage, the developmental process in the plants that insects feed on must also proceed in a similar manner. Otherwise, phenological incompatibilities may occur and this may negatively affect the life cycle of insects (Parmesan et al., 1999).

Long-term observations in Europe and North America have revealed that many insect species experience shifts in their first emergence dates in parallel with the increase in average annual temperatures. For example, a modeling study conducted in the UK predicted that a 2°C increase in average temperature could shorten the developmental period of some species by approximately 2–3 weeks (Cannon, 1998). It was observed that species such as Neophilaenus lineatus (Hemiptera: Cercopidae) completed their development earlier and expanded their distribution areas with this temperature increase. Similarly, it is reported that a 3°C increase in average temperature could bring the activation time of Delia radicum (Diptera: Anthomyiidae), one of the important agricultural pests, forward by approximately 30 days (Cannon, 1998). This means an increased risk of early plant damage. Global studies have shown that many insect species, especially members of the Lepidoptera order, show both a shortening of their developmental period and an increase in the annual number of generations due to temperature increases (Menéndez, 2007). For example, species such as Pieris rapae (Lepidoptera: Pieridae) have the potential to significantly increase the level of pests in agricultural areas due to their earlier flight period, longer active periods, and higher generation production (FAO, 2008). In addition, the earlier start of spring brings forward the egg-laying and larval development periods of insects, which allows for an increase in the number of successive generations throughout the season. Some environmental factors, including climate change, have been reported to cause an increase in the number of diseases and pests in plant production (Avan, 2021). However, the extension of the activity period with increasing temperature may affect the phenology of not only pests but also their natural enemies. However, the differences in the response speeds of these two groups to temperature may cause incompatibilities in biological control interactions. This situation has the potential to increase the population pressure of pests and disrupt the balance in ecosystems (Parmesan & Yohe, 2003)

b- Effect of temperature increase on insect reproductive capacity

Temperature is one of the main determinants of insect physiology, behavior and life cycle. It has a direct effect on reproductive capacity in particular, and temperature increases generally result in increased offspring, increased egg-laying capacity and shorter generation times (Bale et al., 2002). Rising average temperatures with global warming cause females to produce more eggs in many insect species, which accelerates population growth and increases pest potential (Ward & Masters, 2007).

The earlier start of spring and the extension of the growing season as a result of climate change allow species with multiple generations (multivoltine) to increase the annual number of offspring. For example, species with high agricultural importance such as Helicoverpa armigera (Lepidoptera: Noctuidae) are sensitive to temperature increases and show expansion in both offspring and distribution area during longer growing seasons (Zhou et al., 2010). This process not only increases the population of harmful insects, but also increases pest pressure in plant production and the need for more chemical interventions in pest control.

In insects, the metabolic activity that increases with temperature shortens the development period and increases consumption rates. Yamamura and Kiritani (1998) suggested that a 2°C temperature increase can create 1 to 5 additional generations per year in some insect species. This situation is especially evident in species living in subtropical and tropical regions, and with the spread of species towards northern latitudes, it can pose new threats to agricultural systems in these regions. In addition, temperature increases can positively affect not only the number of generations, but also the embryonic development period of eggs and hatching rates (Hance et al., 2007).

However, it cannot be said that temperature increases always have positive effects. Extreme temperatures, especially when they occur above the optimum temperature range, can have negative consequences such as decreased reproductive performance, embryo mortality and decreased egg productivity. For example, in storage pests such as Sitophilus oryzae (Coleoptera: Curculionidae), temperatures above 35°C have been reported to reduce egg-laying rates and negatively affect larval development (Fields, 1992).

c- The effect of temperature increase on the spread of insects

The geographic distribution of insects is largely limited by climatic factors. It is known that most species live within a certain latitude and altitude range, and that these limits are determined by environmental variables such as temperature and humidity (Stewart et al., 2007). As ectotherms, insects obtain their body heat from the environment and are therefore very sensitive to temperature changes. The increase in temperatures together with global climate change causes many species to migrate both towards the poles (latitudinally) and towards higher altitudes (vertically) (Harrington et al., 2001).

According to the models, a 2 °C increase in average temperature corresponds to a latitudinal change of approximately 600 km or an elevation change of 330 m in the distribution of insects. This means a shift of approximately 6 km latitudinally and 3.3 m elevation every year. However, these migration movements are not limited to insects only; because many species depend on certain host plants for their survival. The fact that plants cannot spread as quickly as insects causes the potential distribution areas of some species to be limited due to host restrictions (Samways, 2005). Therefore, while temperature increases facilitate the spread of some species, they may pose a survival threat to others.

As an example of the distribution changes observed in insects due to climate change; the butterfly species Euphydryas editha (Lepidoptera: Nymphalidae) experienced population losses at low latitudes and altitudes in the 1990s despite the presence of habitat and host plants. However, the species has moved to an average latitude of 92 km and altitude of 124 m, forming new populations in the north and higher altitudes. This distribution clearly reveals the effect of climate (Stewart et al., 2007). Similarly, 63% of 35 non-migratory butterfly species in Europe migrated northwards during the century due to a temperature increase of only 0.8 °C (Ward & Masters, 2007).

The effects of increasing temperatures are not limited to distribution. For example, Nezara viridula (Heteroptera: Pentatomidae), a species that could not previously live in cool regions such as England, has established permanent populations in London due to global warming. Experts consider the establishment of this species in England as a concrete indicator of global warming (Bale et al., 2002).

In addition, it is known that increasing temperatures affect the flight behavior and migration timing of insects. While exceeding the temperature threshold earlier causes some species to migrate earlier, mortality rates in insects may increase if the optimum temperature range is exceeded. For example, increased mobility of species such as aphids may also accelerate the spread of plant viruses they carry (Petzoldt & Seaman, 2007).

Climate change affects not only the distribution of insects but also the plants they feed on. Rising temperatures allow some plant species to move to more northern latitudes or higher altitudes, which in turn causes insects associated with those plants to spread to new areas (Reilly, 1996). However, the speed and success of this process varies for each species. As a result, an increase in insect diversity is expected at higher latitudes and altitudes, and it has been reported that this situation may increase the pressure of pest species on agricultural systems (FAO, 2008).

d- Effect of temperature increase on insect populations

Climate, especially temperature, has a direct and strong effect on the development, reproduction, geographical distribution, survival rates and population sizes of insects. Increasing temperatures due to global climate change affect insect populations in many ways. Although it is thought that extreme temperatures may have negative effects on some insect species, the general opinion is that milder winters and extended warm seasons are advantageous for many species. This means a longer and more productive activity period, especially for species living in temperate climate zones (Petzoldt and Seaman, 2007).

Warmer winter months reduce winter mortality in insects and increase survival rates. This effect is especially pronounced in species that can remain active throughout the winter without entering diapause. For example, population losses of species such as Myzus persicae (Homoptera: Aphididae) decrease significantly in warm winters, resulting in higher population densities and earlier migrations in spring (Bale et al., 2002). Thanks to increasing temperatures, not only the populations of these species but also their geographical distribution areas expand, making it possible for them to move towards northern and high altitude regions. On the other hand, it is also known that temperature increases do not have positive effects on all species. It is stated that extreme heat stress can exceed the physiological limits of some species, increase mortality rates or decrease reproductive success. For example, farmers abandoning certain host plants due to climate change can cause the extinction of pest species dependent on that plant (Petzoldt and Seaman, 2007). In addition, it has been observed that some species cannot adapt and become completely extinct as a result of extreme temperature increases. Thomas et al. (2004) emphasized that increases in temperature can cause species to lose their habitats, leading to local or global extinctions. The effects of climate change are not limited to average temperature increases; the frequency and severity of extreme climate events also play a decisive role on insect populations. For example, long periods of drought or unseasonal storms disrupt ecosystem balance and can negatively affect the temporal compatibility of insects with their host plants. In a study by Stewart et al. (2007), it was shown that extreme irregularities in rainfall disrupt the phenological match between the butterfly species Euphydryas editha (Lepidoptera; Nymphalidae) and its host plant, leading to population collapse. Similarly, it was reported that cold and humid weather conditions throughout the winter caused high mortality rates in individuals of the butterfly Danaus plexippus (Lepidoptera; Danainae).

e. The effect of temperature increase on insect wintering

Insects enter a developmental pause phase called diapause in order to adapt to seasonal changes in environmental conditions. Diapause is a process that is genetically controlled and triggered by environmental signals; it is a period in which metabolic activities slow down and development temporarily stops (Denlinger, 2002). However, the temperature increases experienced in recent years due to the effect of global climate change have led to significant changes in the wintering behavior of many species.

For example, Spodoptera littoralis (Lepidoptera: Noctuidae), one of the harmful species distributed in the Mediterranean climate, usually spends the winter in the pupa stage. However, due to increasing winter temperatures, the pupae of this species continue to develop earlier and can reach the butterfly form in mid-winter, which increases the population dynamics and pest potential of the species (Kivan & Kilic, 2002). Similarly, in a study conducted in Japan, it was observed that the diapause period of Drosophila suzukii (Diptera: Drosophilidae) individuals shortened with milder winters, while some individuals skipped diapause altogether and remained active throughout the year (Toxopeus et al., 2021). This situation makes pest control even more difficult, especially for fruit producers. Temperature increases cause negative effects not only on pest species but also on beneficial insect species. For example, parasitoid wasps such as Aphidius ervi (Hymenoptera: Braconidae), one of the biological control agents widely used in Europe, remain in diapause throughout the winter, while temperature increases cause these species to emerge from diapause early and die before finding a suitable host (Tougeron et al., 2017). This directly reduces the success of biological control and reduces the effectiveness of integrated pest management systems. Similarly, beneficial predators such as Coccinella septempunctata (Coleoptera: Coccinellidae) may have difficulty surviving until spring due to the mild winters by depleting their energy reserves in mid-winter.

On the other hand, this increase in temperature causes diapause to completely disappear for some species. For example, Bemisia tabaci (Hemiptera: Aleyrodidae) normally loses its population in the winter months in cool regions, but in regions such as the Mediterranean and Aegean, it can remain active throughout the year thanks to the increasing temperatures in winter (Öztemiz et al., 2008). This leads to increased pesticide use and increased environmental burden.

The effects of temperature on the wintering behavior of insects vary from species to species, but can lead to significant imbalances at the ecosystem level. Shifts in the diapause period necessitate the proliferation of pests, the suppression of beneficial species, the disruption of interactions between species, and the reconsideration of integrated control strategies.

3.2. Effects of increased CO_2 concentration on insects

Increased carbon dioxide (CO_2) levels in the atmosphere affect secondary metabolite production by changing chemical compositions in plants, and this can change the host-finding behavior of pests. These changes can increase the reproductive success of some pest species (Özgen & Karsavuran, 2009). For example, increased CO_2 in some aphid species reduced behavioral responses to alarm pheromones, making them more vulnerable to natural enemies (Awmack et al., 1997). Similarly, it was determined that the hunting efficiency of Cyrtorhinus lividipennis (Hemiptera: Miridae), a predator of Nilaparvata lugens (Hemiptera: Delphacidae), increased at temperatures up to 32°C; however, this efficiency decreased at 35°C (Heong et al., 1995).

The effects of CO_2 on insects are thought to be mostly indirect. These effects do not directly affect the insects but rather the plants on which they feed, thus having secondary effects on the physiology and behavior of the insects. In an experiment conducted under elevated CO_2 conditions, 57% more insect damage was observed in soybean plants grown under high CO_2 levels compared to the control group, necessitating insecticide application (Petzoldt & Seaman, 2007). Increased CO_2 increases the carbon/nitrogen (C:N) ratio in plant tissues, which results in reduced plant quality. Reduced nitrogen content leads some insect species to consume more nutrients, increasing damage to the host plant.

However, the physiological effects of this increased consumption vary according to both the host plant and the pest species. For example, some insect species can tolerate low nitrogen levels, while others experience developmental delays (Cannon, 1998). The decrease in nitrogen content in plant tissues slows down the developmental rate of insects, which may make them more susceptible to parasitoid attack for a longer period of time (Petzoldt & Seaman, 2007). This change in larval performance is often dependent on the type of plant they feed on. For example, the development of Lymantria dispar larvae decreased on poplar under high CO_2, while their developmental performance increased on oak (Cannon, 1998). Another effect of increased CO_2 is on plant water management. Increased CO_2 causes plants to close their stomata to reduce transpiration loss. This leads to an increase in leaf surface temperature and a decrease in the humidity around the leaf. This creates unfavourable microclimatic conditions for some insect species (Samways, 2005).

3.3. The effects of drought on insects

Climatic variability is among the basic environmental factors that determine the structure and functioning of ecosystems. Among these variables, precipitation regime in particular shapes not only the water cycle but also soil moisture, vegetation and microhabitat conditions, creating direct effects on insects, which are organisms sensitive to environmental conditions (Schowalter, 2016). Changes in precipitation amount, frequency and seasonal distribution play a decisive role in the developmental cycle, reproductive success, behavior and population dynamics of insects (Stange & Ayres, 2010). In this context, understanding the effects of drought on insect communities is critical both for assessing the ecological consequences of climate change and for developing sustainable agricultural strategies (Trumble & Butler, 2009).

Drought creates multifaceted effects on insects in agricultural ecosystems, both directly and indirectly. These effects significantly affect not only the biology of insects but also the interspecies interaction networks in which they are located. Increasing drought frequency and severity, especially the management of pests, makes integrated pest management (IPM) approaches more complex, necessitating a re-evaluation (Jactel et al., 2012). Therefore, the use of drought-resistant plant varieties, protection of natural enemies and holistic management of agro-ecosystems are of great importance.

1. Direct Effects

Drought conditions create direct stress factors on the physiological processes and individual behaviors of insects, leading to various biological consequences. This stress is generally associated with reduced soil and air moisture, increased temperatures and restricted access to water.

a) Physiological stress: Drought can cause high mortality rates, especially in species that cannot tolerate water loss during developmental stages such as eggs, larvae and pupae. This leads to rapid population decline (Huberty & Denno, 2004).

b) Disruption of developmental process: Insufficient moisture and high temperatures can cause development to be prolonged or completely stopped in some species. This process can result in morphological abnormalities and developmental disorders, especially in species that undergo complete metamorphosis (holometabolism) (Kingsolver et al., 2011).

c) Behavioral changes: Drought can cause individuals to move to cooler and wetter habitats by changing the sheltering, oviposition and feeding behaviors of insects. While some species increase their nighttime activity, others try to adapt to stressful conditions through behavioral plasticity (Chown & Nicolson, 2004).

2. Indirect Effects

The indirect effects of drought occur through complex relationships between ecosystem components. Changes in plants, natural enemies and symbiotic relationships can indirectly affect the dynamics of pest insects.

a) Changes in plant quality: Drought changes basic physiological characteristics such as water content and nutrient composition (especially nitrogen) in plants. While reduced nutrient quality negatively affects the development of phytophagous insects, some species can feed more efficiently on stressed plants (White, 2009). For example, aphids can more easily obtain nutrients from weakened host plants.
b) Weakening of plant defense mechanisms: Drought can reduce the capacity of plants to produce defensive compounds (e.g. phenolic compounds, resins). This can lead to reduced resistance to bark

beetles, for example, by reducing resin production in conifers (Mattson & Haack, 1987).

c) Affecting natural enemies: Drought affects not only pests but also their natural enemies. Predatory and parasitoid species can become ineffective due to reduced prey density, habitat reduction and physiological stress. This leads to weakening of biological control processes (Thaler, 1999).

d) Changes in food web and interspecific competition: Under drought conditions, some species may become dominant while others may disappear due to habitat loss. This can change the structure of the food chain, creating new interaction patterns where competition intensifies or some species switch hosts (Tylianakis et al., 2008).

e) Changes in the distribution areas of pests: Changes in habitat structure may cause some pest species to migrate to new and more suitable areas. This may create new infection risks in areas where the pest was not seen before (Battisti et al., 2006).

5. Phenological Incompatibilities

Phenology is a branch of science that studies the timing of events in the life cycle of organisms (e.g. flowering, migration, egg-laying) and the relationship between these events and climatic factors. In agricultural ecosystems, it is of great importance to have a harmony between the flowering and fruiting periods of plants and the egg-laying, larval development and feeding timing of insects.

Phenological incompatibility means the disruption of the synchrony between these timings. Climate change can disrupt this natural harmony due to reasons such as temperature increase and shifting seasons; and negatively affect the interaction of pests with plants, pollination and biological control processes (Visser & Both, 2005; Forrest, 2016).

Climate change can disrupt this harmony by affecting both the seasonal cycle of vegetation and the activity timing of insects in different ways. Increasing temperatures can cause timing differences in the interaction between plants, insects and their natural enemies. For example, the egg-laying period of insects can be separated from the flowering period of plants due to increasing temperatures; This may reduce the effectiveness of biological control. In addition, while some natural enemies have difficulty developing in high temperature conditions, it is thought that harmful insects can continue their development and become dominant

5.1 Disruption of Plant-Insect Harmony

Plants and insects have historically co-evolved according to certain environmental conditions such as temperature, day length (photoperiod) and humidity. However, climate change can disrupt this common timing, especially through increased temperature. For example:

- While plant flowering times shift earlier,
- The developmental processes of some insect species cannot keep up with this change,
- This leads to insects not being able to access sufficient nutrients or plants not being able to find sufficient pollinators.

In a long-term study conducted in the northeastern United States by Bartomeus et al. (2011), it was determined that in the last 30 years, plant flowering times shifted earlier by an average of 10 days, but some bumblebee species could not adapt to this change. This situation led to inadequate pollination and therefore decreased crop yields.

Similarly, observations made by Hegland et al. (2009) in Europe showed that the flowering time of apple trees shifted 5–7 days earlier with the increase in spring temperatures; however, the flight season of honey bees had not yet started. Such adaptation disruptions can cause losses in product quality and quantity.

5.2 Mismatches between Pests and Natural Enemies

Phenological mismatches affect not only the plant-pollinator relationship but also the interactions between pests and their natural enemies (predators and parasitoids). This situation poses a significant threat, especially for integrated pest management (IPM) strategies.

For example, the parasitoid wasp species Trichogramma spp. (Hymenoptera: Trichogrammatidae), which is widely used in biological control against corn borer, cannot adapt sufficiently to temperature increases. In contrast, larvae of the harmful species Ostrinia nubilalis (Lepidoptera: Crambidae) hatch earlier, causing Trichogramma to be out of season before it can find the pest (Thomson et al., 2010). In another study, it was observed that the developmental period of aphids from the family Aphididae was shifted two weeks earlier with increasing temperatures; however, ladybug larvae did not develop at this rate (Hance et al., 2007). This mismatch caused aphid populations to increase rapidly, free from predator pressure.

6. Increase and Spread of Invasive Species

Invasive alien species are organisms that are intentionally or unintentionally transported to a new ecosystem outside their natural habitat. These types of insects are usually species that cause damage to agriculture, forests, homes and stored products, and in some cases, they can be disease or vectors (Ward & Masters, 2007; Burkett & Vittor, 2018; Skendžić et al., 2021). In recent centuries, the transfer of these species to regions outside their natural distribution areas has accelerated with the increase in global trade, international travel and agricultural activities (Ricciardi, 2013). In addition, these species cause serious economic losses in agriculture, forestry and aquatic ecosystems (Shrestha, 2019). Only a small portion of alien species adapt to their environment and become established. Only a small portion of established species spread and cause economic damage. (Vander, 2005). Climate change can affect the spread of invasive insect species. Studies predict that with increasing temperatures, the habitats of these species may expand, their populations may increase, and they may produce more than one offspring per year (Bale et al., 2002; Harrington et al., 2007; Verberk et al., 2021). This situation may pose serious risks to sustainable agricultural production. However, climate change is not the only determining factor in the invasive process. In order for a species to become invasive, it must reach a new habitat, survive, and reproduce there. Climate conditions can affect this process positively or negatively. Climate plays an important role in determining the area where a species can spread, its growth and reproductive success, and its seasonal cycles (Masters & Norgrove, 2010). In the past, unsuitable habitats may have prevented the spread of these species due to physical barriers, such as mountain ranges or seas (Vanhanen, 2008). However, all living systems have a temperature tolerance range, and therefore temperature increases can have significant effects on ecosystems. Under suitable conditions, the establishment of sufficient numbers of individuals in an area can lead to the formation of persistent and self-sustaining populations (Simberloff, 2009). The risk of spread depends on the volume of plant trade, the possibility of invasive species being carried on these plants, and the possibility of passing undetected during border controls (Bacon et al., 2014). For example, Drosophila suzukii (Diptera: Drosophilidae) is an insect species that feeds on many different fruit species. It has invaded North and South America and Europe. It is thought that this species was most likely carried through the fresh fruit trade from Southeast Asia. The fact that its eggs or larvae were not detected on the transported fruits has caused their spread (Cini et al., 2014). Invasive species can find host plants in new environments thanks to behavioral responses. Species such as D. suzukii have the ability to feed on more than 30 plant species. This dietary flexibility is considered to be one of the main reasons for their success in invasion (Poyet et al., 2015).

Climate change is accelerating the spread of invasive insects. Parmesan and Yohe (2003) reported an average of 6.1 km per decade. Rising temperatures have allowed these insects to reach areas where they were previously inhospitable (Raza et al., 2015). Invasive insects generally have a wider climate tolerance than native species. This allows them to adapt more easily to different environmental conditions (Walther et al., 2009). Insects are highly sensitive to climate change because many of their physiological processes are temperature-dependent (Vermeij, 1996). Adaptations can occur at the behavioral, physiological, phenotypic, and developmental levels. Changes in environmental factors (temperature, humidity, day length), food resources, predators, or competition can affect this flexibility (Abram et al., 2017). Evolutionary changes in insects can develop as a result of responses to climate change (Snell et al., 2018). In this process, especially in cases where temperature changes are high, adaptations that develop under selection pressure can make it possible to survive in new environments. Thermal adaptation can also occur through behavioral traits that affect the energy metabolism of insects (Chevin et al., 2010).

Conclusion

Climate change creates deep and multidimensional effects on the functioning and sustainability of agricultural ecosystems. The role of insects in this process is of critical importance in terms of both ecosystem functions and agricultural production. Factors such as temperature increases, changes in precipitation regimes, and increased frequency of extreme weather events directly shape the dynamics of insect populations and determine agricultural productivity and ecosystem health.

The effects of climate change on insect populations stand out in two main categories: First, the increase in the populations of harmful insect species and the expansion of their distribution areas, and second, phenological incompatibilities and disruptions in ecosystem functions. In this context, the increase in invasive species poses serious threats to existing agricultural systems; especially the migration of new harmful species from tropical and subtropical regions to temperate regions is accelerating. The spread of invasive species reduces local biodiversity, disrupts natural enemy relationships, and increases agricultural losses.

Phenological incompatibilities, i.e. timing differences between insect life cycles and plant developmental stages, cause deterioration in ecosystem services. For example, early or late activity of pollinator insects directly affects the yield and quality of plants. In addition, interactions between natural enemies and pests may not be as regular and balanced as before due to climate change. This situation reveals the need for revision in integrated pest management (IPM) strategies.

In light of current scientific data and climate models, the need to implement proactive, climate-sensitive, and multidimensional strategies in insect control comes to the fore. Early warning systems, effective use of biological control agents, increasing agricultural diversity, and biosecurity measures are the cornerstones of these strategies. In addition, education and awareness of farmers and agricultural stakeholders are critical elements for sustainable success.

As a result, the role of insects in the new agricultural ecosystem conditions shaped by climate change should be transformed from being a mere threat to a management object for the protection of ecosystem balances and the provision of sustainable agricultural production. In this context, interdisciplinary collaborations and the integration of technological innovations will play a key role in increasing the capacity to adapt to climate change. This study aims to establish a comprehensive basis for policy makers, researchers and producers by revealing the effects of climate change on insect populations and agricultural ecosystems in a scientific framework. Going forward, systematic collection of field data, modeling studies integrating climate and biological data and adaptive management practices at the local level are of great importance in filling the knowledge gaps in this area and developing effective solutions.

REFERENCES

Kazenel, M. R., Wright, K. W., Griswold, T., Whitney, K. D., & Rudgers, J. A. (2024). Heat and desiccation tolerances predict bee abundance under climate change. *Nature*. https://doi.org/10.1038/s41586-024-07241-2

Abram, P. K., Boivin, G., Moiroux, J., & Brodeur, J. (2017). Behavioural effects of temperature on ectothermic animals: Unifying thermal physiology and behavioural plasticity. *Biological Reviews, 92*(4), 1859–1876. https://doi.org/10.1111/brv.12312

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, 74(1–3), 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6

Avan, F. (2021). İklim değişikliğinin tarımsal zararlılar üzerindeki etkisi. *Uluslararası Tarım ve Yaban Hayatı Bilimleri Dergisi*, 7(1), 11–22. https://doi.org/10.24180/ijaws.885693

Avan, M. (2022a). İklim Değişikliği ve Tarımda Dönüşüm, Bitki Patojenlerinin Neden Olduğu Hastalıklara Karşı Kompost ve Kompost Çaylarının Kullanımı. İksad Yayınevi, ISBN: 978-625-8377-92-7, Bölüm 4, ss.107-135

Avan, M. (2022b). Agriculral and Envirolment Report for Sustainable Future. The Role of silicon in Fungal Plant Patogens Control. İksad Publishing, ISBN: 978-625-8246-18-6, ss.101-112

Avan M. (2021). Important Fungal Diseases in Medicinal and Aromatic Plants and Their Control. Turkish Journal of Agricultural Engineering Research, 2(1), 239-259.

Avan, M., Kotan, R. (2021). Fungusların Mikrobiyal Gübre veya Biyopestisit Olarak Tarımda Kullanılması, Uluslararası Doğu Anadolu Fen Mühendislik ve Tasarım Dergisi, 3(1), 167-191.

Awmack, C. S., Harrington, R., & Power, S. A. (1997). Aphid responses to enriched CO_2 are dependent on plant species and genotype. *Journal of Experimental Botany, 48*(299), 1951–1957. https://doi.org/10.1093/jxb/48.11.1951

Bacon, S. J., Aebi, A., Calanca, P., & Bacher, S. (2014). Quarantine arthropod invasions in Europe: The role of climate, hosts and propagule pressure.

Diversity and Distributions, 20(1), 84–94. https://doi.org/10.1111/ddi.12147

https://doi.org/10.1046/j.1365-2486.2002.00451.x

Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., ... & Whittaker, J. B. (2002). Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Global Change Biology, 8*(1), 1–16. https://doi.org/10.1046/j.1365-2486.2002.00451.x

Bartomeus, I., Ascher, J. S., Wagner, D., Danforth, B. N., Colla, S., Kornbluth, S., & Winfree, R. (2011). Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences*, 108(51), 20645–20649. https://doi.org/10.1073/pnas.1115559108

Battisti, A., Stastny, M., Netherer, S., Robinet, C., Schopf, A., Roques, A., & Larsson, S. (2006). Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. *Ecological Applications, 15*(6), 2084–2096. https://doi.org/10.1890/04-1903

Burkett, M., & Vittor, A. (2018). Global climate change and vector-borne diseases. In S. Choffnes, D. A. Relman, & L. Olsen (Eds.), *Global climate change and human health: From science to practice* (pp. 165–184). Jossey-Bass.

Cannon, R. J. C. (1998). The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. *Global Change Biology*, 4(7), 785–796. https://doi.org/10.1046/j.1365-2486.1998.00190.x

Chevin, L. M., Lande, R., & Mace, G. M. (2010). Adaptation, plasticity, and extinction in a changing environment: Towards a predictive theory. *PLoS Biology, 8*(4), e1000357. https://doi.org/10.1371/journal.pbio.1000357

Chown, S. L., & Nicolson, S. W. (2004). *Insect physiological ecology: Mechanisms and patterns*. Oxford University Press.

Cini, A., Ioriatti, C., & Anfora, G. (2014). A review of the invasion of Drosophila suzukii in Europe and a draft research agenda for integrated pest management. *Bulletin of Insectology, 67*(1), 149–160.

Denlinger, D. L. (2002). Regulation of diapause. *Annual Review of Entomology*, 47(1), 93–122. https://doi.org/10.1146/annurev.ento.47.091201.145137

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Naylor, R. L. (2018). Increase in crop losses to insect pests in a warming climate. *Science*, 361(6405), 916–919. https://doi.org/10.1126/science.aat3466

FAO. (2008). *Climate change and biodiversity for food and agriculture*. Food and Agriculture Organization of the United Nations.

FAO-IPPC. (2024). *Climate change and plant pests: New threats to food security*. Food and Agriculture Organization of the United Nations & International Plant Protection Convention.

Fields, P. G. (1992). The control of stored-product insects and mites with extreme temperatures. *Journal of Stored Products Research*, 28(2), 89–118. https://doi.org/10.1016/0022-474X(92)90026-G

Forrest, J. R. K. (2016). Complex responses of insect phenology to climate change. *Current Opinion in Insect Science, 17*, 49–54. https://doi.org/10.1016/j.cois.2016.07.002

Frontiers in Ecology and Evolution. (2019). Climate change impacts on insect pest dynamics and biological control. *Frontiers in Ecology and Evolution*, XX(X), XX–XX. https://doi.org/10.3389/fevo.2019.xxxxxx

Garibaldi, L. A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., ... & Klein, A. M. (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, 339(6127), 1608–1611. https://doi.org/10.1126/science.1230200

Hance, T., van Baaren, J., Vernon, P., & Boivin, G. (2007). Impact of extreme temperatures on parasitoids in a climate change perspective. *Annual Review of Entomology*, 52, 107–126. https://doi.org/10.1146/annurev.ento.52.110405.091333

Harrington, R., Fleming, R. A., & Woiwod, I. P. (2001). Climate change impacts on insect management and conservation in temperate regions: Can they be predicted? *Agricultural and Forest Entomology, 3*(4), 233–240. https://doi.org/10.1046/j.1461-9563.2001.00110.x

Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A. L., & Totland, Ø. (2009). How does climate warming affect plant–pollinator interactions? *Ecology*

Letters, 12(2), 184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x

Heong, K. L., Aquino, G. B., & Barrion, A. T. (1995). Arthropod community structures of rice ecosystems in the Philippines. *Bulletin of Entomological Research, 85*(4), 397–406. https://doi.org/10.1017/S0007485300036199

Huberty, A. F., & Denno, R. F. (2004). Plant water stress and its consequences for herbivorous insects: A new synthesis. *Ecology, 85*(5), 1383–1398. https://doi.org/10.1890/03-0352

IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

İslamoğlu, M. (2012). Mass rearing and release of the egg parasitoid, Trissolcus semistriatus Nees.(Hymenoptera: Scelionidae), a biological control agent of the Sunn pest, *Eurygaster integriceps* Put. Egyptian Journal of Biological Pest Control, 21 (2) p. 110 – 114

Jactel, H., Petit, J., Desprez-Loustau, M. L., Delzon, S., Piou, D., Battisti, A., & Koricheva, J. (2012). Drought effects on damage by forest insects and pathogens: A meta-analysis. *Global Change Biology, 18*(1), 267–276. https://doi.org/10.1111/j.1365-2486.2011.02512.x

Jouquet, P., Traoré, S., Choosai, C., Hartmann, C., & Bignell, D. (2011). Influence of termites on ecosystem functioning: Ecosystem services provided by termites. *European Journal of Soil Biology*, 47(4), 215–222. https://doi.org/10.1016/j.ejsobi.2011.05.005

Kıvan, M., & Kılıç, A. Y. (2002). Spodoptera littoralis (Boisd.)'in bazı biyolojik özellikleri üzerine farklı sıcaklıkların etkileri. *Türk Entomoloji Dergisi*, 26(4), 281–289.

Kingsolver, J. G., Higgins, J. K., & Augustine, K. E. (2011). Fluctuating temperatures and ectotherm growth: Distinguishing non-linear and time-dependent effects. *Journal of Experimental Biology, 214*(7), 1113–1121. https://doi.org/10.1242/jeb.052720

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society*

B: Biological Sciences, 274(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Lehmann, P., Piiroinen, S., Lyytinen, A., & Lindström, L. (2020). Insect pest responses to climate change: From physiology to implications for agro-ecosystems. *Agricultural and Forest Entomology*, 22(1), 75–88. https://doi.org/10.1111/afe.12367

Liebhold, A. M., Brockerhoff, E. G., Garrett, L. J., Parke, J. L., & Britton, K. O. (2011). Live plant imports: The major pathway for forest insect and pathogen invasions of the US. *Frontiers in Ecology and the Environment*, 10(3), 135–143. https://doi.org/10.1890/110198

Losey, J. E., & Vaughan, M. (2006). The economic value of ecological services provided by insects. *BioScience*, 56(4), 311–323. https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2

Masters, G. J., & Norgrove, L. (2010). Climate change and invasive alien species. In *Handbook of climate change and agroecosystems: Impacts, adaptation, and mitigation* (pp. 255–274). Imperial College Press. https://doi.org/10.1142/9781848166554_0011

Mattson, W. J., & Haack, R. A. (1987). The role of drought in outbreaks of plant-eating insects. *BioScience, 37*(2), 110–118. https://doi.org/10.2307/1310365

Memmott, J., Craze, P. G., Waser, N. M., & Price, M. V. (2007). Global warming and the disruption of plant–pollinator interactions. *Ecology Letters*, 10(8), 710–717. https://doi.org/10.1111/j.1461-0248.2007.01061.x

Menéndez, R. (2007). How are insects responding to global warming? *Tiempo*, 3(13), 1–5.

Nichols, E., Spector, S., Louzada, J., Larsen, T., Amezquita, S., & Favila, M. E. (2008). Ecological functions of dung beetles: A review. *Biological Conservation*, 141(6), 1461–1474. https://doi.org/10.1016/j.biocon.2008.04.011

Özgen, I., & Karsavuran, Y. (2009). Küresel iklim değişikliğinin entomolojik açıdan değerlendirilmesi. *Türkiye Entomoloji Dergisi, 33*(1), 21–33.

Öztemiz, S., Şahin, F., & Çobanoğlu, S. (2008). Beyazsinekler (Hemiptera: Aleyrodidae) ve mücadele yöntemleri. *Bitki Koruma Bülteni*, 48(1), 17–30.

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, 37, 637–669. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421(6918), 37–42. https://doi.org/10.1038/nature01286

Parmesan, C., Root, T. L., & Willig, M. R. (1999). Impacts of extreme weather and climate on terrestrial biota. *Bulletin of the American Meteorological Society*, 81(3), 443–450. https://doi.org/10.1175/1520-0477(2000)081<0443:IOEWAC>2.3.CO;2

Petzoldt, C., & Seaman, A. (2007). Climate change effects on insects and pathogens. *New York State Integrated Pest Management Program*, Cornell University. Retrieved from https://nysipm.cornell.edu/sites/default/files/shared/documents/climate-change-effects-insects-pathogens.pdf

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology & Evolution*, 25(6), 345–353. https://doi.org/10.1016/j.tree.2010.01.007

Poyet, M., Le Roux, V., Gibert, P., Meirland, A., Prévost, G., Eslin, P., & Chabrerie, O. (2015). The wide potential trophic niche of the Asiatic fruit fly Drosophila suzukii: The key of its invasion success in temperate Europe? *PLoS ONE, 10*(11), e0142785. https://doi.org/10.1371/journal.pone.0142785

Raza, M. F., Wang, Y., Cai, Z., Bai, S., & Zhang, Y. (2015). The effect of climate change on insect pests and their natural enemies. *Journal of Agricultural Science, 7*(5), 78–84. https://doi.org/10.5539/jas.v7n5p78

Reilly, J. (1996). *Climate change, agriculture, and food security*. Global Environmental Change, 6(1), 24–38. https://doi.org/10.1016/0959-3780(96)00002-6

Ricciardi, A. (2013). Invasive species. In *Encyclopedia of Biodiversity* (2nd ed., Vol. 4, pp. 530–536). Elsevier. https://doi.org/10.1016/B978-0-12-384719-5.00271-0

Roitberg, B. D., & Mangel, M. (2010). *Behavioral ecology of insect parasitoids: From theoretical approaches to field applications*. Wiley-Blackwell.

Samways, M. J. (2005). *Insect diversity conservation*. Cambridge University Press.

Schowalter, T. D. (2016). *Insect ecology: An ecosystem approach* (4th ed.). Academic Press.

Simberloff, D. (2009). The role of propagule pressure in biological invasions. *Annual Review of Ecology, Evolution, and Systematics, 40*, 81–102. https://doi.org/10.1146/annurev.ecolsys.110308.120304

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., & Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects, 12*(5), 440. https://doi.org/10.3390/insects12050440

Snell, R. S., Beckman, N. G., Fraterrigo, J. M., Aslan, C., Rogers, H. S., Futuyma, D. J., ... & Sork, V. L. (2018). Consequences of intraspecific variation in seed dispersal for plant demography, communities, evolution and global change. *AoB Plants, 10*(2), ply005. https://doi.org/10.1093/aobpla/ply005

Stange, E. E., & Ayres, M. P. (2010). Climate change impacts: Insects. In *Encyclopedia of Life Sciences* (pp. 1–7). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470015902.a0022558

Stewart, A. J. A., Hill, J. K., & Thomas, C. D. (2007). Evolutionary changes in ecological traits of British butterflies: Reductions in species' range margins. *Biological Journal of the Linnean Society*, 90(1), 255–265. https://doi.org/10.1111/j.1095-8312.2007.00724.x

Thaler, J. S. (1999). Jasmonate-inducible plant defenses cause increased parasitism of herbivores. *Nature, 399*(6737), 686–688. https://doi.org/10.1038/21439

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., ... & Williams, S. E. (2004). Extinction risk from climate change. *Nature*, 427(6970), 145–148. https://doi.org/10.1038/nature02121

Thomson, L. J., Macfadyen, S., & Hoffmann, A. A. (2010). Predicting the effects of climate change on natural enemies of agricultural pests.

Biological Control, 52(3), 296–306. https://doi.org/10.1016/j.biocontrol.2009.01.022

Tirado, R., Simon, G., & Johnston, P. (2013). Bees in decline: A review of factors that put pollinators and agriculture in Europe at risk. *Greenpeace Research Laboratories Technical Report (Review)*, 1–34.

Topal, E., Yücel, E., & Güler, B. (2016). İklim değişikliğinin arıcılık sektörü üzerindeki etkileri. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi*, 19(4), 577–584. https://doi.org/10.18016/ksutarimdoga.vi.XXXX

Tougeron, K., Devotto, L., & van Baaren, J. (2017). Diapause expression in a warm climate: Is the common cue reliable? *Environmental Entomology*, 46(3), 761–770. https://doi.org/10.1093/ee/nvx093

Toxopeus, J., Jakobs, R., & Sinclair, B. J. (2021). Evolutionary responses of Drosophila suzukii to mild winters: Evidence for cold tolerance plasticity and adaptation. *Ecological Entomology*, 46(1), 54–66. https://doi.org/10.1111/een.12949

Trumble, J. T., & Butler, C. D. (2009). Climate change will exacerbate California's insect pest problems. *California Agriculture, 63*(2), 73–78. https://doi.org/10.3733/ca.v063n02p73

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batáry, P., ... & Westphal, C. (2012). Landscape moderation of biodiversity patterns and processes—Eight hypotheses. *Biological Reviews*, 87(3), 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x

Tylianakis, J. M., Didham, R. K., Bascompte, J., & Wardle, D. A. (2008). Global change and species interactions in terrestrial ecosystems. *Ecology Letters, 11*(12), 1351–1363. https://doi.org/10.1111/j.1461-0248.2008.01250.x

Vander, Z. A. (2005). *Invasion biology*. Oxford University Press.

Vanhanen, H. (2008). Invasive insects in Europe – Role of climate change. *Silva Fennica, 42*(2), 331–338. https://doi.org/10.14214/sf.254

Verberk, W. C. E. P., Overgaard, J., Ern, R., Bayley, M., Wang, T., Boardman, L., & Terblanche, J. S. (2021). Does oxygen limit thermal tolerance in arthropods? A critical review of current evidence. *Comparative*

Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 254, 110893. https://doi.org/10.1016/j.cbpa.2021.110893

Vermeij, G. J. (1996). Adaptations of mollusks to physical stress. *American Malacological Bulletin, 12*(1-2), 129–135.

Visser, M. E., & Both, C. (2005). Shifts in phenology due to global climate change: The need for a yardstick. *Proceedings of the Royal Society B: Biological Sciences, 272*(1581), 2561–2569. https://doi.org/10.1098/rspb.2005.3356

Walther, G. R., Roques, A., Hulme, P. E., Sykes, M. T., Pyšek, P., Kühn, I., ... & Zobel, M. (2009). Alien species in a warmer world: Risks and opportunities. *Trends in Ecology & Evolution, 24*(12), 686–693. https://doi.org/10.1016/j.tree.2009.06.008

Ward, N. L., & Masters, G. J. (2007). Linking climate change and species invasion: An illustration using insect herbivores. *Global Change Biology*, 13(8), 1605–1615. https://doi.org/10.1111/j.1365-2486.2007.01399.x

White, T. C. R. (2009). Plant vigour versus plant stress: A false dichotomy. *Oikos, 118*(6), 807–808. https://doi.org/10.1111/j.1600-0706.2009.17424.x

Yamamura, K., & Kiritani, K. (1998). A simple method to estimate the potential increase in the number of generations under global warming in temperate zones. *Applied Entomology and Zoology*, 33(2), 289–298. https://doi.org/10.1303/aez.33.289

Zhou, X., Lei, Z., & Chen, M. (2010). Climate warming increases the potential geographic range of the cotton bollworm *Helicoverpa armigera*. *Environmental Entomology*, 39(4), 1265–1274. https://doi.org/10.1603/EN09176

CHAPTER 7

EVALUATION OF THE EFFECT OF SOIL CULTIVATION METHODS ON SOIL QUALITY

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INTRODUCTION

Soil management strategies play a critical role in maintaining soil quality and ensuring sustainable crop productivity (Aziz et al., 2009). Various management practices frequently influence the biological, chemical, and physical properties of soil, leading to alterations in soil function quality (Islam and Weil, 2000; Aziz et al., 2009; Derpsch et al., 2010; Wolfarth et al., 2011; Ding et al., 2011). Improper soil use can result in degradation and reduced productivity due to erosion, depletion of organic matter, and nutrient losses (Ramos et al., 2011).

All physical, chemical, and biological properties of soil are interconnected, and especially, reduced tillage activities significantly affect these characteristics (Thomas et al., 2007). In no-till systems, more plant biomass accumulates on the surface. This accumulation provides several benefits, including the preservation of soil moisture, reduction of temperature, and increased microbial activity, resulting in marked improvements in soil structure (especially in N, SOM, SOC content, and CEC), and a decrease in the C/N ratio (Madejon et al., 2009; Naudin et al., 2010; Derpsch et al., 2010; Moussa-Machraoui et al., 2010; Benito, 2010; Álvaro-Fuentes et al., 2012). Soilless farming practices promote the accumulation of carbon in microaggregates, supporting the formation of macroaggregates. This carbon transfer is particularly valuable for long-term soil carbon sequestration (Shan et al., 2010; Erkossa, 2011). Moreover, zero tillage methods tend to reduce bulk density in the topsoil (Jina et al., 2011).

Since soil properties are interdependent, the effectiveness of production technologies aimed at improving soil quality can be evaluated by measuring and analyzing specific soil characteristics. Although a substantial change in a single property may not significantly impact the entire system, minor alterations across multiple properties can collectively result in meaningful outcomes (Reganold and Palmer, 1995). Given its complex nature, soil quality cannot be measured directly; instead, it is typically assessed indirectly through changes in soil properties resulting from management practices. While traditional assessments have primarily focused on chemical and physical properties (Larson and Pierce, 1994), recent research highlights the importance of biological indicators, which often respond more quickly to management interventions (Islam and Weil, 2000; Kennedy and Papendick, 1995).

Therefore, a comprehensive evaluation of soil quality should integrate biological, chemical, and physical parameters (Parkin et al., 1996).

Soil organic matter (SOM) has long been regarded as an indicator of soil quality due to its contribution to soil fertility (Islam and Weil, 2000). However, some researchers argue that SOM alone is insufficient and that evaluating various soil properties together yields more reliable results (Islam and Weil, 2000). In this context, parameters such as particulate organic matter, active carbon, total nitrogen, microbial biomass, enzyme activities, soil pH, CEC, salinity, bulk density, amino sugars, and soil aggregation are considered dynamic indicators of quality due to their quick responses to management systems (Islam and Weil, 2000; Wander, 2004; Aziz et al., 2009; Ding et al., 2011). Microbial life, a component of SOM, is regarded as a strong indicator of soil quality (Islam and Weil, 2000). High-quality soils are typically biologically active and host a balanced microbial community. Microbial biomass consists of primary decomposers that play a role in breaking down organic matter and contributing to nutrient cycling. Fungi, actinomycetes, and bacteria enhance soil aggregation, improve water retention and porosity, reduce erosion, and support carbon storage (Kennedy and Papendick, 1995).

Soil Quality and Its Determining Properties

It is recommended to use specific parameters collectively in the assessment of soil quality. Larson and Pierce (1991) suggested using a small but effective dataset to determine soil quality and emphasized that these measurements should be performed using standardized methodologies. Dumanski and Pieri (2000) stated that a few traceable indicators can be useful for identifying long-term trends. Suitable quality indicators should include physical, chemical, and biological characteristics affected by soil management (Islam and Weil, 2000; Aparicio and Costa, 2007).

Arshad and Coen (1992) recommended measuring sensitive parameters such as root depth, water holding capacity, bulk density, penetration resistance, hydraulic conductivity, aggregate stability, organic matter content, nutrient availability, pH, and electrical conductivity to evaluate soil quality. Similarly, Larson and Pierce (1994) supported the minimum data set approach but included particle size distribution instead of aggregate stability. A set of 15 physical, chemical, and biochemical indicators is used to define soil functions.

In this study, to assess the productivity function of Arik soils, indicators such as plant-available P and K content, available water capacity (AWC), penetration resistance (PR), potentially mineralizable nitrogen (PMN), microbial biomass carbon (MBC), and pH were evaluated (Cherubin et al., 2017). Physical properties such as soil bulk density, soil aggregate structure, capillary and non-capillary porosity, field capacity, and saturation capacity were determined. Soil organic carbon, total nitrogen, Olsen phosphorus, and available potassium were analysed. Additionally, biological properties such as soil catalase and urease activity, alkaline phosphatase, invertase, and microbial colony-forming units (CFU) were identified.

A search conducted in the Web of Science database (https://www.webofscience.com/wos/woscc/summary/a91f59c1-81a2-4221-90f1-ef205303abd1-016c448413/relevance/1) on 02.07.2025 using the keywords “soil tillage,” “soil quality index,” and “soil quality index sqi” retrieved a total of 1,387 documents. For bibliometric analysis of the keywords used in these documents, the VOSviewer software was utilized (Figure 1). The bibliometric analysis revealed associations with terms such as carbon sequestration (19), enzyme activity (82), soil erosion (18), organic matter (31), organic carbon (101), microelements (9), soil aggregation/structure (27), microbial biomass (13), beta-glucosidase (9), microbial community (73), phosphorus (8), and bulk density (13).

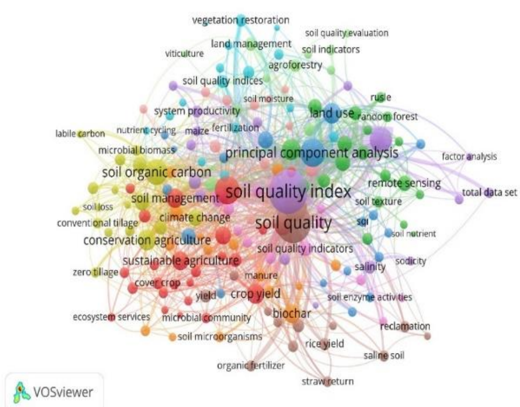

Figure 1. Bibliometric analysis of keywords used in studies related to soil tillage and soil quality

Soil Tillage and the Physical Quality Index

Soil tillage practices significantly alter soil structure by increasing porosity; however, they also accelerate the breakdown of soil aggregates. Incorporating plant residues into the soil increases the amount of organic matter and enhances contact between soil and plant material, contributing to increased biomass. Particularly, the ploughing method increases soil porosity but also accelerates the decomposition of organic matter on the soil surface. This can lead to a more rapid loss of soil nutrients (Morris et al., 2004). Furthermore, soils that are ploughed are more exposed to environmental cycles such as freeze–thaw and wet–dry, which increases the rate of macroaggregate breakdown (Six et al., 2004; Shan et al., 2010).

In contrast, conservation tillage practices promote the slow decomposition of easily decomposable organic matter fractions in the soil—known as particulate organic matter (POM)—by microorganisms, thus maintaining and enhancing aggregate stability (Six et al., 2000). POM is a mobile and biologically active component of soil organic carbon, primarily consisting of plant residues and organic materials derived from the decomposition of soil microorganisms. As a critical indicator of soil health, POM plays a significant role in nutrient cycling and improves soil physical structure by increasing water retention and aeration.

The effects of long-term management practices on soil organic matter, particularly POM, have been confirmed in numerous scientific studies (Mando et al., 2003). Measurements of POM show a strong correlation with nutrient recycling and improvements in soil physical conditions (Wander et al., 1994). Therefore, POM is not only an indicator of the amount of organic matter present in the soil but also a key parameter reflecting the vitality and productivity of the soil ecosystem.

Soil Tillage and the Biological Quality Index

Biological indicators of soil quality are among the parameters that respond most rapidly to environmental changes, playing a critical role in the early evaluation of soil health. Biological indicators such as microbial biomass carbon (MBC) and basal respiration (BR) are much more dynamic than soil organic carbon content, responding sensitively to environmental or management changes within days or weeks (Dilly et al., 2011). This rapid response makes it essential to include biological indicators in Soil Quality Index (SQI) assessments. When biological parameters are excluded, soil quality is often overestimated, and the biological impacts of different tillage practices tend to be overlooked.

Microbial communities play a central role in the transformation of organic matter, nutrient cycling, and the improvement of soil structure. Therefore, biological indicators are vital for reflecting the environmental and ecosystem function impacts of soil tillage practices (Bünemann et al., 2018). Especially under conservation tillage methods, biological activities increase, while in intensive tillage systems, these activities tend to decline. Consequently, incorporating soil biological quality indicators into SQI calculations enables a more realistic, comprehensive, and early-stage monitoring of soil health, thereby supporting sustainable soil management

The Effect of Soil Tillage Methods on Soil Quality

Over the past decade, different soil tillage techniques and crop residue management practices have led to significant variations in functional capacity, even among similar soils under the same climatic conditions. Some findings regarding the effects of these practices on soil quality are summarized in Table 1.

Table 1. Effects of soil tillage methods on soil quality

Soil Cultivation Method	Impact on Soil Quality (SQI)	Effect on Yield	The Role of Biological Indicators	Literature
Direct Seeding (NT)	High at the surface and decreasing with depth were observed. SQI decreases in the lower layers due to compaction and nutrient stratification.	Limited yields in some crops except soybeans	MBC and PMN were low, physical limitations were observed	Hammac et al., 2016; Büchi et al., 2017
Strategic Processing (ST)	Higher SQI than NT at all depths; close to NT at the surface, superior in the substratum	Soybean yields increased, wheat and corn slightly decreased	SQI more consistent with biological indicators	Peixoto et al., 2020
Conventional Machining (CT-1/CT-2)	SQI values are lowest; organic matter loss is high, structure and water retention are negatively affected	High fertilizer requirement, poor nutrient cycling	Biological contributions may appear low, SQI may appear too high	Blanco-Canqui and Lal, 2009; Cherubin et al, 2018
Preventive Method Recommendations	The effect of ST may be short-term; it must be supported by other methods	Necessary for sustainable yield in the long term	Monitoring of biological indicators is recommended	Blanco-Canqui ve Wortmann, 2020
General Observation	ST may alleviate the disadvantages of NT systems. Assessments without including biological indicators may be misleading.	Variable yield effects depending on environment and product	Biological parameters are critical for early warning	Dilly et al., 2011

CT-1 / CT-2: Variations of conventional tillage systems
SQI: Soil Quality Index
MBC: Microbial Biomass Carbon
PMN: Potentially Mineralizable Nitrogen

Conclusıon

Integrating soil functions into soil quality assessments enables a more comprehensive and accurate analysis of the advantages and disadvantages of different soil tillage methods. Soil quality cannot be fully understood through evaluations based solely on physical or chemical properties. Therefore, considering biological processes and indicators is crucial for monitoring the complex functions occurring within the soil. Functions such as soil productivity, water and nutrient cycling, and carbon sequestration are shaped not only by structural characteristics but also by biological factors such as microbial activity. In this context, indicators like microbial biomass carbon (MBC) and potentially mineralizable nitrogen (PMN) reflect changes in the soil rapidly and sensitively, making them essential components in Soil Quality Index (SQI) calculations.

Long-term conservation tillage systems offer significant advantages in preventing soil degradation, increasing organic matter content, and reducing erosion. Particularly, no-till (NT) systems contribute positively to soil health by promoting organic matter accumulation on the surface. However, over time, several disadvantages may arise, including subsoil compaction, nutrient stratification, and limited microbial activity. These issues can reduce soil functionality and restrict yield potential in no-till systems.

To address such limitations, strategic tillage (ST) practices have been developed. These involve limited and targeted interventions at specific depths and intervals, aiming to improve the physical and biological properties of the soil without disrupting the foundational structure of no-till systems. ST alleviates subsurface compaction, supports root development, and enhances the mobility of water and nutrients, thereby improving soil functionality. Nevertheless, studies have reported that the effects of ST are not long-lasting and typically persist for only 1–2 years. Therefore, ST should be considered a short-term solution. To ensure long-term soil health sustainability, it is important to adopt integrated approaches alongside ST, such as controlled traffic farming, the use of cover crops, organic matter amendments, and diversification in crop rotation.

The success of soil tillage systems relies not only on physical interventions but also on the holistic evaluation of biological and chemical processes. Thus, adopting a multidisciplinary and function-based approach in soil quality assessments plays a key role in the development of sustainable agricultural practice.

REFERENCES

A’ lvaro-Fuentes, J., Joaquın Morell, F., Plaza-Bonilla, D., Arrue, J., Cantero-Martinez, C., 2012. Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil and Tillage Research 120, 32–39.

Am. J. Alter. Agric., 7: 25-31.

Aparicio, V.C., Costa, J.L., 2007. Soil quality indicators under continuous cropping systems in the Argentinean Pampas. Soil and Tillage Research 96, 155–165.

Arshad, M.A. and Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria.

Aziz, I., Mahmood, T., Raut, Y., Lewis, W., Islam, R., Weil, R.R., 2009. Active organic matter as a simple measure of field soil quality. In: ASA International Meetings, Pittsburg, PA.

Benitio, A., 2010. Carbon accumulation in soil. Ten year study of conservation tillage and crop rotation in a semi-arid areas of Castile-Leon, Spain Aurora Sombrero. Soil and Tillage Research 107, 64–70.

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. Crit. Rev. Plant Sci. 28 (3), 139–163.

Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res. 198, 104534.

Büchi, L., Wendling, M., Amoss´e, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland. Soil Tillage Res. 174, 120–129.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., M¨ader, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality - a critical review. Soil Biol. Biochem. 120, 105–125.

Cherubin, M.R., Oliveira, D.M.D.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V., Paiva, S.R.D., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. Sci. Agric. (Piracicaba. Braz) 75 (3), 255–272.

Cherubin, M.R., Oliveira, D.M.D.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V., Paiva, S.R.D., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. Sci. Agric. (Piracicaba. Braz) 75 (3), 255–272.

Derpsch, R., Friedrich, T., Kassam, K., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering 3 (1), 1–25.

Dilly, O., Nii-Annang, S., Franke, G., Fischer, T., Buegger, F., Zyakun, A., 2011. Resilience of microbial respiration, respiratory quotient and stable isotope characteristics to soil hydrocarbon addition. Soil Biol. Biochem. 43, 1808–1811.

Ding, X., Zhang, B., Zhang, X., Yang, X., Zhang, X., 2011. Effects of tillage and crop rotation on soil microbial residues in a rainfed agroecosystem of northeast China. Soil and Tillage Research 114, 43–49.

Dumanski, J., Pieri, C., 2000. Land quality indicators: research plan. Agriculture, Ecosystems and Environment 81, 93–102.

Hammac, W.A., Stott, D.E., Karlen, D.L., Cambardella, C.A., 2016. Crop, tillage, and landscape effects on near-surface soil quality indices in Indiana. Soil Sci. Soc. Am. J. 80, 1638–1652.

Islam, K.R., Weil, R.R., 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation 55, 69–78.

Islam, K.R., Weil, R.R., 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation 55, 69–78.

Jina, H., Hongwena, L., Rasaily, R.G., Qingjiea, W., Guohuaa, C., Yanboa, S., Xiaodonga, Q., Lijinc, L., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. Soil and Tillage Research 113, 48–54.

Kennedy, A.C., Papendick, R.I., 1995. Microbial characteristics of soil quality. Journal of Soil and Water Conservation 50, 243–248.

Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. In: Wolf, K., et al. (Eds.), Evaluation for Sustainable Land Management Contami-nated Soil' 88. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 1495–1503.

Larson, W.E., Pierce, F.J., 1994. The dynamics of soil quality as a measure of sustainable management. In: Doran, J.W., et al. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI, pp. 37–51.

Madejon, E., Murillo, J.M., Moreno, F., Lopez, M.V., Alvaro-Fuentes, J., Cantero, 2009. Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas. Soil and Tillage Research 105, 55–62.

Mando, A., Ouattara, B., Se'dogo, M.P., Stroosnijder, L., Ouattara, K., Brussaard, L., Vanlauwe, B., 2003. Long term effects of tillage and organic input on Ferric Lixisol organic matter and crop performance under Sudano-Sahelian conditions. Soil and Tillage Research 80, 95–101.

Morris, D.R., Gilbert, R.A., Reicosky, D.C., Gesch, R.W., 2004. Oxidation potentials of soil organic matter in histosols under different tillage methods. Soil Science Society of America Journal 68, 817–826.

Moussa-Machraoui, S., Errouissi, F., Ben-Hammouda, M., Nouira, S., 2010. Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semi-arid conditions in northwestern Tunisia. Soil and Tillage Research 106, 247–253.

Naudin, K., Goze, E., Balarabe, O., Giller, K.E., Scope, E., 2010. Impact of no tillage and mulching practices on cotton production in North Cameroon: a multi-locational on-farm assessment. Soil and Tillage Research 108, 68–76.

Parkin, T.B., Doran, J.W., Franco-Vizcaino, E., 1996. Field and laboratory tests of soil respiration.Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. SSSA Spec. Publ. 49, Soil Sci. Soc. Am., Madison, WI, pp. 231–246.

Peixoto, D.S., da Silva, L.D.C.M., de Melo, L.B.B., Azevedo, R.P., Araújo, B.C.L., de Carvalho, T.S., Moreira, S.G., Curi, N., Silva, B.M., 2020.

Occasional tillage in no-tillage systems: a global meta-analysis. Sci. Total Environ. 745, 140887.

Ramos, M.E., Robles, A.B., Sanchez-Navarro, A., Gonzalez-Rebollar, J.L., 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112, 85–91.

Reganold, J.P., Palmer, A.S., 1995. Significance of gravimetric versus volumetric measurements of soil quality under biodynamic, conventional, and continu- ous grass management. Journal of Soil and Water Conservation 50, 298–305.

Shan, H., Yan-Ni, S., Wen-Yi, R., Wu-Ren, L., Wei-Jian, Z., 2010. Long-term effect of no-tillage on soil organic carbon fractions in a continuous maize cropping system of northeast China. Soil Science Society of China 20 (3), 285–292.

Shan, H., Yan-Ni, S., Wen-Yi, R., Wu-Ren, L., Wei-Jian, Z., 2010. Long-term effect of no-tillage on soil organic carbon fractions in a continuous maize cropping system of northeast China. Soil Science Society of China 20 (3), 285–292.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota and soil organic matter dynamics. Soil and Tillage Research 79, 7–31.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no tillage agriculture. Soil Biology and Biochemistry 32, 2099–2103.

Thomas, G.A., Dalal, R.C., Standley, J., 2007. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil and Tillage Research 94, 295–304.

Wander, M.M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F., Weil, R. (Eds.), Advances in Agroecology. CRC Press, Boca Raton, FL, pp. 67–102.

Wander, M.M., Traina, S.J., Stinner, B.R., Peters, S.E., 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Science Society of America Journal 58, 1130–1139.

Wolfarth, F., Schrader, S., Oldenburg, E., Weinert, J., Brunotte, J., 2011. Earthworms promote the reduction of Fusariumbiomass and deoxynivalenol content in wheat straw under field conditions. Soil Biology and Biochemistry 43, 1858–1865.

CHAPTER 8

EFFECTS OF CLIMATE CHANGE ON PHYTOPATHOGENS AND HOST-PATHOGENS RELATIONSHIPS

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INTRODUCTION

During cultivation, plants are exposed to many microorganisms, some of which have the ability to cause diseases, leading to serious losses. These exposed disease agents and pests cause serious product losses and are also widespread due to the effect of abiotic environmental factors (Islamoğlu, 2021a, 2021b, 2024). Global climate changes, pioneered by human activities, have now become an accepted phenomenon all over the world. There have recently been serious increases in the average temperatures in the atmosphere and the temperatures detected on the surface and in the seas. These serious increases in temperatures have significantly accelerated the hydrological cycle, allowing for the formation of heat waves, storm formation and floods with heavy rainfall (IOM, 2008; Sheffield et al., 2012).

Climate change has become a significant potential threat to the survival of people along with agricultural production (İslamoğlu, 2023). In addition, it creates multifaceted effects on the spread, severity and emergence of plant diseases, affecting dynamics such as pathogen evolution, host-pathogen relationships and the formation of new pathogenic variants. Changing environmental conditions can trigger the adaptation processes of pathogens, paving the way for them to adapt to new environments and the re-emergence of controlled diseases. However, climate change can affect not only disease spread but also the virulence levels of pathogens (Singh et al., 2023). Considered one of the greatest threats on a global scale, climate change causes economic and human losses; it causes approximately 1.2 trillion US dollars in material damage and 400 thousand agricultural-related deaths annually. The increase in average temperature by 0.74°C in the last century and the increase in atmospheric CO_2 levels from 280 ppm in 1750 to 418 ppm in 2022 have increased the pressure on the agricultural sector (EPA, 2023). Such changes directly affect the development and yield of many agricultural products; while at the same time, they change the biological cycle, distribution areas and severity of diseases (Moullec et al., 2019). In this context, the need for the development of new and durable agricultural products is increasing. However, the development process of such products requires a long time, on average 20 years (Sreenivas, 2022).

The transformations caused by climatic changes in agricultural and ecological systems bring not only crop losses but also wider ecosystem problems such as loss of biodiversity (Kashyap et al., 2018; Singh et al., 2023). Therefore, understanding the complexity of disease dynamics due to climate change is of great importance to sustain both ecosystem health and food security. Increased temperatures have been reported to expand the geographical distribution of wheat stem rust agents such as *Puccinia graminis* f. sp. *tritici* (Singh et al., 2023). On the other hand, the extinction of *Triphragmium ulmarie*, a parasite on *Filipendula ulmaria*, has been documented in some regions due to increasing summer temperatures over a 30-year period (Zhan et al., 2018).

Climate projections predict that extreme events such as storms, droughts, and heat waves will occur more frequently, and that plant diseases will increase in various regions (Cook et al., 2016). Such climatic factors can affect the susceptibility of hosts to diseases, leading to serious changes in agricultural production (Moullec et al., 2019). Global warming, in particular, can disrupt plant development and cause serious crop losses, together with changes in average temperatures, precipitation patterns, and drought periods (Ebi et al., 2016). Such environmental stresses make plants more vulnerable to pathogens and increase the risk of infection (Devendra, 2012). While pathogens develop different virulence strategies to overcome the defenses of host plants, plants also activate defense responses against these attacks (Olori-Great and Opara, 2017; Doehlemann et al., 2017). For example, the defense response of avocado fruit against *Colletotrichum gloesporioides* with epicatechin compound is an example of these interactions (Djami-Tchatchou et al., 2013).

Abiotic stress factors such as salinity, drought and high temperature complicate plant-pathogen interactions by affecting both pathogen virulence and host defense (Sun et al., 2021; Adhikari et al., 2013). Understanding these processes is of great importance for the development of cultivars resistant to climate change, the implementation of new control methods and the adoption of integrated disease management systems (Chakraborty and Newton, 2011; Desai et al., 2021). The development of predictive modeling approaches has become a great necessity, especially in order to predict the severity of diseases in field conditions. In addition, it is inevitable for sustainable food production systems to be integrated with strong disease control strategies (Singh et al., 2023). In this context, greenhouse gas emissions, deforestation and various anthropogenic activities, which are among the main causes of climate change, are seen to significantly alter plant health and pathogen dynamics by affecting environmental parameters such as temperature and soil pH.

1. FUNDAMENTALS AND MECHANISMS OF CLIMATE CHANGE

Climate change occurs due to the combined effects of both natural processes and human activities (fossil fuel consumption, deforestation, agriculture). These activities accelerate the accumulation of greenhouse gases such as CO_2, CH_4, N_2O, HFC, PFC and SF_6 in the atmosphere (IPCC, 1995). Tropical deforestation reduces carbon storage capacity and increases CO_2 emissions while expanding agricultural land (Hunjan and Lore, 2020). In addition, agricultural practices such as fertilization and pesticide use also increase greenhouse gas emissions (Nda et al., 2018).

Increasing greenhouse gases cause global temperatures to rise, precipitation patterns to deteriorate, and the frequency of extreme weather events to increase. This situation has been confirmed by the IPCC and paves the way for radical changes in the dynamics of plant diseases (Kabir et al., 2023; Trenberth, 2018).

2. BASIC CLIMATE VARIABLES AND PHYTOPATHOGENE INTERACTIONS

2.1 *Temperature*

Temperature is one of the most important environmental factors affecting plant physiology and development, and it also affects the life cycles, spread and pathogenicity of pathogens seen in plants (Hunjan and Lore, 2020). Along with all these factors, temperature changes determine many factors such as the speed, duration, sporulation and spread of existing inoculums caused by pathogens (Kweku et al., 2019). Increasing temperatures, especially encourage the proliferation of fungal and bacterial pathogens, and weaken the host's defense mechanism (Chaloner et al., 2021; Devi et al., 2022). For example, wheat rust epidemics are more common with temperature (Charaya et al., 2021; Singh et al., 2023).

2.2 *Rainfall*

While rainfall is one of the most important factors affecting the availability of water and nutrients, it is also an important environmental factor affecting soil moisture, pH, pesticide leaks in the soil, surface runoff, and the presence and spread of inoculum produced by the pathogen (Chen et al., 2023). Increasing rainfall causes the development and spread of diseases caused by fungi, especially oomycete fungi (Beyer et al., 2022; Dutta et al., 2020; Lim et al., 2023). While excessive rainfall makes control measures difficult, drought increases the dependence on irrigation with the decrease in rainfall and can prepare suitable ground for some bacterial (e.g. *Erwinia tracheiphila*) and nematode-borne diseases (e.g. *Meloidogyne* spp.) (Lim et al., 2023; Erayya et al., 2023).

2.3. *Humidity*

Humidity is an important environmental factor affecting processes such as evaporation and transpiration in host plants and the infection and survival of plant pathogens (Dixit et al., 2023) and creating the necessary water source for the pathogen (Nath, 2021). High humidity increases spore germination, infection rate and post-storage disease risks. For example, gray mold (*Botrytis cinerea*) and anthracnose (*Colletotrichum* spp.) (Ji et al., 2021; Moradinezhad and Ranjbar, 2023), scab (*Streptomyces scabies*) (Maurya et al., 2022) spread thanks to this. In addition, decreasing humidity affects the quality and quantity of pollen and nectar, as well as the pollination and reproduction of plants (Biella et al., 2022).

2.4 *Extreme Weather Events*

While extreme weather events cause physical damage, physiological stress and some biochemical changes in host plants (Singh et al., 2023), extreme events such as storms, temperature increases, frost events and hail disrupt the physical integrity of the plant and lead to pathogen entry. They also accelerate the spread of vectors such as aphids (Hong et al., 2021; Gullino et al., 2022; Bastas, 2022). Hot and cold air waves can cause heat and oxidative stress, disrupt photosynthesis and respiration, and make pathogens such as leaf spots and black rot more susceptible (Rivero et al., 2022; Tanveer et al., 2023)

2.5 *Solar Radiation and Wind*

Radiation generated by the sun can affect the increase and spread of plant diseases (Bornman et al., 2015). While UV radiation inactivates some pathogen spores (Campillo et al., 2012), wind facilitates long-distance spread by accelerating spore and inoculum transport (Krafft et al., 2019). For example, Cercospora leaf spot, an important leaf disease of beets, and gray mold in strawberries could be prevented as a result of exposure to UV light (Deepshikha et al., 2017). Changes in wind patterns have effects on light penetration and nutrient distribution, which are important for plant development. These effects increase pathogen outbreaks by providing the necessary conditions for the development and spread of plant disease agents (Deng et al., 2018). Strong winds, on the other hand, cause physical damage to plants, allowing pathogens to enter these damaged tissues (Krafft et al., 2019). For example, while powdery mildew and rust fungi infect cereals in this way (El Jarroudi et al., 2020), *Xanthomonas axonopodis* pv. *citri* (citrus canker) allows the inoculum to be spread by wind (Esker et al., 2007).

3. CHANGES OBSERVED IN THE DYNAMICS OF PHYTOPATHOGENS

While the effects of these changing climate events on a small number of host-pathogen relationships have been identified (Overstreet, 2007), it is known that drought in particular has significant effects on the formation of parasitic diseases (Figure 1).

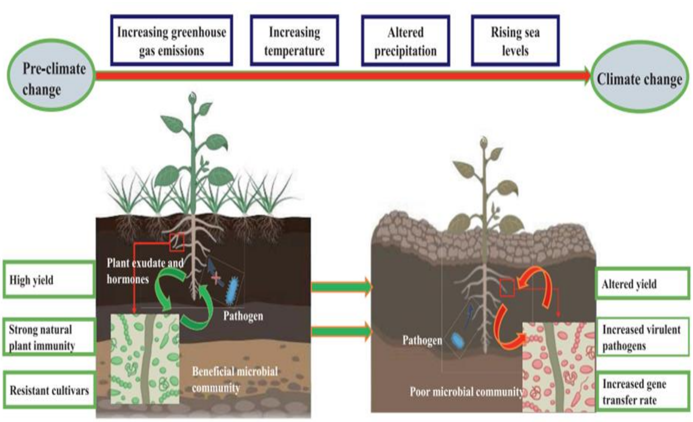

Fig. 1. Impact of climate change on plant-pathogen interactions (Lahlali et al., 2024).

With the increases in plant diseases, global food security and environmental sustainability are under threat and are weakening primary productivity and biodiversity on a global scale. With climate change, phytopathogens are spreading to new geographies, more aggressive strains are emerging and epidemic risk is increasing (Singh et al., 2023), changing the sensitivity of the host, and affecting the development and survival rates of pathogens. As a result, it is obvious that these will cause problems in obtaining healthy products. In addition to these, it is thought that the specific pathogen mechanism and suitable infection conditions, host specificity and infection mechanism will also be affected (Elad and Pertot, 2014). Models show that increasing temperature may increase pathogen pressure, especially at high latitudes (Myers et al., 2021; Kumar and Mukhopadhyay, 2024) (Figure 2).

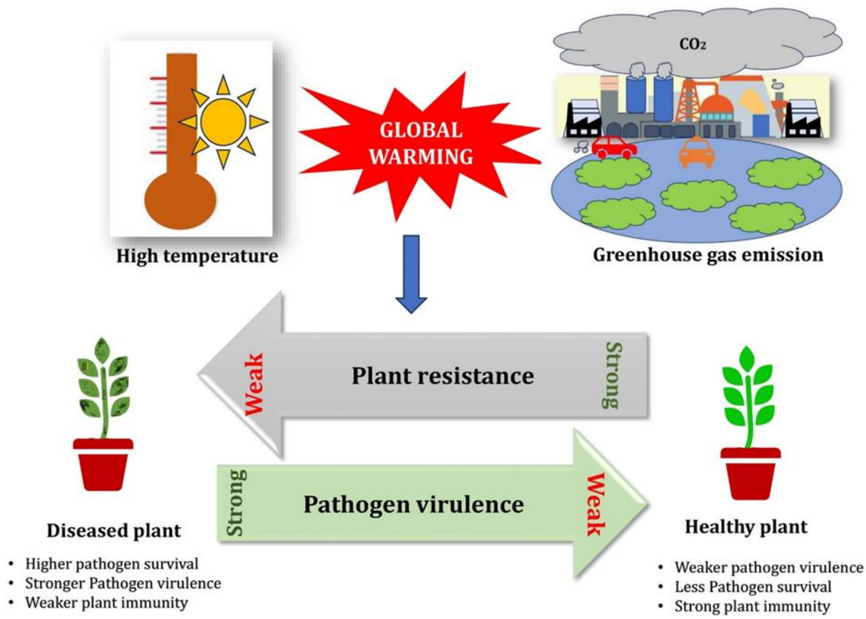

Fig.2. Potential shifts in plant pathogen interactions caused by climate change (Kumar and Mukhopadhyay, 2025)

4. CHANGING BALANCES IN HOST-PATHOGEN INTERACTIONS

Climate changes observed on a global scale cause changes in basic environmental factors and create significant effects on plant ecosystems. Some factors such as temperature, sunlight duration, precipitation and availability of nutrients (e.g. nitrogen, phosphorus and potassium) are very important in determining plant development. With these changes, CO_2 levels accelerate plant development by increasing photosynthesis. Again, increasing CO_2 levels, high temperatures and disruptions in precipitation patterns cause changes in the size, structure, density and microclimate of plant development. Increasing temperatures and changing precipitation also affect pests and pathogens (Dutta et al., 2023; Pangga et al., 2013) (Figure 3).

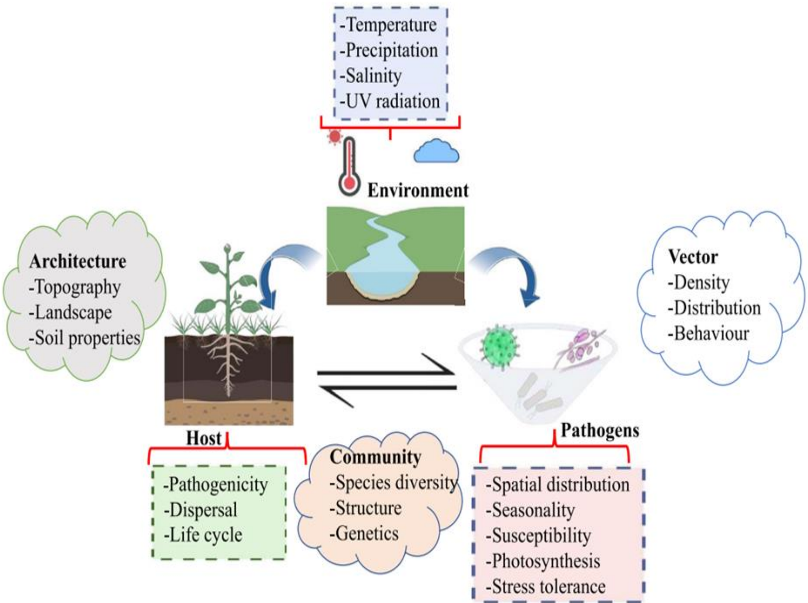

Fig. 3. Climate change factors triggering the interaction between host plants and plant pathogens (Lahlali et al., 2024).

5. EFFECTS OF CO_2 AND O_3

High CO_2 can increase photosynthesis and carbohydrate accumulation while preventing pathogen entry through stomatal closure. O_3 can cause biomass and yield reductions, while it can be balanced by the effect of CO_2 (Manning and Tiedemann, 1995; Sandermann, 1996). The combined effect of these gases modifies the expression of SUV defense pathways and the capacity to resist pathogens in a complex manner (Campillo et al., 2012).

6. THE ROLE OF NUTRIENTS ON THE HOST-PATHOGENE BALANCE

6.1 *Phosphate*

It has been determined that *Colletotrichum tofieldiae*, an endophytic fungus, transfers phosphate to *Arabidiopsis* and increases the development and yield of the plant (Hiruma et al., 2016).

6.2 *Nitrogen*

The energy cost of *Rhizobium* nodulation in legumes is optimized according to the nitrogen saturation of the environment (Takahara et al., 2013; Tsikou et al., 2018). However, it is known that forming nodules is costly in terms of energy for the legume host. Therefore, it is thought that it will not be very effective in terms of cost when plants are grown in an environment rich in nitrogen (Morgan et al., 2005).

6.3 *Iron*

In iron deficiency, the ISR mechanism is activated through molecules such as phenolic metabolites and compounds that enable the movement of iron; this makes an important contribution to the suppression of the pathogen (Van der Ent et al., 2008; Zamioudis et al., 2014).

CONCLUSION

Climate change is reshaping the interaction balance of phytopathogens and host plants in a complex way through environmental factors such as temperature, humidity, precipitation, CO_2 and O_3. This situation poses serious risks to agricultural yield, food security and ecosystem health. In order to cope with these potential threats, climate-adaptive plant breeding, integrated disease management, awareness and policy-supported strategy integrations are needed (Coakley et al., 1999; Chakraborty, 2011; Kumar and Mukhopadhyay, 2024). Climate change is radically changing the interactions between plants and pathogens both through direct environmental effects and indirect mechanisms. Factors such as temperature increase, deviations in precipitation patterns and changes in atmospheric gas concentrations are reshaping both the life cycles of pathogens and the physiological responses of host plants. These conditions can lead to the spread of pathogens to new areas, faster and more severe infections and the reemergence of some diseases.

The increase in gases such as carbon dioxide (CO_2) and ozone (O_3) in the atmosphere directly affects plant development, in some cases reducing resistance to diseases and in some conditions limiting pathogen development. However, these effects are not linear or always predictable; each plant-pathogen interaction can respond differently to environmental variables. For this reason, interdisciplinary and systems approach studies are of great importance in order to fully understand the effects of climate change. While currently developed epidemiological models generally evaluate biotic and abiotic factors separately, it is known today that even microscale climatic effects significantly shape plant-pathogen interactions. In this context, supporting next-generation prediction models with multi-layered and integrated data systems will enable the creation of more effective strategies in terms of both scientific accuracy and agricultural disease management. The negative effects of climate change not only on agricultural productivity but also on ecosystem balance and biodiversity should be taken into consideration. In this direction, not only the development of climate-resistant plant species; At the same time, integrated disease management, agroecological approaches and the expansion of sustainable agricultural systems should also be among the strategic priorities.

As a result, the effects of climate change on plant diseases are one of the main factors that will shape future agricultural production patterns and the sustainability of food systems. Therefore, focusing scientific research on climate-based disease predictions and integrating the obtained data into decision-making processes is a critical need for both food security and the protection of ecosystem health.

REFERENCES

Adhikari, B.N., Hamilton, J.P., Zerillo, M.M., Tisserat, N., Levesque, C.A., Buell, C.R. (2013). Comparative genomics reveals insight into virulence strategies of plant pathogenic oomycetes. PLoS One 8, e75072.

Bastas, K.K. (2022). Impact of climate change on food security and plant disease. In: Kumar, A. (Ed.), Microbial Biocontrol: Food Security and Post Harvest Management. Springer, Cham, Switzerland, pp. 1–22.

Bergot, M., Cloppet, E., P erarnaud, V., Deque, M., Marçais, B., Desprez-Loustau, M.L. (2004). Simulation of potential range expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. Biol. 10, 1539–1552. https://doi.org/ 10.1111/j.1365-2486.2004.00824.x.

Beyer, M., Pallez-Barthel, M., Dam, D., Hoffmann, L., El Jarroudi, M. (2022). Enhancing septoria leaf blotch forecasts in winter wheat I: the effect of temperature on the temporal distance between critical rainfall periods and the breaking of the control threshold. *J. Plant Dis*. *Prot.* 129, 37–44.

Biella, P., Tommasi, N., Guzzetti, L., Pioltelli, E., Labra, M., Galimberti, A. (2022). City climate and landscape structure shape pollinators, nectar and transported pollen along a gradient of urbanization. *J. Appl. Ecol*. 59, 1586–1595.

Bornman, J.F., Barnes, P.W., Robinson, S.A., Ballar e, C.L., Flint, S.D., Caldwell, M.M. (2015). Solar ultraviolet radiation and ozone depletion-driven climate change: effects on terrestrial ecosystems. *Photochem. Photobiol. Sci*. 14, 88–107.

Campillo, C., Fortes, R., Prieto, M.H., Babatunde, E.B. (2012). Solar radiation effect on crop production. In: Babatunde, E.B. (Ed.), Solar Radiation. IntechOpen, London, UK, pp. 167–194.

Chakraborty, S., Newton, A.C. (2011). Climate change, plant diseases and food security: an overview. *Plant Pathol.*, 60, 2–14. https://doi.org/10.1111/j.1365-3059.2010.02411.x.

Charaya, M.U., Upadhyay, A., Bhati, H.P., Kumar, A. (2021). Plant disease forecasting: past practices to emerging technologies. In: Nehra, S. (Ed.), Plant Disease Management Strategies. *Agrobios Research*, Rajasthan, India, pp. 1–30.

Chaloner, T.M., Gurr, S.J., Bebber, D.P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. *Nat. Clim. Change* 11, 710–715. https://doi.org/10.1038/s41558-021-01104-8.

Chen, W., Modi, D., Picot, A. (2023). Soil and phytomicrobiome for plant disease suppression and management under climate change: a review. *Plants*, 12, 2736.

Coakley, S.M., Scherm, H., Chakraborty, S. (1999). Climate change and plant disease management. *Annual Review of Phytopathology*. Sep; 37:399–426. DOI:10.1146/annurev.phyto.37.1.399

Cook, J., Oreskes, N., Doran, P.T., Anderegg, W.R.L., Verheggen, B., Maibach, E.W., Carlton, J.S., Lewandowsky, S., Skuce, A.G., Green, S.A., Nuccitelli, D., Jacobs, P., Richardson, M., Winkler, B., Painting, R., Rice, K. (2016). Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environ. Res. Lett*. 11, 48002.

Deepshikha Kumari, B., Devi, E.P., Sharma, G., Rawat, S., Jaiswal, J.P. (2017). Irradiation as an alternative method for post-harvest disease management: an overview. *Int. J. Agric. Environ. Biotechnol*., 10, 625–633.

Deng, J., Zhang, W., Qin, B., Zhang, Y., Paerl, H.W., Salmaso, N. (2018). Effects of climatically-modulated changes in solar radiation and wind speed on spring phytoplankton community dynamics in Lake Taihu, China. PLoS One 13, e0205260

Desai, S., Dubey, S.C., Taduri, M., Sultana, U., Pinisetty, S. (2021). Crop disease management strategies for rainfed cropping systems under changing climate scenarios. *Indian Phytopathol*., 74, 485–494. https://doi.org/10.1007/s42360-021- 00339-x

Devendra, C. (2012). Climate Change Threats and Effects: Challenges for Agriculture and Food Security. Academy of Sciences Malaysia, Kuala Lumpur, Malaysia.

Devi, R., Kaur, T., Kour, D., Yadav, A., Yadav, A.N., Suman, A., Ahluwalia, A.S., Saxena, A.K. (2022). Minerals solubilizing and mobilizing microbiomes: A sustainable approach for managing minerals' deficiency in agricultural soil. *J. Appl. Microbiol*., 133, 1245–1272. https://doi.org/10.1111/JAM.15627

Dixit, S., Sivalingam, P.N., Murali-Baskaran, R.K., Senthil-Kumar, M., Ghosh, P.K. (2023). Plant responses to concurrent abiotic and biotic stress: unravelling physiological and morphological mechanisms. *Plant Physiol. Rep*., 29, 6–17.

Djami-Tchatchou, A.T., Allie, F., Straker, C.J. (2013). Expression of defence-related genes in avocado fruit (cv. Fuerte) infected with Colletotrichum gloeosporioides. *S. Afr. J. Bot*., 86, 92–100.

Doehlemann, G., Okmen, B., Zhu, W., Sharon, A. (2017). Plant pathogenic fungi. *Microbiol. Spectr*. 5, 1–23

Dutta, S., Kamei, A., Goldar, S., Datta, G., Bharati, D.R.S., Ghorai, A.K., Pathak, S., Roy Barman, A., Jash, S., Ray, S.K. (2020). Influence of weather variables on spore biology of Corynespora cassiicola, an incitant of target leaf spot disease of tomato. *Arch. Phytopathol. Plant Protect.*, 53, 127–140.

Ebi, K.L., Ziska, L.H., Yohe, G.W. (2016). The shape of impacts to come: lessons and opportunities for adaptation from uneven increases in global and regional temperatures. *Clim. Change*, 139, 341–349.

Elad, Y., Pertot, I. (2014). Climate change impacts on plant pathogens and plant diseases. *J. Crop Improv*. 28, 99–139. https://doi.org/10.1080/15427528.2014.865412.

El Jarroudi, M., Karjoun, H., Kouadio, L., El Jarroudi, M. (2020). Mathematical modelling of non-local spore dispersion of wind-borne pathogens causing fungal diseases. *Appl. Math. Comput*., 376, 125107

EPA (U.S. Environmental Protection Agency), (2023). Climate Change Impacts on Agriculture and Food Supply.

Erayya, S.S., Managanvi, K., Kumar, S., Alipatra, A. (2023). Emerging diseases of vegetables due to changing climate. In: Solankey, S.S., Kumari, M. (Eds.), Advances in Research on Vegetable Production Under a Changing Climate, Vol. 2. Springer, Cham, Switzerland, pp. 323–340.

Esker, P.D., Sparks, A.H., Antony, G., Bates, M., Dall'Acqua, W., Frank, E.E., Huebel, L., Segovia, V., Garrett, K.A. (2007). Ecology and Epidemiology in R: Modeling Dispersal Gradients. *The American Phytopathological Society*, USA.

Gullino, M.L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K.A., Hurley, B.P., Juroszek, P., Lopian, R., Makkouk, K., Pan, X., Pugliese, M., Stephenson, T. (2022). Climate change and pathways used by pests as challenges to plant health in agriculture and forestry. *Sustainability*, 14, 12421.

He, Y., Zhuang, H., Xu, J., Luo, X., & Wang, X. (2022). "Temperature-sensitive CBP60g modulates plant immunity by regulating salicylic acid biosynthesis under high temperature." *Nature Communications*, 13, 1292. https://doi.org/10.1038/s41467-022-28903-2

Hiruma, K., Gerlach, N., Sacrista´ n, S., Nakano, R.T., Hacquard, S., Kracher, B., Neumann, U., Ramı´rez, D., Bucher, M., O'Connell, R.J., and Schulze-Lefert, P (2016). Root endophyte *Colletotrichum tofieldiae* confers plant fitness benefits that are phosphate status dependent. *Cell*, 165, 464–474.

Hong, C., Hansen, M.A., Bush, E.A., Day, E.R., Del-Pozo, A., Derr, J.F. (2021). Home Grounds and Animals PMG-Home Ornamentals. Virginia Cooperative Extension, Fergie, USA

Hunjan, M.S., Lore, J.S. (2020). Climate change: impact on plant pathogens, diseases, and their management. In: Jabran, K., Florentine, S., Chauhan, B. (Eds.), *Crop Protection Under Changing Climate*. Springer, Cham, Switzerland, pp. 85–100

IOM (2008). Global Climate Change and Extreme Weather Events: Understanding the Contributions to Infectious Disease Emergence. The National Academies Press, Washington, DC.

IPCC (The Intergovernmental Panel on Climate Change) (1995). IPCC Second Assessment Report. http://www.ipcc.ch.

İslamoğlu, M. (2021a). Sürdürülebilirlik için Gıda, Çevre, Tarımsal Ormancılık ve Tarımda Yeni Araştırmalar. Gelişen Dünyada Biyolojik Mücadelenin Yeri ve Önemi, Edited by: K. Bellitürk, M.F. Baran ve A. Çelik İKSAD Yayınevi. ISBN: 978-625-7562-28-7.

İslamoğlu, M. (2021b). Agrıcultural Researches Resourcebook. The Place and Importance of Biological Control in Turkey and Some Application Examples. Edited by: A. Çelik, K. Bellitürk ve M.F. Baran. İKSAD Yayınevi.

İslamoğlu, M. (2023). Tarım Bilimlerinde Yenilikçi Multidisipliner Yaklaşımlar. İklim Değişikliklerinin Bitki Zararlılarına Potansiyel Etkileri. Edited by: M. Avan. İKSAD Yayınevi.

İslamoğlu, M. (2024). Gelecekte Tarım ve İnovasyon. Böceklerin Olumsuz Abiyotik Çevre Koşullarına Adaptasyon Yetenekleri –I. Edited by: M.F. Baran ve A. Çelik. İKSAD Yayınevi.

Ji, T., Salotti, I., Dong, C., Li, M., Rossi, V. (2021). Modeling the effects of the environment and the host plant on the ripe rot of grapes, caused by the *Colletotrichum* species. *Plants*, 10, 2288.

Kabir, M., Habiba, U.E., Khan, W., Shah, A., Rahim, S., De los Rios-Escalante, P.R., Farooqi, Z.U.R., Ali, L., Shafiq, M. (2023). Climate change due to increasing concentration of carbon dioxide and its impacts on environment in 21st century; a mini review. *J. King Saud Univ. Sci*., 35, 102693. https://doi.org/10.1016/ j.jksus.2023.102693.

Kashyap, P.L., Srivastava, A.K., Tiwari, S.P., Kumar, S. (2018). Microbes nanotechnology for climate resilient agriculture. In: Kashyap, P.L., Srivastava, A.K., Tiwari, S.P., Kumar, S. (Eds.), *Micorbes for Climate Resilient Agriculture*, Wiley, Hoboken, USA, pp. 279–344

Kennedy, C.R. (1998). Aquatic birds as agents of parasite dispersal: a field test of the effectiveness of helminth colonisation strategies. *Bull. Scand. Soc. Parasitol*., 8, 23–28.

Krafft, C., Volokitin, A.S., Gauthier, G. (2019). Turbulence and microprocesses in inhomogeneous solar wind plasmas. *Fluids*, 4, 69. https://doi.org/10.3390/ fluids4020069

Kumar, D., Mukhopadhyay, R. (2025). Climate change and plant pathogens: Understanding dynamics, risks and mitigation strategies. *Plant Pathology*, (Wiley). 2024 Nov; (Early View). DOI:10.1111/ppa.14033

Kweku, D., Bismark, O., Maxwell, A., Desmond, K., Danso, K., Oti-Mensah, E., Quachie, A., Adormaa, B. (2019). Greenhouse effect: greenhouse gases and their impact on global warming. *J. Sci. Res. Rep*. 17, 1–9. https://doi.org/10.9734/jsrr/2017/39630

Lahlali, R., Taoussi, M., Laasli, S. E., Gachara, G., Ezzouggari, R., Belabess, Z., ... & Ait Barka, E. (2024). Effects of climate change on plant pathogens and host-pathogen interactions. *Crop and Environment*, 3(3), 159-170.

Lim, J.A., Yaacob, J.S., Mohd Rasli, S.R.A., Eyahmalay, J.E., El Enshasy, H.A., Zakaria, M.R.S. (2023). Mitigating the repercussions of climate change on diseases affecting important crop commodities in Southeast Asia, for food security and environmental sustainability-A review. Front. Sustain. *Food Syst*. 6, 1030540

Maurya, M.K., Yadav, V.K., Singh, S.P., Jatoth, R., Singh, H.K., Singh, D. (2022). Impact of climate change on diseases of crops and their management-a review. *J. Agric. Sci. Technol*. B 12, 1–15

Moradinezhad, F., Ranjbar, A. (2023). Advances in postharvest diseases management of fruits and vegetables: a review. *Horticulturae*, 9, 1099.

Morgan, J.A.W., Bending, G.D., and White, P.J. (2005). Biological costs and benefits to plant-microbe interactions in the rhizosphere. *J. Exp. Bot*., 56, 1729–1739

Moullec, F., Barrier, N., Drira, S., Guilhaumon, F., Marsaleix, P., Somot, S., Ulses, C., Velez, L., Shin, Y.J. (2019). An end-to-end model reveals losers and winners in a warming Mediterranean Sea. *Front. Mar. Sci*., 6, 345.

Myers, T.A., Scott, R.C., Zelinka, M.D., Klein, S.A., Norris, J.R., Caldwell, P.M. (2021). Observational constraints on low cloud feedback reduce uncertainty of climate sensitivity. *Nat. Clim. Change*, 11, 501–507.

Nath, S. (2021). Dew as source of emerging contaminants in agricultural system. In: Sustainable Agriculture Reviews 50. Springer, Cham, Switzerland, pp. 61–78

Lim, J.A., Yaacob, J.S., Mohd Rasli, S.R.A., Eyahmalay, J.E., El Enshasy, H.A., Zakaria, M.R.S. (2023). Mitigating the repercussions of climate change on diseases affecting important crop commodities in Southeast Asia, for food security and environmental sustainability-A review. *Front. Sustain. Food Syst*., 6, 1030540.

Olori-Great, N.G., Opara, E.U. (2017). Defence mechanisms in plants against invading plant pathogenic microbes in Nigeria. *J. Agric. Sustain*., 10, 80–96.

Overstreet, R.M. (2007). Effects of a hurricane on fish parasites. *Parassitologia*, 49, 161–168.

Manning, W.J., Tiedemann, A.V. (1995). Climate change: potential effects of increased atmospheric carbon dioxide (CO2), ozone (O3), and ultraviolet-B (UV-B) radiation on plant diseases. *Environmental Pollution*, 88, 219–45.

Nda, M., Adnan, M.S., Ahmad, K.A., Usman, N., Razi, M.A.M., Daud, Z. (2018). A review on the causes, effects and mitigation of climate changes on the environmental aspects. *Int. J. Integr. Eng.*, 10, 169–175. https://doi.org/10.30880/ijie.2018.10.04.027

Pangga, I.B., Hanan, J., Chakraborty, S. (2013). Climate change impacts on plant canopy architecture: implications for pest and pathogen management. *Eur. J. Plant Pathol.*, 135, 595–610. https://doi.org/10.1007/s10658-012-0118-y.

Rivero, R.M., Mittler, R., Blumwald, E., Zandalinas, S.I. (2022). Developing climate resilient crops: improving plant tolerance to stress combination. *Plant J.*, 109, 373–389

Sandermann, H. (1996). Ozone and plant health. *Annual Review of Phytopathology*, 34, 347–66.

Sheffield, J., Wood, E.F., Roderick, M.L. (2012). Little change in global drought over the past 60 years. *Nature*, 491, 435–438.

Singh, B.K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J.E., Liu, H., Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. *Nat. Rev. Microbiol.*, 21, 640–656.

Sreenivas, S. (2022). Impact of climate change on crop-pathogen interaction: a review. *Int. J. Adv. Agric. Sci. Technol.*, 9, 1–4. https://doi.org/10.4.

Sun, C., Huang, Y., Lian, S., Saleem, M., Li, B., Wang, C. (2021). Improving the biocontrol efficacy of Meyerozyma guilliermondii Y-1 with melatonin against postharvest gray mold in apple fruit. Postharvest *Biol. Technol.*, 171, 111351. https://doi.org/ 10.1016/j.postharvbio.2020.111351.

Szidat, L. (1968). Uber die Beziehungen zwischen sonnenflecken-zyklen und para sitar bedingten massensterben von wirbellosen und wirbeltieren. *Z. Parasi tenkd.*, 30, 1–17.

Takahara, M., Magori, S., Soyano, T., Okamoto, S., Yoshida, C., Yano, K., Sato, S., Tabata, S., Yamaguchi, K., Shigenobu, S., et al. (2013). Too much love, a novel Kelch repeat-containing F-box protein, functions in the long-dis tance regulation of the legume-Rhizobium symbiosis. *Plant Cell Physiol.*, 54, 433–447.

Tanveer, M., Mahmood, A., Sarfraz, B., Zia, M.A., Javaid, M.M., Bibi, S., Naqve, M., Nadeem, M.A., Azeem, M., Jabbar, A. (2023). Mechanism and approaches to enhancing heat stress tolerance in crop plants. In: Hasanuzzaman, M. (Ed.), Climate Resilient Agriculture, Vol 2: *Agro-Biotechnological Advancement for Crop Production*. Springer, Cham, Switzerland, pp. 499–520

Trenberth, K.E. (2018). Climate change caused by human activities is happening and it already has major consequences. *J. Energy Nat. Resour. Law* 36, 463–481. https:// doi.org/10.1080/02646811.2018.1450895.

Tsikou, D., Yan, Z., Holt, D.B., Abel, N.B., Reid, D.E., Madsen, L.H., Bhasin, H., Sexauer, M., Stougaard, J., and Markmann, K. (2018). Systemic control of legume susceptibility to rhizobial infection by a mobile microRNA. *Science*, 362, 233–236.

Van der Ent, S., Verhagen, B.W.M., Van Doorn, R., Bakker, D., Verlaan, M.G., Pel, M.J.C., Joosten, R.G., Proveniers, M.C.G., Van Loon, L.C., Ton, J., and Pieterse, C.M. (2008). MYB72 is required in early signaling steps of rhizobac teria-induced systemic resistance in Arabidopsis. *Plant Physiol*., 146, 1293–1304.

Zamioudis, C., Hanson, J., and Pieterse, C.M.J. (2014). b-Glucosidase BGLU42 is a MYB72-dependent key regulator of rhizobacteria-induced sys temic resistance and modulates iron deficiency responses in Arabidopsis roots. *New Phytol*., 204, 368–379.

Zhan, J., Ericson, L., Burdon, J.J. (2018). Climate change accelerates local disease extinction rates in a long-term wild host–pathogen association. *Glob. Change Biol*., 24, 3526–3536.

CHAPTER 9

NON-NATIVE PLANT SPECIES, ECOSYSTEM SERVICES, AND AGRO-ECOSYSTEM RESILIENCE IN TURKEY UNDER CLIMATE CHANGE

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INTRODUCTION

Invasive non-native species are regarded as the main driver of global environmental change (Didham et al., 2005), contributing to biodiversity decline (Butchart et al., 2010; Gentili et al., 2021) and economic losses (Diagne et al., 2021; Haubrock et al., 2021; Macêdo et al., 2024). A recent evaluation by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) indicated that invasive alien species (IAS) have significantly contributed to 60% recorded plant and animal extinctions globally (Roy et al., 2023) and are responsible for over US$423 billion in annual economic losses (Roy et al., 2023).

Turkey sits at the crossroads of Europe and Asia, serving as a crucial biodiversity hotspot (Mittermeier et al., 2011; Şekercioğlu et al., 2011). Nevertheless, introduction and spread of non-native plant species is a growing concern in the country (Byfield & Baytop, 1998; Sevgi et al., 2017; Uludag et al., 2017). The increased pressure on native ecosystems and opportunities for the spread of some non-native species due to changes in temperature and precipitation complicates the issue (Farooq et al., 2017; Onen, Farooq, et al., 2016; Onen, Sarı, et al., 2016; Onen & Farooq, 2015). Consequently, it is essential to evaluate the benefits of some exotic plants to ecosystems (including food production, erosion management, or habitat restoration) against the threats that invasive species bring to Turkey's agricultural systems and cultural heritage. This chapter examines exotic plant species in Turkey and their impact on the resilience of agro-ecosystems to climate change and other ecosystem services. Recent policy and scientific developments inform sustainable management strategies that mitigate damage while optimizing resource use.

Non-Native Plant Species in Turkey: An Overview

Turkey’s unique geographic location and varied climatic zones have traditionally enabled the cultivation and accidental introduction of several exotic plant species. The country hosts over 12,000 vascular plant species, with an estimated 1.5–3% classified as alien (non-native) species (Arslan et al., 2015; Barneby et al., 1986; Güner & Aslan, 2012). This indicates around 180–360 non-native plant species documented in Turkey’s flora (Uludag et al., 2017). Not all these alien species are invasive or harmful; many are isolated or harmless. Nonetheless, a portion has emerged as invasive alien species, spreading rapidly and exerting significant impacts on ecosystems or agriculture (Onen et al., 2017; Ozaslan et al., 2016). A thorough inventory conducted in the 2010s found around 80–100 invasive alien plant species in Turkey, with additional species constantly being recorded as botanical surveys progress (Arslan et al., 2015). The occurrence of invasive plants in Turkey has been documented in scientific literature since at least the 1960s; nevertheless, systematic national monitoring of these species has only recently increased (Atasoy & Çorbacı, 2018).

Non-native flora has been introduced through numerous pathways (Yazlık & Ambarlı, 2022). Certain species were intentionally imported for agricultural, horticultural, forestry, or soil improvement purposes. Sunflower (*Helianthus annuus*) and maize (*Zea mays*), now major crops in Turkey, are New World species imported centuries ago that provide significant provisioning services as oilseed and grain crops (Uludag et al., 2017). Eucalyptus trees (e.g., *Eucalyptus camaldulensis*) were introduced in the mid-20th century to drain malarial swamps and provide fast-growing timber, while black locust (*Robinia pseudoacacia*) was introduced for the reclamation of mined lands and as a source of resistant wood and nectar for honey production. Other species arrived accidentally as contaminants in trade items or inside ship ballast water, among other means. Common ragweed (*Ambrosia artemisiifolia*), a North American weed, possibly entered by imported grain or seed and is now found in areas of Thrace and the eastern Black Sea regions (Celenk, 2019; Farooq et al., 2016; Onen et al., 2014; Ozaslan et al., 2016). Likewise, silverleaf nightshade (*Solanum elaeagnifolium*) and field bindweed (*Convolvulus arvensis*), both native to remote areas, have emerged as problematic weeds in Turkish agricultural fields, likely imported by tainted seed or equipment.

The geographical distribution of invasions in Turkey is erratic (Tarkan et al., 2024). Regions that are warmer and wetter, characterized by significant human activity, typically have a greater number of alien species. The Black Sea and Marmara areas in northern Turkey contain the greatest diversity of invasive plant species, around 25–35 species each, while the Aegean and Mediterranean regions, located on the western and southern shores, host roughly 15–20 species. Conversely, the arid Central Anatolia and colder Eastern Anatolia have a lower incidence of reported invasive plant species, around a dozen in each region (Tarkan et al., 2025). These patterns indicate both climatic suitability and access points, i.e., port cities and transit routes in the Marmara and Aegean regions (e.g., Istanbul, Izmir) have historically served as gateways for plant introductions, while the humid environment of the Black Sea coast supports numerous invasive weeds. Table 1 presents examples of significant non-native plant species in Turkey, their modes of introduction, and the related ecological services or risks for each species.

Table 1. Key non-native plant species in Turkey, introduction purpose, and noted ecosystem service benefits vs. risks.

Species (Origin)	**Introduction Purpose**	**Ecosystem Service(s)**	**Notable Risk/Impact**
Robinia pseudoacacia L. (N. America)	Soil reclamation, timber, and beekeeping (ornamental planting in rural areas)	Nitrogen-fixing improves soil; nectar source for honey (acacia honey); fast-growing timber	Invasive in forests/grasslands, forms dense thickets through root suckers, outcompetes native vegetation
Ambrosia artemisiifolia L. (N. America)	Unintentional introduction (contaminant in grain/seed imports)	*Minor*: pollen is food for some insects	Highly allergenic pollen causing public health issues; invades croplands, reducing yields and increasing control costs.
Pontederia crassipes Mart. (S. America)	Ornamental pond plant (introduced for decorative water gardens)	Phytoremediation, can be used as compost or biomass fuel	Chokes waterways and irrigation canals, depletes oxygen in aquatic systems, leading to fish mortality; listed as a quarantine pest in Turkey.
Ailanthus altissima (Mill.) Swingle (Asia)	Introduced as an urban ornamental/shade tree in 19th–20th century	Urban greening, hardy tree that grows in poor soils, providing shade and	Extremely invasive in urban and rural habitats; produces abundant wind-dispersed seeds,

		aesthetic value in cities	infiltrates cracks in infrastructure, and its root system and allelopathic chemicals inhibit native plant regeneration.
Phragmites australis (Cav.) Steud. (Mediterranean/Asia)	Introduced for erosion control and as a reed for musical instruments	Stabilizes soil on riverbanks and slopes; traditional uses (thatch, reed instruments)	Forms monocultures in riparian areas, consuming substantial water and altering fire regimes
Opuntia ficus-indica (L.) Mill. (Central America)	Introduced as a fruit crop and natural fence in rural areas	Provisioning (edible fruits, fodder in droughts); living fences for erosion control	Can naturalize in dry shrublands, displacing native flora; dense cactus thickets impede grazing
Camellia sinensis (L.) Kuntze (South/East Asia)	Introduced as a crop (tea plantations in Black Sea region	Provisioning (economic crop); cultural ecosystem service (tea culture)	*Minimal invasive risk*: confined to managed plantations in Rize province; climate limits
Eucalyptus camaldulensis Dehnh. (Australia)	Introduced for swamp drainage (malaria control) and fast-growing timber/pulpwood in mid-1900s	Regulating service (drained waterlogged soils); provisioning (timber); windbreaks in agricultural areas	High water uptake can lower water tables; leaf litter alters soil chemistry. In river valleys it can naturalize and compete with native riparian trees.

Sources: (Arslan et al., 2015; Atasoy & Çorbacı, 2018)

Turkey's engagement with non-native flora involves both notable agricultural successes and harmful ecological invaders. Numerous commercially significant crops in the country, except wheat, are of non-native origin but have been well integrated into Turkish agriculture throughout history.

Conversely, modern invasive weeds and pest plants have occasionally spread more rapidly than the development of awareness or regulatory frameworks. The subsequent sections explore the dual characteristics of non-native plant species: the ecosystem services and advantages they offer, as well as the negative impacts they may impose on ecology and agriculture, particularly in the context of a changing climate.

Ecosystem Services Provided by Non-Native Species

Non-native plant species in Turkey are sometimes criticized; however, it is vital to understand that some provide valuable ecosystem services and socioeconomic benefits, especially in agro-ecosystems (Kumar Rai & Singh, 2020; Lazzaro et al., 2018; Pejchar & Mooney, 2009). Numerous imported plants were intentionally brought due to their provision of characteristics that native species either could not give or were insufficiently available (Mack, 2001). Essential categories of ecosystem services, i.e., provisioning, regulating, and cultural etc. provided by non-native plants (Fisher & Kerry Turner, 2008; Simpson et al., 2023; Wallace, 2007) are discussed in this chapter. The provision of these services will potentially improve agro-ecosystem resilience and human well-being.

Provisioning Services

Several exotic plant species constitute the base of Turkey's agricultural production, providing food, fiber, and fuel (Uludag et al., 2017). Staple crops such as maize, tomatoes, potatoes, and sunflowers (all originating from the New World) significantly enhance Turkey's food security and agricultural income (Aytop et al., 2014). These species have been effectively integrated into local agro-ecosystems and breeding initiatives, frequently outperforming indigenous wild plants in both yield and economic value. Fodder crops and forages, such alfalfa (*Medicago sativa*), originally from Southwest Asia but enhanced with exotic types (Wang & Şakiroğlu, 2021), and sorghum hybrids from Africa are utilized to maintain cattle during arid seasons; hence, strengthening provisioning services in pasture systems. In forestry, fast-growing exotic species such as *Pinus radiata* (Monterey pine) and *Cupressus arizonica* (Arizona cypress) have been tested for timber and windbreak applications in Turkey's climate-stressed marginal regions, enhancing wood production. A significant provisioning advantage of beekeeping is the North American black locust *(Robinia pseudoacacia*), which produces ample nectar and is esteemed as a honey source (beekeepers in Turkey highly regard the light acacia honey) (Atanasov et al., 2023). In the same way, several invasive weeds, such as Canadian goldenrod (*Solidago canadensis*), yield late-season blossoms that beekeepers utilize for nectar production. Certain non-native plants accidentally assist pollination services and honey production.

Regulating Services

Several non-native species have been intentionally employed to regulate ecological processes (Gaertner et al., 2017), particularly in response to land degradation and climatic variability (Russo et al., 2025). Tree and shrub species from dry or saline ecosystems, such as Australian saltbush species (*Atriplex* spp.) and *Acacia saligna*, have been introduced in Central Anatolia to mitigate desertification, consolidate soils, and reduce wind erosion. Due to their drought tolerance and rapid growth, these plants may rapidly establish ground cover and windbreak functions in areas where natural vegetation fails, hence managing soil erosion and microclimates. Research suggests that non-native tree species are at least as successful as native species in climate management, erosion control, and soil fertility augmentation. *Casuarina equisetifolia* (beach she-oak), native to Australasia, has been introduced throughout the Aegean and Mediterranean beaches to stabilize sand dunes (Konic et al., 2024). It enhances nitrogen fixation and establishes windbreaks, protecting agricultural areas and communities from sand invasion. The planting of resistant exotic trees like *Eucalyptus* and *Populus* hybrids in riparian zones has mitigated waterlogging and salinity by reducing water tables (Minhas et al., 2020), as demonstrated in the Göksu Delta and Amik Plain drainage operations during the mid-20^{th} century. Although these imports are controversial, they were driven by the regulatory functions certain species may provide in disturbed ecosystems.

Several experts have recommended the planned use of non-native plants to sustain specific regulating services under changing climate (Russo et al., 2025). If a native tree species essential for watershed protection becomes unstable due to increasing temperatures, a non-native species adapted to the altered environment may be introduced to perform this function, a process known as "assisted migration" for ecosystem functionality. Recent research in

Austria shown that integrating native and non-native trees in forest regeneration might enhance wood output and species variety under future climatic conditions, compared to relying only on native species (Konic et al., 2024). Despite being experimental in nature, these techniques highlight the potential of selectively chosen non-native species to enhance ecosystem control in a changing climate.

Cultural and Supporting Services

Non-native plants provide cultural services and sustain ecosystems (Castro-Díez et al., 2019; Dickie et al., 2014). Turkey's urban and rural environments include ornamental plants, including tulips (Atak, 2023) (imported from Central Asia) and both native and hybrid trees such as *Platanus orientalis* (oriental plane) (Kamer Aksoy, 2022) and *Platanus × hispanica* (London plane) in public parks. Turkish urban ecosystems get benefits from the shade, cooling effects, and aesthetic value of exotic ornamental plants, enhancing human well-being. Non-native urban trees may enhance urban biodiversity by providing habitat and nectar beyond the natural flowering period, as well as cultural ecosystem services, without adversely affecting native fauna in urban environments. The Japanese pagoda tree (*Styphnolobium japonicum*), cultivated along highways in Ankara and Istanbul, resists pollution and drought while providing aesthetically pleasing flowers and pollen for urban bees (Türkdoğdu & Altinçekiç, 2018). These trees have exceptional urban tolerance, indicating a niche in which non-native species may thrive.

Non-native species could improve nitrogen fixation and soil health. *Robinia pseudoacacia* leaf litter enhances nitrogen and organic matter in nutrient-deficient soils, facilitating the rehabilitation of mining sites (Su & Shangguan, 2023). Acacia and Prosopis species introduced to the arid regions of southeastern Turkey improve soil structure and fertility, consequently supporting native plant communities (Riley, 2021). Nurse trees that provide shade and soil moisture for the native plants' seedlings have been shown to assist the regeneration of native species.

Numerous non-native plant species in Turkey enhance agricultural production, facilitate land restoration, and shape cultural identity, shown by tea growing in Rize and the flourishing citrus orchards along the Mediterranean coast using Southeast Asian orange and lemon cultivars. These contributions emphasize the need to achieve a "balance", i.e., increasing the beneficial roles of desirable non-native species (responsibly) while mitigating the introduction and spread of invasive and harmful ones.

Negative Impacts of Non-Native Species

Despite their benefits, several non-native plant species pose risks to Turkey's environment, agriculture, and public health (Ozaslan et al., 2016; Tarkan et al., 2024, 2025). Invasive alien plants, by definition, establish self-sustaining colonies and spread aggressively, adversely affecting native species and human well-being. Recent investigations and assessments confirm these primary negative effects (Roy et al., 2023).

Invasive flora may displace native species, hence reducing biodiversity (Gentili et al., 2021). Native riparian flora is being replaced by *Impatiens balsamina* and *Reynoutria* species along Black Sea waterways. The unique dune flora is inhibited by mats of *Carpobrotus edulis* (Hottentot fig, originating from South Africa) in coastal dunes (Sazlı & Karataş, 2024). Invasive species such as *Ailanthus altissima* rapidly colonize disturbed forest gaps, limiting the regeneration of native forests (Ulus et al., 2021; Yazlık et al., 2018). Invasive species alter ecological processes beyond simple species extinction. Approximately 80% of non-native plant species in Turkey have environmental effects, primarily influencing the nitrogen cycle, water availability, and disturbance regimes (Yazlık et al., 2018). *Acacia saligna* thickets in the Aegean region enrich soils with nitrogen and augment fuel loads, altering the disturbance dynamics to which native plants are adapted. The invasive water fern *Azolla filiculoides* may blanket water surfaces, reducing light and oxygen levels, hence impacting aquatic food webs. Following the removal of the invasive species, the restoration of nutritional and hydrological cycles may be challenging.

Numerous invasive species are weeds that decrease agriculture production, increase maintenance costs, and threaten wildlife. A total 21 non-native plant species have been reported as agricultural weeds in Turkey in a recent study (Yazlık et al., 2018). Examples include Johnson grass (*Sorghum halepense*), field bindweed (*Convolvulus arvensis*), common cocklebur (*Xanthium strumarium*), and silverleaf nightshade (*Solanum elaeagnifolium*). Farmers must use more pesticides and exert greater effort to control them due to their competition with crops for water, light, and nutrients. Thistles such as *Onopordum acanthium* can diminish rangeland forage (Baştürk & Peker, 2021). Certain invasive species are poisonous. *Datura stramonium* (jimsonweed), introduced from the Americas, poses a risk to animals if ingested alongside feed in maize and cotton fields (KORKMAZ et al., 2019). Similarly, it poses significant health risks for humans (Disel et al., 2015; Gunaydın et al., 2017; Özkaya et al., 2015; Tarkan et al., 2024). In a recent analysis, agriculture constituted 70% of the total economic costs of invasive species in Turkey from 1960 to 2022, amounting to US$2.85 billion. Among these expenses include crop losses, weed management expenditures, and post-harvest contamination, including Xanthium burrs that decrease cotton quality. The analysis indicated that management expenditures in Turkey exceed direct damage costs (US$2.89 billion compared to $28 million), demonstrating that invasive species are being managed with significant resources, despite the possibility of unquantified damages.

Invasive plant species may adversely affect human and animal health. Common ragweed (*Ambrosia artemisiifolia*) pollen is a significant cause of allergic rhinitis and asthma (Celenk, 2019; Celenk & Malyer, 2017; Farooq et al., 2017; Zemmer et al., 2012). Ragweed pollen is increasing in Istanbul and other areas, especially during late summer, and climate change may exacerbate the number of allergy patients in Turkey, like trends seen in Europe. Giant hogweed (*Heracleum mantegazzianum*), known for inducing severe skin photosensitivity, may proliferate in the Black Sea region. Silverleaf nightshade may cause gastrointestinal distress in calves, but perennial ragwort (*Senecio jacobaea*) poses a poisoning risk to horses and cattle if it thrives in meadows, as seen in Europe (Aboling, 2023). Invasive species such as *Sorghum halepense* may accumulate nitrates under drought circumstances, posing a toxic threat to animals (Peerzada et al., 2023). All these challenges impact the economic welfare of farmers and public health.

Invasive plants damage infrastructure and landscapes, resulting in economic losses (Booy et al., 2017). Rapidly proliferating woody invasive species such as *Ailanthus* damage existing masonry and pavement, increasing infrastructure damage in urban historic sites and highways (Trotta et al., 2020). The removal of water hyacinth and water lettuce from canals, pipelines, and hydroelectric dam intakes is necessary to guarantee water supply and energy generation, which has a significant cost (Harun et al., 2021). Like neighboring countries, mesquite (*Prosopis juliflora*) cultivated in rural regions along the Mediterranean coast may dominate irrigation channels and agricultural fields, creating thick thorny obstacles that hinder automated farming access (Shiferaw et al., 2023). Caribbean pine (*Pinus caribaea*), an introduced species, was cultivated in the 20th century and has shown more susceptibility to insect infestations and wildfires than native forests, posing risks to nearby communities.

Recent Turkish case studies reveal these extensive harmful impacts. An extensive impact assessment of 51 high-priority invasive plant species in Turkey revealed that 80% had environmental implications and 78% had socio-economic effects, mostly affecting agriculture and health (Yazlık et al., 2018). The Black Sea region has the highest concentration of invasive flora and exerts the most significant environmental effect. Invasive *Reynoutria* species affect sedimentation patterns and flood dynamics. The elevated population density and intensive agriculture in Marmara (northwest Turkey) suggest that invasive species such as ragweed and Amaranthus may disrupt human activities and need significant management efforts. Invasive plants can interact with other elements of change, increasing problems (Roy et al., 2023). Certain Anatolian rangelands have experienced overgrazing and mismanagement, facilitating the proliferation of Russian thistle (*Salsola tragus*) and alkali swampweed (*Heliotropium curassavicum*) (Kandemir et al., 2020). Climate change, as discussed in the subsequent section, could worsen these consequences by increasing ecosystem susceptibility to invasion and extending the development or reproductive season of invasive species. In conclusion, Turkey derives advantages from certain non-native flora, however experiences significant costs due to invasive species.

Climate Change and the Dynamics of Non-Native Species

Climate change is altering temperature and precipitation patterns in Turkey (Demircan et al., 2017), significantly affecting the introduction, establishment, and spread of non-native plant species. Climate change often exacerbates the dynamics of invasive species and diminishes ecosystem resistance to invasions. This section examines the impact of increasing temperatures, altered precipitation patterns, and increased frequency of severe events on non-native flora, as well as the potential implications for Turkish agro-ecosystems.

Non-native plants can thrive in the current unsuitable areas with temperatures increase under changing climate (Alexander, 2013). Frost-sensitive invaders might settle in new locations due to milder winter limits (Hanberry et al., 2024). Globally, thermophilic species are moving north and up, including in Turkey (Guven et al., 2018). In southern Turkey, parthenium weed (*Parthenium hysterophorus*) and tropical soda apple (*Solanum viarum*) may grow if winter frosts decrease. Opuntia and Agave will shift inland from the Aegean coast to imitate deserts as temperatures increase. One study revealed that future climatic scenarios might expand invasive species distribution by 77% in high-value European ecosystems at low invasion risk (Gallardo et al., 2024). This European finding suggests that as the climate warms, even high-altitude or Black Sea regions of Turkey may see more invasion pressure.

Heatwaves, droughts, wildfires, intense rainfall, and flooding are increasing because of climate change (Clarke et al., 2022). These changes could benefit invasive flora (Sheppard et al., 2012). These extremes may stress or eliminate native species, resulting in niches or barren areas that rapidly colonizing invaders readily occupy. Invasive species such as *Acacia saligna*, *Eucalyptus camaldulensis*, and *Nicotiana glauca* (tree tobacco) outcompete native regrowth after catastrophic wildfires, which are projected to rise in the Aegean and Mediterranean regions due to hotter, drier summers. Floods can spread riparian weed seeds (de Rouw et al., 2018), such as mile-a-minute vine (*Persicaria perfoliata*), downstream, and with more erratic high rainfall, this phenomenon may become more pronounced. High-emission scenarios predict a ~37% increase in agricultural droughts in Turkey by 2050 (Çeliktopuz, 2024), rendering crops and pastures more vulnerable to drought-resistant invasive species such as *Centaurea solstitialis* and yellow starthistle. Flash floods may erode soil and disperse invasive propagules (Čuda et al., 2017). In conclusion, climate-induced disturbances modify ecosystems, benefiting opportunistic non-native species throughout the recovery phase.

Invasive species exploit the impacts of climate change on phenology (Wolkovich & Cleland, 2014). Extended growing seasons and milder winters may enable some non-native plants to germinate earlier, grow more rapidly, and produce a greater quantity of seeds annually (Mulder & Spellman, 2019).

Invasive plant species in temperate regions may respond more intensively to elevated CO_2 levels and temperature than native species, hence conferring a competitive edge (Dukes et al., 2011). The common cocklebur and Bermuda buttercup (*Oxalis pes-caprae*) may flower and produce seeds early in spring in Turkey, so replenishing seed banks prior to the completion of the cycle of native annuals. Moreover, elevated CO_2 concentrations may directly facilitate the proliferation of some invasive species. Vines and invasive ruderal plants exhibit accelerated growth and enhanced herbicide resistance under elevated CO_2 conditions (Waryszak et al., 2018). Weed management may become more challenging if higher pesticide dosages are required to achieve same efficacy under high-CO_2 concentration.

Climate change and invasive species may engage in feedback loops (Sinclair et al., 2020). Invasive plants often thrive in disturbed, variable environments generated by climate change (Turbelin & Catford, 2021). Their proliferation may subsequently weaken ecosystem resistance to climatic effects. Invasive plants may increase fire frequency by contributing flammable biomass, hence maintaining a landscape conducive to invasiveness and fire susceptibility, a phenomenon seen in Mediterranean ecosystems invaded by African pyrophytic grasses (Wyse et al., 2018). Likewise, an invasive species that drains water resources, such as *Eucalyptus* trees or dense thickets of *Prosopis*, can worsen drought effects on the area, hindering the recovery of local flora in a drier environment (Antunes et al., 2018). Consequently, invasive species and climatic stress often interact synergistically, amplifying one other's effects (Thompson & Ziska, 2014). This synergy eventually reduces overall ecosystem resistance, and the ability of the ecosystem to withstand and recover from shocks is compromised by the simultaneous impact of invasive species and climatic extremes.

Given these dynamics, it is evident that climate change warrants a stricter approach to invasive species management in Turkey. Range expansion models and observational data indicate that several invasive species will migrate to higher latitudes and elevations; formerly safe regions (e.g., montane zones) may require surveillance (Farooq, 2018; Kadıoğlu & Kekeç, 2020; Öztop, 2023). Conventional pest management cycles must be modified as phenological patterns change. Conservation and agricultural agencies in Turkey are integrating climate factors into invasive species risk assessments. Climate adaptation and invasive species control must be addressed simultaneously. Any climate change adaptation strategy for agriculture, including the introduction of drought-resistant crops or alterations in planting schedules, must incorporate steps that prevent opportunistic weeds from benefiting from the new conditions. Similarly, invasive species management initiatives, such as the eradication of emerging weed populations, should be focused on the regions where climate change is expected to facilitate the spread of those weeds.

In conclusion, climate change is altering the invasive species dynamics in Turkey by facilitating new invasions, expediting their spread, and intensifying their effects. The coming decades may witness an influx of non-native flora in previously uninhabited regions, unless preventative measures are implemented. The next a section examines Turkey’s response through management strategies and policies, emphasizing the necessity of incorporating climate prediction into these initiatives.

Management Strategies and Policy Recommendations

Addressing the simultaneous problems of invasive species and climate change need comprehensive management measures and proactive policies. The awareness of invasive alien plants has increased in Turkey during recent years, leading to new activities at both governmental and grassroots levels. This section discusses current management strategies, significant policy advancements (including Turkey's inaugural national plan on invasive species), and proposals for integrated management aimed at strengthening agro-ecosystem resistance.

The most cost-effective way to manage invasive species is to prevent their entry at the border (Fernandez & Sheriff, 2013). Turkey has enhanced its phytosanitary regulations to align with international standards, therefore preventing accidental imports. Regulating imported seeds, animal feed, and wooden packaging mitigates the introduction of weed seeds and plant pathogens (Giray & Özkan, 2012). Turkey has expanded its quarantine list to include more risky species. The list now includes two plants, i.e., *Pontederia crassipes* and *Arceuthobium* spp. The new regulatory framework evaluates proposed plant imports, including novel agricultural varieties and ornamental species, for invasive potential through risk assessments (Yazlık & Ambarlı, 2022). Horizon scanning, often conducted with European and regional collaborators, forecasts which invasive plant species absent from Turkey pose a significant concern in future climatic conditions and may need prevention or surveillance. Due to the volume of trade and Turkey's large land borders (Frede & Yetkiner, 2017), the complete eradication of invasive species is impossible, although customs and agricultural quarantine authorities have enhanced their screening capabilities at major ports and borders. Investments in biosecurity, such as seed detection canines, diagnostic laboratories for seed contamination, and the harmonization of regional quarantine lists, are essential. The One Health concept, integrating plants, environmental, and human health, advocates comprehensive preventive strategies.

Given that not all invasions can be prevented, early detection of emerging invasive populations is essential. Turkey has initiated the training of agricultural extension staff, park rangers, and citizen volunteers via "invasive watch" programs to detect and report unusual plant invasions. If a farmer in Thrace identifies an unexpected aggressive vine in a fallow field, a reporting channel is available to notify authorities and university specialists. Upon confirmation of a new invasive species, a swift reaction may be undertaken, often including eradication or containment if the population remains confined. These initiatives are being codified inside Turkey's national invasive species response strategy, which underscores EDRR as a critical element. It is advisable to use digital technologies (smartphone applications, GPS mapping) to facilitate real-time reporting and data sharing on invasive species occurrences. Another approach is to construct seed banks of indigenous species for re-vegetation efforts after the removal of invasive species, so mitigating the risk of re-invasion.

Integrating Non-Native Species into Sustainable Agro-Ecosystems

A significant distinction in the discussion on non-native species is that not all such species are harmful in an agricultural environment; in fact, many are essential to modern agro-ecosystems. The objective is to incorporate beneficial non-native flora while managing or eliminating invasive species. As climate change intensifies, Turkish agriculture and agro-forestry may need adaptation by the introduction of new species or types, some of which may be non-native. This section examines options for using beneficial non-native species to enhance sustainability and resilience, as well as for managing landscapes to reduce the danger of invading species dominance.

Crop diversity is a key component of sustainable agro-ecosystems, serving to mitigate the impacts of climatic extremes (Gawdiya et al., 2025). Turkey is currently experimenting with the introduction or expansion of alternative crops that are more adapted to warmer or drier climates. For instance, quinoa (*Chenopodium quinoa*) from South America has been tested in Central and Southeast Anatolia as a drought-resistant cereal (Aydoğdu & Koç, 2021), while sorghum and millet, originating from Africa, are being advocated as substitutes for water-intensive maize or rice in certain regions (Karaman et al., 2022). Properly managed introductions may enhance resilience by yielding harvests under climatic circumstances that may lead to the failure of conventional crops. Researchers evaluate the capacity of non-native crops to naturalize beyond cultivation to prevent them from becoming invasive. Furthermore, adhering to sound agricultural practices—such as harvesting prior to seed shatter and managing volunteer plants—mitigates crop escape. It is essential to choose non-native species that occupy a necessary ecological niche (e.g., heat tolerance, salinity tolerance) while exhibiting little invasive potential. Utilizing Turkey's robust agricultural research infrastructure (TAGEM, universities) to assess and cultivate novel climate-resilient flora (including desert legumes, perennial cereals, or exotic fruit trees such as dragonfruit already cultivated in Alanya) would be beneficial. These initiatives must include risk assessments to prevent the introduction of potential invasive species alongside the desired characteristics.

Incorporating trees into agricultural landscapes (agroforestry) offers shade, wind protection, and soil benefits which are becoming increasingly significant under climate change (Matocha et al., 2012). Non-native tree species frequently appear in global agroforestry systems, and some types may be suitable for Turkey (Dimitrova et al., 2022). *Paulownia tomentosa* (princess tree), indigenous to East Asia, has been utilized in agroforestry studies in the Aegean region due to its quick growth, shade provision, and valuable timber (Ilter & Türe, 2025). It sequesters carbon well and may be intercropped with minimal competition. Nonetheless, *Paulownia* may exhibit invasive characteristics in some environments (propagating by wind-dispersed seeds), necessitating careful site selection and ongoing monitoring. The fundamental approach is “appropriate species, appropriate location”: using non-native perennials that provide ecosystem services (shade, fodder, nutrient cycling) while ensuring they are managed to prevent their escape into natural ecosystems. This sometimes involves using sterile or non-seeding cultivars where accessible, or proactively regulating reproduction (e.g., coppicing trees prior to seed maturation). In windbreaks, non-indigenous trees such as *Eucalyptus camaldulensis* or Casuarina can be highly successful; however, they must be excluded from neighboring natural wetlands or dunes.

Land-use planning may establish invasion-free zones (critical conservation areas where non-native species should not be introduced or allowed to spread) and sacrifice zones (highways or urban peripheries where certain non-natives may be tolerated or strictly managed). Establishing ornamental non-native species that do not spread, such as hybrid orchard fruit trees or sterile ornamental shrubs, in buffer zones around national parks may enhance local livelihoods more effectively than harmful species. Despite changes in the landscape, careful biosecurity measures (such as sanitizing footwear, vehicles, and using native plant species for restoration) may preserve essential protected zones against the introduction of new invasive species. In agricultural landscapes characterized by "functional biodiversity," combinations of cover crops that include non-native species such as clovers or vetches enhance soil health and interrupt insect cycles, however they may be cycled or terminated before becoming invasive. The objective is to establish strong agro-ecosystems in which native or non-native plants dominate most niches, hence restricting invading species spread.

Future Perspectives and Conclusions

The relationships among non-native plant species, ecosystem services, and agro-ecological resilience in Turkey are complex and will continue evolving due to globalization and climate change. As previously reported, non-native species represent a double-edged sword; some are essential for Turkey’s agricultural and environmental management, while others pose significant dangers to ecological and economic stability. Achieving this equilibrium requires evidence-based policy, public awareness, and an adaptable management strategy capable of adapting to new data and evolving circumstances.

Climate forecasts for Turkey comprise an increase in the frequency of droughts, heat waves, and severe precipitation events, all of which may facilitate the establishment and spread of invasive species. Meanwhile, increased trade and travel, including novel trade routes such as the Belt and Road, will intensify propagule pressure. Turkey must thus prepare for an increase in invasion threats including previously identified invasive species. Tropical and subtropical weeds could grow onto a warmer Mediterranean coast. Monitoring and predictive modeling, using AI and climate models to anticipate potential invaders, will be essential tools for maintaining a proactive stance.

In the next years, Turkey is expected to use modern technology for the control of invasive species. Remote sensing by satellites or drones may identify significant changes in vegetation that signify invasion, such as the detection of the purple bloom of *Impatiens glandulifera* along rivers or the shift in spectral signature from a native steppe to one invaded by an invasive plant. Similarly, gene editing and biotechnology might provide innovative control strategies, such as creating a biocontrol fungus targeting Ailanthus altissima or using genetic techniques to cause sterility in invading populations. The scientific community in Turkey, in partnership with global researchers, may both contribute to and benefit from these developments. All technological innovations must be carefully assessed for ecological safety.

There is an increasing understanding that just eradicating invasive species is insufficient; rather, restoration of the ecosystems that have been damaged is also necessary. Future initiatives in Turkey will likely focus on ecological restoration after the invasion, including the replanting native species, reconstruction of soil communities, and the reinstating of ecosystem processes. This not only assists in preserving the successes achieved via the eradication of invasive species (preventing reinvasion) but also restores the comprehensive range of ecosystem services that healthy ecosystems provide (pollination, water purification, carbon sequestration, etc.).

The formulation of Turkey's National IAS Strategy is a significant achievement. The difficulty will be sustaining momentum and getting funds until 2035 and beyond. To maintain priority, invasive species concerns need continuous public participation and governmental support. This may be accomplished by highlighting the relationships between invasive species and related problems, such as associating ragweed management with public health concerns (allergies) or tying the control of invasive waterweeds to recreational fishing and tourism. When farmers, fishermen, and local people see concrete advantages from invasive species control, such as improved harvests or enhanced water quality, they become strong supporters of ongoing efforts. Consequently, the expansion of community-based initiatives, such as "Farmer Field Schools" focused on integrated weed control and citizen science mapping of invasive flora, would be crucial. Educational curriculum may include modules on invasive species and climate, equipping the future generation to be knowledgeable stewards.

In the future, Turkey will continue in collaborating with regional neighbors via institutions such as the Mediterranean Invasive Species Network and with global organizations like the Convention on Biological Diversity's invasive species objectives and IPBES. The dissemination of knowledge on effective management strategies, early warning systems for emerging invaders, and coordinated responses—such as the synchronized eradication of water hyacinth along the shared Meriç/Maritsa River with Greece—will become more vital. Climate change may alter the dispersal of invasive species across political borders, necessitating a collaborative approach. Turkey's geographical position as an interface between continents uniquely enables it to contribute to international research and policy regarding invasive species. For instance, Turkish scientists can investigate the shifting ranges of invasive species from the Middle East into Europe via Turkey as a "corridor" in the context of climate change, thereby informing broader theories and management strategies.

In conclusion, Turkey's future agro-ecosystems would likely include a synthesis of traditional crops and native species with imported species, some selected for resilience and others coming accidentally. The objective of sustainable management is not to eliminate all non-native species, but to cultivate a system that maximizes advantages while minimizing negative effects. This involves strict control of high-risk invasive species, judicious use of advantageous exotics, rapid response upon detection of new invasions, and restoration of ecosystems to a functioning condition, even if they do not replicate historical states. By adopting an adaptive management strategy—gaining insights from each success or failure and modifying tactics—Turkey can enhance the resilience of its agro-ecosystems. Managing non-native species is essential for developing resilience, since uncontrolled invasions may compromise an ecosystem's capacity to withstand further shocks.

REFERENCES

Aboling, S. (2023). Do Poisonous Plants in Pastures Communicate Their Toxicity? Meta-Study and Evaluation of Poisoning Cases in Central Europe. Animals, 13(24), 3795. https://doi.org/10.3390/ani13243795

Alexander, J. M. (2013). Evolution under changing climates: climatic niche stasis despite rapid evolution in a non-native plant. Proceedings of the Royal Society B: Biological Sciences, 280(1767), 20131446. https://doi.org/10.1098/rspb.2013.1446

Antunes, C., Pereira, A. J., Fernandes, P., Ramos, M., Ascensão, L., Correia, O., & Máguas, C. (2018). Understanding plant drought resistance in a Mediterranean coastal sand dune ecosystem: differences between native and exotic invasive species. Journal of Plant Ecology, 11(1), 26–38. https://doi.org/10.1093/jpe/rtx014

Arslan, Z. F., Uludag, A., & Uremis, I. (2015). Status of invasive alien plants included in EPPO Lists in Turkey. EPPO Bulletin, 45(1), 66–72. https://doi.org/10.1111/epp.12176

Atak, E. (2023). Importance of the Tulip in Turkish Culture and as Art from Central Asia to Anatolia. Central Asiatic Journal, 65(1–2), 151–168. https://doi.org/10.13173/CAJ/2022/1-2/11

Atanasov, A. Z., Hristakov, I. S., Koszel, M., & Przywara, A. (2023). Monitoring Agrometeorological Factors and Weight of the Bee Hive During Black Locust (*Robinia pseudoacacia*) Flowering. In Lecture Notes in Civil Engineering 289, 239–251. https://doi.org/10.1007/978-3-031-13090-8_25

Atasoy, M., & Çorbacı, Ö. L. (2018). The Invasive Alien Plants of Turkey A Checklist and Environmental Hazards. Journal of Applied Environmental and Biological Sciences, 8(5), 1–8.

Aydoğdu, M., & Koç, A. (2021). Screening quinoa (*Chenopodium quinoa*) germplasm for resistance to downy mildew (*Peronospora variabilis*) in Turkey. Crop and Pasture Science, 72(6), 416–425. https://doi.org/10.1071/CP20508

Aytop, Y., Çukadar, M., & Şahin, A. (2014). Agricultural Sector Profile of Turkey in the World. Turkish Journal of Agricultural and Natural Sciences, 1(1), 688–694.

Barneby, R. C., Davis, P. H., Mill, R. R., & Tan, K. (1986). Flora of Turkey and the East Aegean Islands. Volume 9. Brittonia, 38(2), 161. https://doi.org/10.2307/2807269

Baştürk, A., & Peker, S. (2021). Antioxidant Capacity, Fatty Acid Profile and Volatile Components of the *Onopordum anatolicum* and *Onopordum heteracanthum* Species Seeds Grown in Van, Turkey. Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 11(4), 2810–2822. https://doi.org/10.21597/jist.895713

Booy, O., Cornwell, L., Parrott, D., Sutton-Croft, M., & Williams, F. (2017). Impact of Biological Invasions on Infrastructure. In Impact of Biological Invasions on Ecosystem Services (pp. 235–247). Springer International Publishing. https://doi.org/10.1007/978-3-319-45121-3_15

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., … Watson, R. (2010). Global Biodiversity: Indicators of Recent Declines. Science, 328(5982), 1164–1168. https://doi.org/10.1126/science.1187512

Byfield, A., & Baytop, A. (1998). Three alien species new to the flora of Turkey. Turkish Journal of Botany, 22, 205–208.

Castro-Díez, P., Vaz, A. S., Silva, J. S., van Loo, M., Alonso, Á., Aponte, C., Bayón, Á., Bellingham, P. J., Chiuffo, M. C., DiManno, N., Julian, K., Kandert, S., La Porta, N., Marchante, H., Maule, H. G., Mayfield, M. M., Metcalfe, D., Monteverdi, M. C., Núñez, M. A., … Godoy, O. (2019). Global effects of non-native tree species on multiple ecosystem services. Biological Reviews, 94(4), 1477–1501. https://doi.org/10.1111/brv.12511

Celenk, S. (2019). Detection of reactive allergens in long-distance transported pollen grains: Evidence from *Ambrosia*. Atmospheric Environment, 209, 212–219. https://doi.org/10.1016/j.atmosenv.2019.04.040

Celenk, S., & Malyer, H. (2017). The occurrence of Ambrosia pollen in the atmosphere of Northwest Turkey: investigation of possible source regions. International Journal of Biometeorology, 61(8), 1499–1510. https://doi.org/10.1007/s00484-017-1328-y

Çeliktopuz, E. (2024). A Detailed Examination of Türkiye's Projected Precipitation and Growth Season Trends under Climate Change Condition. Black Sea Journal of Agriculture, 7(3), 215–223. https://doi.org/10.47115/bsagriculture.1416956

Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. Environmental Research: Climate, 1(1), 012001. https://doi.org/10.1088/2752-5295/ac6e7d

Čuda, J., Rumlerová, Z., Brůna, J., Skálová, H., & Pyšek, P. (2017). Floods affect the abundance of invasive *Impatiens glandulifera* and its spread from river corridors. Diversity and Distributions, 23(4), 342–354. https://doi.org/10.1111/ddi.12524

de Rouw, A., Ribolzi, O., Douillet, M., Tjantahosong, H., & Soulileuth, B. (2018). Weed seed dispersal via runoff water and eroded soil. Agriculture, Ecosystems & Environment, 265, 488–502. https://doi.org/10.1016/j.agee.2018.05.026

Demircan, M., Gürkan, H., Eskioğlu, O., Arabacı, H., & Coşkun, M. (2017). Climate Change Projections for Turkey: Three Models and Two Scenarios. Turkish Journal of Water Science and Management, 1(1), 22–43. https://doi.org/10.31807/tjwsm.297183

Diagne, C., Leroy, B., Vaissière, A.-C., Gozlan, R. E., Roiz, D., Jarić, I., Salles, J.-M., Bradshaw, C. J. A., & Courchamp, F. (2021). High and rising economic costs of biological invasions worldwide. Nature, 592(7855), 571–576. https://doi.org/10.1038/s41586-021-03405-6

Dickie, I. A., Bennett, B. M., Burrows, L. E., Nuñez, M. A., Peltzer, D. A., Porté, A., Richardson, D. M., Rejmánek, M., Rundel, P. W., & van Wilgen, B. W. (2014). Conflicting values: ecosystem services and invasive tree management. Biological Invasions, 16(3), 705–719. https://doi.org/10.1007/s10530-013-0609-6

Didham, R. K., Tylianakis, J. M., Hutchison, M. A., Ewers, R. M., & Gemmell, N. J. (2005). Are invasive species the drivers of ecological change? Trends in Ecology & Evolution, 20(9), 470–474. https://doi.org/10.1016/j.tree.2005.07.006

Dimitrova, A., Csilléry, K., Klisz, M., Lévesque, M., Heinrichs, S., Cailleret, M., Andivia, E., Madsen, P., Böhenius, H., Cvjetkovic, B., De Cuyper, B., de Dato, G., Ferus, P., Heinze, B., Ivetić, V., Köbölkuti, Z., Lazarević, J., Lazdina, D., Maaten, T., … Montagnoli, A. (2022). Risks, benefits, and knowledge gaps of non-native tree species in Europe. Frontiers in Ecology and Evolution, 10. https://doi.org/10.3389/fevo.2022.908464

Disel, N. R., Yilmaz, M., Kekec, Z., & Karanlik, M. (2015). Poisoned after Dinner: Dolma with Datura Stramonium. Turkish Journal of Emergency Medicine, 15(1), 51–55. https://doi.org/10.5505/1304.7361.2015.70894

Dukes, J. S., Chiariello, N. R., Loarie, S. R., & Field, C. B. (2011). Strong response of an invasive plant species (*Centaurea solstitialis* L.) to global environmental changes. Ecological Applications, 21(6), 1887–1894. https://doi.org/10.1890/11-0111.1

Farooq, S. (2018). Experimental and ecological niche modelling approaches to predict potential distribution areas of some invasive weeds in Turkey [Doctoral Thesis, Gaziosmanpaşa Üniveristesi]. https://acikbilim.yok.gov.tr/handle/20.500.12812/617417

Farooq, S., Onen, H., & Ozaslan, C. (2017). Pollens in air, infested sunflower fields and highways: is Turkey underestimating the risk of common ragweed invasion? 2nd International Balkan Agriculture Congress, 17.

Farooq, S., Onen, H., Yildiz, H., Gunal, H., & Ozaslan, C. (2016). Will Climate Change Impact Distribution of Common Ragweed in Turkey? In C. Ries & Y. Krippel (Eds.), NEOBIOTA 2016 - 9th International Conference on Biological Invasions (p. 80).

Fernandez, L., & Sheriff, G. (2013). Optimal Border Policies for Invasive Species Under Asymmetric Information. Environmental and Resource Economics, 56(1), 27–45. https://doi.org/10.1007/s10640-013-9637-z

Fisher, B., & Kerry Turner, R. (2008). Ecosystem services: Classification for valuation. Biological Conservation, 141(5), 1167–1169. https://doi.org/10.1016/j.biocon.2008.02.019

Frede, J., & Yetkiner, H. (2017). The regional trade dynamics of Turkey: a panel data gravity model. The Journal of International Trade & Economic Development, 26(6), 633–648. https://doi.org/10.1080/09638199.2017.1279205

Gaertner, M., Wilson, J. R. U., Cadotte, M. W., MacIvor, J. S., Zenni, R. D., & Richardson, D. M. (2017). Non-native species in urban environments: patterns, processes, impacts and challenges. Biological Invasions, 19(12), 3461–3469. https://doi.org/10.1007/s10530-017-1598-7

Gallardo, B., Bacher, S., Barbosa, A. M., Gallien, L., González-Moreno, P., Martínez-Bolea, V., Sorte, C., Vimercati, G., & Vilà, M. (2024). Risks posed by invasive species to the provision of ecosystem services in Europe. Nature Communications, 15(1), 2631. https://doi.org/10.1038/s41467-024-46818-3

Gawdiya, S., Sharma, R. K., Singh, H., & Kumar, D. (2025). Crop diversification as a cornerstone for sustainable agroecosystems: tackling biodiversity loss and global food system challenges. Discover Applied Sciences, 7(5), 373. https://doi.org/10.1007/s42452-025-06855-z

Gentili, R., Schaffner, U., Martinoli, A., & Citterio, S. (2021). Invasive alien species and biodiversity: impacts and management. Biodiversity, 22(1–2), 1–3. https://doi.org/10.1080/14888386.2021.1929484

Giray, H., & Özkan, Z. (2012). European Union food safety policies and lessons / homework for Turkey. Journal of Food, Agriculture and Environment, 10(3–4).

Gunaydın, Y. K., Yildiz, C. G., Isikoglu, V., Kokulu, K., Muracar, N., Akilli, N. B., Koylu, R., & Cander, B. (2017). Datura Stramonium Poisoning: Two Case Reports. Journal of Emergency Medicine Case Reports, 8(1), 4–6. https://doi.org/10.5152/jemcr.2016.1471

Güner, A., & Aslan, S. (2012). Türkiye bitkileri listesi:(damarlı bitkiler). Nezahat Gökyiğit Botanik Bahçesi Yayınları.

Guven, K., Matpan Bekler, F., & Gul Guven, R. (2018). Thermophilic and Halophilic Microorganisms Isolated from Extreme Environments of Turkey, with Potential Biotechnological Applications. In Microorganisms for Sustainability (Vol. 8, pp. 219–264). https://doi.org/10.1007/978-981-13-0329-6_8

Hanberry, B., Abrams, M., & Nowacki, G. (2024). Potential Interactions between Climate Change and Land Use for Forest Issues in the Eastern United States. Land, 13(3), 398. https://doi.org/10.3390/land13030398

Harun, I., Pushiri, H., Amirul-Aiman, A. J., & Zulkeflee, Z. (2021). Invasive Water Hyacinth: Ecology, Impacts and Prospects for the Rural Economy. Plants, 10(8), 1613. https://doi.org/10.3390/plants10081613

Haubrock, P. J., Turbelin, A. J., Cuthbert, R. N., Novoa, A., Taylor, N. G., Angulo, E., Ballesteros-Mejia, L., Bodey, T. W., Capinha, C., Diagne, C., Essl, F., Golivets, M., Kirichenko, N., Kourantidou, M., Leroy, B., Renault, D., Verbrugge, L., & Courchamp, F. (2021). Economic costs of invasive alien species across Europe. NeoBiota, 67, 153–190. https://doi.org/10.3897/neobiota.67.58196

Ilter, E., & Türe, C. (2025). Impacts of Global Warming on the Geographical Distribution of Paulownia tomentosa in Europe. Biology Bulletin, 52(3), 92. https://doi.org/10.1134/S1062359024608942

Kadıoğlu, İ., & Kekeç, M. (2020). İklim Değişikliğine Bağlı Olarak *Xanthium strumarium* L.'un Türkiye'de Gelecekte Dağılım Alanlarının Belirlenmesi. Türkiye Herboloji Dergisi, 23(1), 1–14.

Kamer Aksoy, Ö. (2022). Predicting the Potential Distribution Area of the *Platanus orientalis* L. in Turkey Today and in the Future. Sustainability, 14(18), 11706. https://doi.org/10.3390/su141811706

Kandemir, N., Çelik, A., Shah, S. N., & Razzaq, A. (2020). Comparative micro-anatomical investigation of genus *Heliotropium* (Boraginaceae) found in Turkey. Flora, 262, 151495. https://doi.org/10.1016/j.flora.2019.151495

Karaman, K., Kardeş, Y. M., Doran, T., Akçura, M., & Kaplan, M. (2022). GT-biplot analysis of some biochemical characteristics and mineral composition of different sorghum (*Sorghum bicolor* L.) sprouts. Cereal Chemistry, 99(6), 1272–1281. https://doi.org/10.1002/cche.10590

Konic, J., Heiling, C., Haeler, E., Chakraborty, D., Lapin, K., & Schueler, S. (2024). The potential of non-native tree species to provide major ecosystem services in Austrian forests. Frontiers in Plant Science, 15. https://doi.org/10.3389/fpls.2024.1402601

Korkmaz, M. F., Bostanci, M., Onur, H., & Çağan, E. (2019). *Datura stramonium* poisoning: a case report and review of the literature. The European Research Journal, 5(1), 186–188. https://doi.org/10.18621/eurj.392041

Kumar Rai, P., & Singh, J. S. (2020). Invasive alien plant species: Their impact on environment, ecosystem services and human health. Ecological Indicators, 111, 106020. https://doi.org/10.1016/j.ecolind.2019.106020

Lazzaro, L., Essl, F., Lugliè, A., Padedda, B. M., Pyšek, P., & Brundu, G. (2018). Invasive alien plant impacts on human health and well-being. In Invasive species and human health (pp. 16–33). CABI. https://doi.org/10.1079/9781786390981.0016

Macêdo, R. L., Haubrock, P. J., Klippel, G., Fernandez, R. D., Leroy, B., Angulo, E., Carneiro, L., Musseau, C. L., Rocha, O., & Cuthbert, R. N. (2024). The economic costs of invasive aquatic plants: A global perspective on ecology and management gaps. Science of The Total Environment, 908, 168217. https://doi.org/10.1016/j.scitotenv.2023.168217

Mack, R. N. (2001). Motivations and consequences of the human dispersal of plants. In The Great Reshuffling: Human dimensions in invasive alien species.

Matocha, J., Schroth, G., Hills, T., & Hole, D. (2012). Integrating Climate Change Adaptation and Mitigation Through Agroforestry and Ecosystem Conservation (pp. 105–126). https://doi.org/10.1007/978-94-007-4676-3_9

Minhas, P. S., Yadav, R. K., & Bali, A. (2020). Perspectives on reviving waterlogged and saline soils through plantation forestry. Agricultural Water Management, 232, 106063. https://doi.org/10.1016/j.agwat.2020.106063

Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). Global Biodiversity Conservation: The Critical Role of Hotspots. In Biodiversity Hotspots (pp. 3–22). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-20992-5_1

Mulder, C. P. H., & Spellman, K. V. (2019). Do longer growing seasons give introduced plants an advantage over native plants in Interior Alaska? Botany, 97(6), 347–362. https://doi.org/10.1139/cjb-2018-0209

Onen, H., & Farooq, S. (2015). Current Status and Future Prospects of Invasive Plants in Turkey. CIHEAM Watch Letter, 33(June).

Onen, H., Farooq, S., Gunal, H., & Ozaslan, C. (2016). Successful Adaptations to Adverse Environmental Conditions: More Areas under the Risk of

Ragweed Invasion? In C. Ries & Y. Kripple (Eds.), NEOBIOTA 2016 - 9th International Conference on Biological Invasions (p. 22).

Onen, H., Farooq, S., Gunal, H., Ozaslan, C., Erdem, H. (2017). Higher Tolerance to Abiotic Stresses and Soil Types May Accelerate Common Ragweed (*Ambrosia artemisiifolia*) Invasion. Weed Science, 65(01), 115–127. https://doi.org/10.1614/WS-D-16-00011.1

Onen, H., Gunal, H., & Ozcan, S. (2014). The Black Sea highway: the route of common ragweed (*Ambrosia artemisiifolia* L.) invasion in Turkey. 8th International Conference on Biological Invasions from Understanding to Action, Antalya, Turkey.

Onen, H., Sarı, T., & Farooq, S. (2016). E-Commerce: An Open Gateway for Plant Invasion in Turkey. Turkey 6th Plant Protection Congress with International Participation, 821.

Ozaslan, C., Onen, H., Farooq, S., Gunal, H., & Akyol, N. (2016). Common ragweed: An emerging threat for sunflower production and human health in Turkey. Weed Biology and Management, 16(1), 42–55. https://doi.org/10.1111/wbm.12093

Özkaya, A. K., Güler, E., Karabel, N., Namlı, A. R., & Göksügür, Y. (2015). *Datura stramonium* poisoning in a child. Turkish Journal of Pediatrics, 57(1), 82–84.

Öztop, Z. (2023). *Xanthium spinosum* L.'un İklim Değişikliğine Bağli Olarak Global Düzeyde Potansiyel Dağilim Alanlarinin Belirlenmesi. [Mastes Thesis]. Harran University.

Peerzada, A. M., Ali, H. H., Hanif, Z., Bajwa, A. A., Kebaso, L., Frimpong, D., Iqbal, N., Namubiru, H., Hashim, S., Rasool, G., Manalil, S., van der Meulen, A., & Chauhan, B. S. (2023). Eco-biology, impact, and management of *Sorghum halepense* (L.) Pers. Biological Invasions, 25(4), 955–973. https://doi.org/10.1007/s10530-017-1410-8

Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. Trends in Ecology & Evolution, 24(9), 497–504. https://doi.org/10.1016/j.tree.2009.03.016

Riley, I. T. (2021). A Case for Assessing *Allocasuarina* and *Casuarina* Spp. for Use in Agroecosystem Improvement in Semi-Arid Areas with A Focus on Central Anatolia, Turkey. Frontiers of Agricultural Science and Engineering, 8(4), 568. https://doi.org/10.15302/J-FASE-2019270

Roy, H. E., Pauchard, A., Stoett, P., Truong, T. R., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Sankaran, K., & McGeoch, M. A. (2023). IPBES Invasive Alien Species Assessment: Summary for Policymakers. IPBES.

Russo, A., Esperon-Rodriguez, M., St-Denis, A., & Tjoelker, M. G. (2025). Native vs. Non-Native Plants: Public Preferences, Ecosystem Services, and Conservation Strategies for Climate-Resilient Urban Green Spaces. Land, 14(5), 954. https://doi.org/10.3390/land14050954

Sazlı, N., & Karataş, D. (2024). Reviewing the Optimal Conditions for Efficiently Harnessing the Phytotherapeutic Potential of the Invasive *Carpobrotus edulis* (L.) N.E. Br Plant Threatening Plant Diversity. Soma Meslek Yüksekokulu Teknik Bilimler Dergisi, 1(37), 38–49. https://doi.org/10.47118/somatbd.1498192

Şekercioğlu, Ç. H., Anderson, S., Akçay, E., Bilgin, R., Can, Ö. E., Semiz, G., Tavşanoğlu, Ç., Yokeş, M. B., Soyumert, A., İpekdal, K., Sağlam, İ. K., Yücel, M., & Nüzhet Dalfes, H. (2011). Turkey's globally important biodiversity in crisis. Biological Conservation, 144(12), 2752–2769. https://doi.org/10.1016/j.biocon.2011.06.025

Sevgi, E., Kızılarslan Hançer, Ç., Yılmaz, H., & Akkaya, M. (2017). A new alien species record for the flora of Turkey: *Proboscidea louisianica* (Miller) Thell. Eurasian Journal of Forest Science, 5(2), 19–25. https://doi.org/10.31195/ejejfs.351280

Sheppard, C. S., Alexander, J. M., & Billeter, R. (2012). The invasion of plant communities following extreme weather events under ambient and elevated temperature. Plant Ecology, 213(8), 1289–1301. https://doi.org/10.1007/s11258-012-0086-5

Shiferaw, H., Alamirew, T., Dzikiti, S., Bewket, W., Zeleke, G., Teketay, D., & Schaffner, U. (2023). Water abstraction of invasive *Prosopis juliflora* and native *Senegalia senegal* trees: A comparative study in the Great Rift Valley Area, Ethiopia. Science of The Total Environment, 862, 160833. https://doi.org/10.1016/j.scitotenv.2022.160833

Simpson, M., Everard, M., Ricaurte, L., & McInnes, R. J. (2023). Ecosystem services. In Ramsar Wetlands (pp. 179–194). Elsevier. https://doi.org/10.1016/B978-0-12-817803-4.00014-0

Sinclair, J. S., Brown, J. A., & Lockwood, J. L. (2020). Reciprocal human-natural system feedback loops within the invasion process. NeoBiota, 62, 489–508. https://doi.org/10.3897/neobiota.62.52664

Su, Z., & Shangguan, Z. (2023). Nitrogen addition decreases the soil cumulative priming effect and favours soil net carbon gains in *Robinia pseudoacacia* plantation soil. Geoderma, 433, 116444. https://doi.org/10.1016/j.geoderma.2023.116444

Tarkan, A. S., Bayçelebi, E., Giannetto, D., Özden, E. D., Yazlık, A., Emiroğlu, Ö., Aksu, S., Uludağ, A., Aksoy, N., Baytaşoğlu, H., Kaya, C., Mutlu, T., Kırankaya, Ş. G., Ergüden, D., Per, E., Üremiş, İ., Candan, O., Kekillioğlu, A., Yoğurtçuoğlu, B., … Haubrock, P. J. (2024). Economic costs of non-native species in Türkiye: A first national synthesis. Journal of Environmental Management, 358, 120779. https://doi.org/10.1016/j.jenvman.2024.120779

Tarkan, A. S., Yapıcı, S., Kurtul, I., Błońska, D., Vilizzi, L., Bas, H., Farooq, S., Aldemir, C., Ucma Uysal, T., Giannetto, D., Bilge, G., Çiftçioğlu, M., Najafi-Majd, E., Aktay-Sözüer, L., Kaya, C., Bayçelebi, E., Aydin, I., Haubrock, P., Briski, E., & Soto, I. (2025). The first national assessment of established non-native species in Türkiye. https://doi.org/10.3897/arphapreprints.e161414

Thompson, J. P., & Ziska, L. H. (2014). Communicating the dynamic complexities of climate and ecology: species invasion and resource changes. In Invasive species and global climate change (pp. 9–21). CABI. https://doi.org/10.1079/9781780641645.0009

Trotta, G., Savo, V., Cicinelli, E., Carboni, M., & Caneva, G. (2020). Colonization and damages of Ailanthus altissima (Mill.) Swingle on archaeological structures: Evidence from the Aurelian Walls in Rome (Italy). International Biodeterioration & Biodegradation, 153, 105054. https://doi.org/10.1016/j.ibiod.2020.105054

Turbelin, A., & Catford, J. A. (2021). Invasive plants and climate change. In Climate Change (pp. 515–539). Elsevier. https://doi.org/10.1016/B978-0-12-821575-3.00025-6

Türkdoğdu, H., & Altinçekiç, T. H. (2018). Research on current planting of Istanbul O-1, O-2 highways, and some connection roads. Kastamonu

Üniversitesi Orman Fakültesi Dergisi, 18(2), 138–151. https://doi.org/10.17475/kastorman.330919

Uludag, A., Aksoy, N., Yazlık, A., Arslan, Z. F., Yazmış, E., Uremis, I., Cossu, T. A., Groom, Q., Pergl, J., Pyšek, P., & Brundu, G. (2017). Alien flora of Turkey: checklist, taxonomic composition and ecological attributes. NeoBiota, 35, 61–85. https://doi.org/10.3897/neobiota.35.12460

Ulus, A., Yilmaz, H., Akkemik, Ü., & Yilmaz, O. Y. (2021). Assessing Street-Level Distribution Of Tree Of Heaven (*Ailanthus altissima*) in Istanbul (Turkey). Applied Ecology and Environmental Research, 19(4), 2793–2802. https://doi.org/10.15666/aeer/1904_27932802

Wallace, K. J. (2007). Classification of ecosystem services: Problems and solutions. Biological Conservation, 139(3–4), 235–246. https://doi.org/10.1016/j.biocon.2007.07.015

Wang, Z., & Şakiroğlu, M. (2021). The Origin, Evolution, and Genetic Diversity of Alfalfa. https://doi.org/10.1007/978-3-030-74466-3_3

Waryszak, P., Lenz, T. I., Leishman, M. R., & Downey, P. O. (2018). Herbicide effectiveness in controlling invasive plants under elevated CO_2: Sufficient evidence to rethink weeds management. Journal of Environmental Management, 226, 400–407. https://doi.org/10.1016/j.jenvman.2018.08.050

Wolkovich, E. M., & Cleland, E. E. (2014). Phenological niches and the future of invaded ecosystems with climate change. AoB PLANTS, 6. https://doi.org/10.1093/aobpla/plu013

Wyse, S. V., Perry, G. L. W., & Curran, T. J. (2018). Shoot-Level Flammability of Species Mixtures is Driven by the Most Flammable Species: Implications for Vegetation-Fire Feedbacks Favouring Invasive Species. Ecosystems, 21(5), 886–900. https://doi.org/10.1007/s10021-017-0195-z

Yazlık, A., & Ambarlı, D. (2022). Do non-native and dominant native species carry a similar risk of invasiveness? A case study for plants in Turkey. NeoBiota, 76, 53–72. https://doi.org/10.3897/neobiota.76.85973

Yazlık, A., Pergl, J., & Pyšek, P. (2018). Impact of alien plants in Turkey assessed by the Generic Impact Scoring System. NeoBiota, 39, 31–51. https://doi.org/10.3897/neobiota.39.23598

Zemmer, F., Karaca, F., & Ozkaragoz, F. (2012). Ragweed pollen observed in Turkey: Detection of sources using back trajectory models. Science of the Total Environment, 430, 101–108. https://doi.org/10.1016/j.scitotenv.2012.04.067

CHAPTER 10

SUSTAINABLE SOIL MANAGEMENT IN A CHANGING CLIMATE THE BIOLOGICAL AND ECONOMIC IMPACTS OF ORGANIC AND MICROBIAL INPUTS

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INTRODUCTION

Climate change is increasingly disrupting the balance and productivity of agricultural ecosystems across the globe. With temperatures rising, rainfall patterns becoming less predictable, and extreme weather events occurring more frequently, soils and, by extension, the crops they support are under mounting pressure. As the very basis of plant growth and a key player in carbon storage, nutrient cycling, and broader ecosystem stability, soil has become one of the most vulnerable components of farming systems today.

Unfortunately, these climatic pressures are being exacerbated by unsustainable land management and farming practices. The results are now hard to ignore: depleted organic matter, rising salinity, erosion, and diminished microbial life are all clear signs of accelerating soil degradation. Together, these issues point to the urgent need for soil management approaches that not only protect the environment but also respond effectively to shifting climate realities.

In response, the use of organic soil amendments such as gyttja, biochar, vermicompost, and well-rotted farmyard manure has attracted renewed interest. These materials can significantly improve soil structure, moisture retention, pH balance, and the overall conditions for microbial life. Alongside these, microbial inoculants like plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi have shown promise in enhancing nutrient uptake, buffering stress, and activating soil enzymes that support plant vigor.

Exploring how organic and microbial inputs interact under climate-induced stress is becoming increasingly important. Integrated applications of these inputs may not only help crops tolerate drought or salinity more effectively, but also support climate goals like carbon sequestration and long-term land productivity.

At the same time, it’s important to consider the economic dimension. These nature-based approaches can reduce dependence on synthetic inputs, which are both costly and environmentally taxing, and offer new income streams through carbon markets and sustainability certifications. For both farmers and policymakers, these benefits matter.

This chapter aims to explore the potential of organic and microbial inputs as tools for building resilient, productive, and economically viable agroecosystems. Drawing on field research and relevant studies, we outline how these interventions can be implemented in real-world farming conditions while also considering the broader economic incentives and constraints that shape their adoption.

1. Concept of Soil Health and Its Key Components

Soil health is a broad and dynamic concept closely related to what we often call soil quality that reflects how well the soil can support life, whether in the form of crops, animals, or broader ecosystem services (Li et al., 2024). Since soil itself is a living, constantly evolving system, its role goes far beyond just being a growing medium. It helps feed the global population, cycles nutrients, stores carbon, and plays a part in regulating climate (Kumar et al., 2024; Rusu et al., 2025). As the pace of climate change increases, safeguarding soil health is no longer just a priority it's becoming a necessity (Millán et al., 2019).

What makes soil health especially complex is that it isn't based on a single factor. Instead, it results from the interaction of physical, chemical, and biological components that work together to support a resilient and productive farming system (Figure 1). On the physical side, soil texture, porosity, bulk density, and water-holding capacity all determine how well plant roots can grow and how easily water can move through the soil (Sharma et al., 2021; Castellini et al., 2025). These traits also influence how the soil responds to climate-related pressures like drought (Rivier et al., 2022). When the soil becomes overly compacted or loses its structure, it's more susceptible to erosion and flooding two factors that gradually reduce yields and degrade land quality over time (Matisic et al., 2024; Castellini & Iovino, 2024). Encouragingly, applying organic materials such as compost, biochar, or vermicompost has been shown to reverse some of this damage. These amendments help soils aggregate more effectively, lower compaction, and improve their ability to retain moisture (Rao et al., 2017; Mulatu & Bayata, 2024).

Chemically, soil health relies on a balance of essential nutrients, a neutral to stable pH, adequate cation exchange capacity (CEC), and minimal salt accumulation (Mosa et al., 2020). When these elements are thrown off often due to over-irrigation or improper fertilizer use the result can be nutrient deficiencies, acidification, or salinity buildup. These imbalances don't just affect plant growth; they also disrupt soil microbiota, further weakening soil function (Sikdar et al., 2020; Demirkıran & Bellitürk, 2022). Here too, organic inputs prove valuable. Humic-rich substances from these amendments help buffer chemical fluctuations and enhance nutrient retention (Debicka, 2024; Kamal et al., 2023). For instance, biochar has been observed to improve both CEC and nutrient-holding capacity (Riddle, 2018; Saltalı et al., 2023). Meanwhile, gyttja a humus-rich organic sediment has shown promise in alleviating salt stress impacts, providing another tool for improving soil chemical health (Debicka, 2024).

In the past, biological factors were often treated as secondary in soil science, but they are now recognized as some of the most telling indicators of soil health (Bhaduri et al., 2022; Daunoras et al., 2024). These include microbial abundance and diversity, enzymatic activity, and the presence of beneficial soil organisms (Semenov et al., 2025). A microbiologically rich soil tends to be more resilient under environmental stress, better at nutrient cycling, and more supportive of plant development (Rahul et al., 2022). Specific enzymes like dehydrogenase (DHA), urease, and catalase are frequently measured as indicators of soil biological activity. Their responsiveness to environmental shifts and agricultural inputs makes them useful tools for assessing soil condition (Utobo & Tewari, 2015; Igbinosa, 2015; Latkovic et al., 2020). Numerous studies have shown that applying organic amendments enhances microbial respiration, increases microbial biomass carbon (MBC), and boosts enzyme activity all signs of a biologically active and functioning soil system (Afzaal et al., 2018).

Soil health, in essence, is about keeping a balance between its physical, chemical, and biological dimensions (Peterson et al., 2021). When one aspect falters for instance, when soil is compacted and poorly aerated microbial communities begin to decline, nutrient cycling slows down, and plant productivity suffers (Župunski et al., 2022). Even when physical conditions are adequate, problems like imbalanced pH or excessive salinity can disrupt microbial and enzymatic activity (Louis et al., 2016; Bogati & Walczak, 2022). These issues are further compounded by climate change, which amplifies stress through erratic weather patterns, prolonged droughts, and increased salinization. These stressors destabilize soil processes and impair its overall function (Srivastava et al., 2016).

Addressing these multifaceted challenges demands an integrated approach one that restores physical structure, stabilizes chemical properties, and supports the biological life within the soil. In this context, organic inputs and microbial inoculants represent powerful tools. Beyond their ecological benefits, they also offer practical economic advantages by reducing dependence on synthetic inputs, stabilizing yields, and improving input-use efficiency. In an era increasingly focused on climate-smart agriculture, investing in soil health is not only environmentally wise but also a crucial step toward securing sustainable food systems for the future.

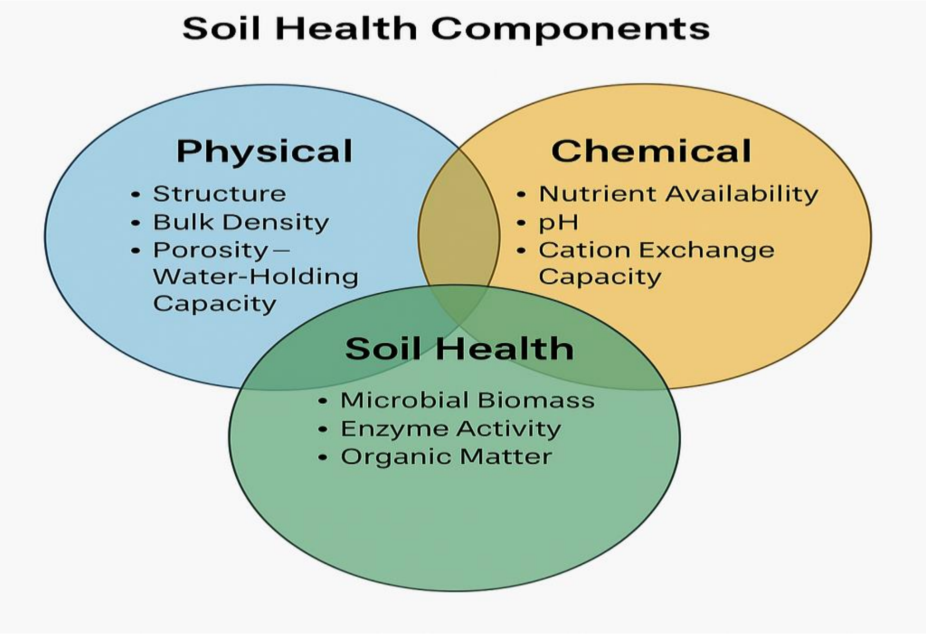

Figure 1. The three core components of soil health are physical, chemical, and biological and their interaction in maintaining overall soil functionality.

2. Effects of Organic Amendments on Soil Properties

Organic soil amendments are gaining increasing attention as essential tools for improving soil quality, especially in the face of mounting climate-related pressures on agriculture (Aytenew & Bore, 2020). Materials such as biochar, compost, vermicompost, farmyard manure, and gyttja offer multiple benefits, influencing the physical, chemical, and biological properties of soil all at once. Because they serve a wide variety of functions, these inputs are often at the center of strategies aimed at making soil management both more sustainable and more resilient (Yakupoğlu et al., 2022).

From a physical standpoint, organic materials help improve soil structure by enhancing aggregation, increasing porosity, and reducing bulk density. These changes make it easier for water to infiltrate and be retained in the soil an especially critical advantage in regions where drought is common and water conservation is a constant concern (Lal, 2020). For instance, vermicompost has been shown to loosen compacted soil and increase moisture retention, making it particularly effective in sandy or degraded conditions (Castellini et al., 2024).

On the chemical side, organic amendments improve soil fertility by raising the cation exchange capacity (CEC), balancing pH, and increasing the soil's organic matter content (Bashir et al., 2021). Biochar, in particular, stands out due to its porous texture and large surface area it can act as a long-term reservoir for nutrients, contributing to stable fertility over time (Hossain et al., 2020). Research suggests that biochar improves CEC, reduces nutrient leaching, and buffers pH, especially in soils that tend to be acidic (Liu et al., 2025). Likewise, gyttja a sediment naturally rich in humic substances has proven useful in enhancing organic carbon levels and mitigating salt stress, making it a promising amendment for saline or sodic soils (Mosa et al., 2020).

From a biological perspective, organic amendments breathe life into the soil. They help stimulate microbial activity, enhance enzyme function, and promote the diversity of beneficial microorganisms all key elements for efficient nutrient cycling and strong plant development (Shu et al., 2022). Applications of compost or farmyard manure, for instance, have been linked to increased microbial biomass carbon (MBC), while biochar, particularly when used alongside microbial inoculants, can boost enzyme activities such as dehydrogenase and urease (Pokharel et al., 2020).

A particularly promising approach involves pairing organic amendments with plant growth-promoting bacteria (PGPB) like Bradyrhizobium japonicum. This combination can significantly improve nodulation and nitrogen fixation in legumes, while also enhancing root structure and shoot growth even under challenging conditions like salinity or drought (Szpunar Krok et al., 2023).

Still, it’s important to note that the benefits of organic amendments aren’t uniform across all environments. Their effectiveness can vary depending on soil type, local climate, amendment composition, and application rate. This variability underscores the need for localized trials and longer-term studies to tailor use for maximum benefit. That said, the general consensus from recent research is clear: organic amendments play a vital role in supporting soil function and increasing its capacity to withstand the mounting stresses of climate change (Table 1).

Table 1: Some exemplary studies on the effects of various organic changes on soil characteristics

Study	Organic Amendment	Soil Type	Key Effects
Liu et al. (2020)	Biochar	Sandy loam	Increased total porosity and water retention capacity
Kabir et al. (2023)	Biochar	Various	Improved soil structure and water retention capacity
Iqbal et al. (2024)	Vermicompos t	Loamy soil	Improved soil structure and water retention capacity
Al Maamori et al. (2023)	Vermicompos t	Clay loam	Increased organic matter and nutrient content
Saltali et al. (2023)	Gyttja	Serpentin e soil	Decreased erosion susceptibility and heavy metal contents
Saltali and Kara (2022)	Gyttja	Acidic soil	Improved pH and nutrient availability
Lishan and Alemu (2024)	Farmyard manure	Sandy loam	Enhanced soil pH, organic carbon, and nutrient availability
Kumar et al. (2021)	Farmyard manure	Loamy soil	Increased microbial biomass and enzyme activities
Karamina and Fikrinda (2020)	Compost	Sandy soil	Improved soil organic matter and physical properties
Masud et al. (2020)	Poultry litter Biochar	Acidic soil	Ameliorated soil acidity and enhanced maize growth

3. Microbial Activity and Enzyme Indicators

Microbial activity is widely regarded as one of the most responsive and telling indicators of soil health and for good reason. Soil microbes are essential for breaking down organic materials, recycling nutrients, and facilitating the complex interactions between plants and their environment (Nikitin et al., 2022). Since these microbial communities are highly sensitive to environmental shifts and land management changes, they serve as a useful gauge for evaluating how well organic amendments perform under climate-related stress (Philippot et al., 2024).

Numerous studies have shown that inputs like biochar, vermicompost, gyttja, and well-rotted farmyard manure can significantly improve both microbial activity and diversity, even across a wide variety of soil types (Liu et al., 2025; Iqbal et al., 2024; Saltalı et al., 2023). These materials supply a steady stream of organic carbon, nutrients like nitrogen, and key micronutrients. At the same time, they enhance soil aeration and structure conditions that microbes depend on to flourish (Matisic et al., 2024). Vermicompost, in particular, is known for its abundance of microbial metabolites and humic substances, making it especially effective at encouraging microbial growth and function (Rehman et al., 2023).

One of the most common tools for evaluating microbial health in soil is enzyme activity analysis. These biochemical tests help shed light on the metabolic activity of microbial populations and are highly sensitive to changes in organic matter and environmental conditions (Paz-Ferreiro and Fu, 2016).

Dehydrogenase activity (DHA) is one of the most commonly used indicators of microbial activity in soils, largely because dehydrogenase enzymes are only found in living cells. This makes DHA a good reflection of the size and vitality of the active microbial population. When organic carbon is added to soil such as through compost or manure DHA levels tend to rise noticeably (Filipović et al., 2020). A number of studies have reported significant increases in DHA following applications of vermicompost or farmyard manure, especially in soils facing salinity or water stress challenges (Iqbal et al., 2024; Mbarki et al., 2020).

Urease activity is another important marker of soil biological health. It indicates the soil’s capacity to convert organic nitrogen into ammonium, a plant-available form of nitrogen. Organic inputs that are rich in nitrogen like compost, manure, or legume-based residues have been shown to significantly enhance urease activity (Abdo et al., 2020). This is particularly useful in low-input farming systems, where synthetic fertilizers are limited or absent (Ullah et al., 2023).

Catalase activity, on the other hand, gives insight into how well soil microbes can manage oxidative stress. This enzyme breaks down hydrogen peroxide a potentially harmful byproduct of aerobic respiration helping to protect microbial cells. When catalase levels are high, it often signals that the microbial community is healthy and active under aerobic conditions, with good oxygen availability in the soil. Some studies have found that biochar can enhance catalase activity, likely by improving soil porosity and oxygen diffusion (Wang et al., 2022).

Although less studied compared to other organic materials, gyttja a humus-rich sediment has been gaining attention for its positive effects on microbial activity. Its high levels of humic substances and organic carbon make it especially valuable in degraded or saline soils. Applications of gyttja have been linked to increases in both dehydrogenase and urease activity, particularly in soils with poor fertility or elevated salt levels (Saltalı et al., 2023; Saltalı and Kara, 2022).

Overall, enzyme activity assays offer a cost-effective and insightful way to assess the biological function of soils. When used alongside measurements of microbial biomass and diversity, they provide a more complete picture of how organic amendments are influencing soil health. Because these enzyme responses are often faster than physical or chemical changes, they are particularly useful for monitoring short- and medium-term shifts in soil condition.

4. Plant Physiological Responses to Organic and Microbial Amendments

Plant growth and overall productivity are deeply influenced by soil health a connection that becomes even more crucial in regions affected by drought, salinity, or nutrient limitations, all of which are becoming more widespread due to climate change (Elbasiouny et al., 2022). In this context, organic soil amendments and microbial inoculants are drawing growing interest not only for their role in improving soil conditions but also for their ability to enhance plant physiological functions. Their positive effects range from boosting photosynthetic activity to encouraging stronger root development and helping plants better regulate their internal defense systems (Sivaram et al., 2023).

One of the earliest physiological responses observed in plants treated with these amendments is an increase in chlorophyll content. This is commonly measured using a SPAD (Soil Plant Analysis Development) meter, a simple yet reliable tool to assess leaf greenness and, indirectly, nitrogen status (Barutçular et al., 2016). Higher SPAD values are typically associated with improved nitrogen uptake and enhanced photosynthetic efficiency. Inputs such as vermicompost, compost, and biochar have consistently been shown to elevate SPAD readings under both optimal and stress conditions. This improvement is largely due to their ability to enhance the availability of critical nutrients like nitrogen and magnesium, which are key components in chlorophyll synthesis (Iqbal et al., 2023).

Beyond supporting above-ground growth, both organic and microbial applications significantly contribute to the development of plant root systems, enhancing the plant's ability to access water and nutrients more efficiently. For example, amendments like farmyard manure and gyttja have been found to improve soil structure and reduce compaction, which encourages deeper and more widespread root growth (Iqbal et al., 2024; Saltalı et al., 2023). Meanwhile, microbial inoculants such as Bradyrhizobium japonicum and arbuscular mycorrhizal fungi take this a step further by forming symbiotic associations with plant roots. These relationships not only enhance phosphorus uptake but also improve water-use efficiency benefits that become particularly important under stressful conditions like drought or salinity (Takács et al., 2018).

Equally important is the role of these treatments in helping plants manage oxidative stress, a common physiological response to environmental challenges. Under such stress, plants tend to generate elevated levels of reactive oxygen species (ROS), which can damage cellular structures and interfere with normal metabolic processes. Organic inputs and beneficial microorganisms help mitigate these effects by stimulating the plant's antioxidant defense system, including enzymes like superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX). These enzymes work to neutralize ROS, safeguarding cellular integrity and enhancing the plant’s resilience against adverse environmental conditions (Sachdev et al., 2021; Wang et al., 2024).

Many organic amendments also stimulate the production of osmoprotectants in plants, such as proline, which plays a key role in maintaining cellular stability and water balance particularly in environments affected by drought or salinity (Singh et al., 2015). Research has consistently shown elevated proline levels in plants cultivated in soils amended with biochar, vermicompost, or plant growth-promoting rhizobacteria (PGPR), often accompanied by a noticeable reduction in stress-related indicators like malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) (Malik et al., 2022).

These physiological and biochemical changes work synergistically to improve overall plant performance. Benefits include increased total biomass, healthier root-to-shoot ratios, and more efficient water usage. Ultimately, the enhanced nutrient uptake, improved microbial interactions, and strengthened stress responses provided by these treatments lead to better crop yields whether under favorable conditions or in the face of climate-induced challenges. A detailed overview of these effects on soil and plant responses can be found in Table 2.

Table 2. Summary of Soil and Plant Effects of Organic and Microbial Amendments

	Short Term Effects	**Long Term Effects**
Soil Level Effects	Enhanced microbial activity Increased enzyme levels Improved pH and nutrient availability	Improved soil structure and porosity Carbon sequestration Increased soil fertility sustainability
Plant Level Effects	Improved chlorophyll (SPAD) Stimulated root growth Increased osmoprotectants (Proline)	Higher stress tolerance (e.g., drought, salinity) Greater biomass/yield Resilience against oxidative damage (lower MDA, H_2O_2)

To sum up, using organic and microbial inputs in crop production presents a practical and balanced way to improve plant health and productivity. These inputs don't just help plants grow better or produce more; they also give plants a stronger defense system to deal with stress from the environment. By improving both the soil and how plants respond to challenges like drought or salinity, these treatments play a key role in building a more sustainable and climate-ready type of farming.

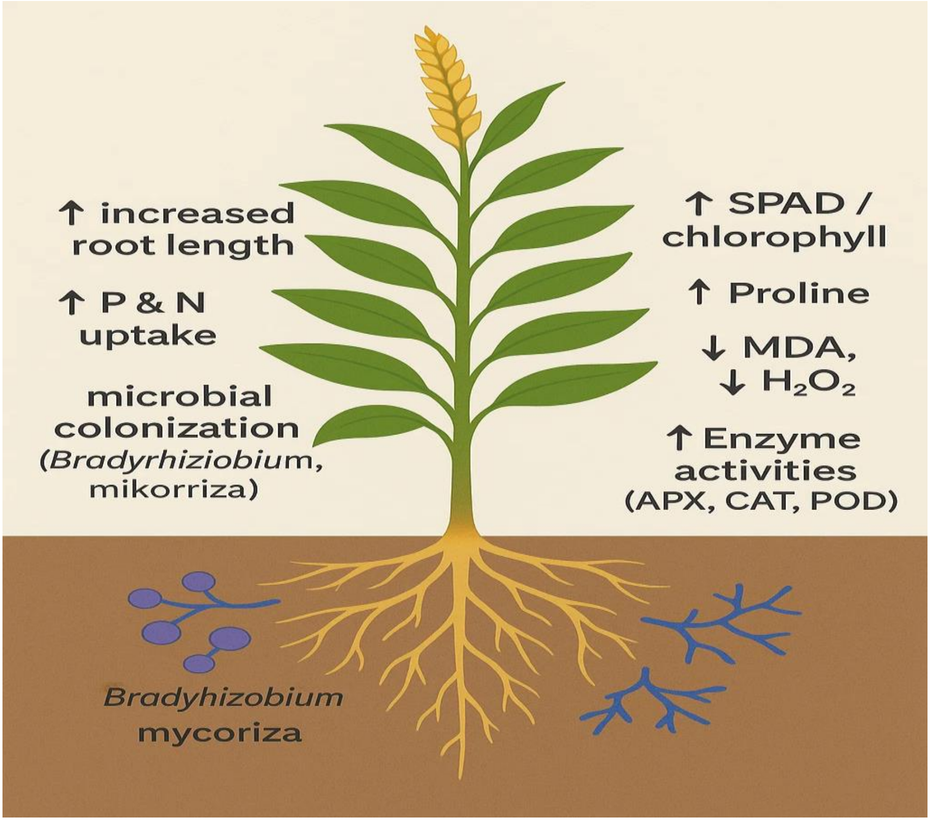

Figure 2: Plant Physiological Responses under Organic and Microbial Treatments

5. Organic and microbial applications from an economic perspective

In today's world, where climate issues are more serious than ever, the economic side of using agricultural inputs is just as important as their environmental benefits. Organic and microbial soil amendments like biochar, vermicompost, and plant growth-promoting rhizobacteria (PGPR) have drawn interest because of their ability to improve soil conditions. Still, if these tools are going to be widely used, farmers need to see results that are both reliable and repeatable. The problem is, even though microbial products tend to work well under controlled or experimental conditions, their effects don't always hold up in different soil types, crop species, or environments. That inconsistency makes it hard to apply them across the board in real-life farming (Naamala and Smith, 2020).

Introducing organic and microbial inputs into regular farming isn't always easy, especially since conventional agriculture is still heavily shaped by the agrochemical market. Even though laws around chemical use are getting tighter and their prices are going up, farmers are also facing more social and policy pressure to cut down on chemical residues in both food and soil. At the same time, shrinking profit margins, more emphasis on integrated pest management (IPM), and rising demand for organic food are pushing farmers to look for new ways to manage their fields (Sessitsch et al., 2018; Phillips, 2020).

In the long run, for organic and microbial options to really take hold in agriculture, it's not enough for them to work they also need to make financial sense and be easy enough for farmers to apply. With the negative impacts of conventional fertilizers becoming more obvious, researchers are putting more focus on sustainable alternatives. In that light, improving how plants, nutrients, and microbes work together has become a key focus not just for the sake of soil health, but also to improve efficiency, raise yields, and help farmers cut costs overall (Jacoby et al., 2017).

Recent research has shown that plant growth-promoting rhizobacteria (PGPR) can play a major role in supporting plant growth even in tough conditions like nutrient-poor soils, environmental stress, or contaminated areas. These beneficial microbes help stabilize yields, especially in regions facing harsh climates, giving farmers a valuable tool to reduce production risks while also supporting long-term economic and environmental sustainability. Interest in this field has grown rapidly in recent years, thanks in part to advances in biotechnology that make it easier to identify and understand how specific microbial communities function (Castiglione et al., 2021).

At the same time, agroecological methods have started getting more attention, especially as farmers and researchers look for ways to reduce chemical use and rely more on natural ecological balances and biodiversity (Le Mire et al., 2016). The basic idea behind agroecology is to protect biodiversity, support natural biological processes, and keep the nutrient and energy cycles of the ecosystem running smoothly. In this context, biostimulants products that not only help plants grow directly but also encourage the activity of useful microbes in the soil are proving to be valuable tools for increasing yield without harming the environment (Hellequin et al., 2020). Their growing popularity isn’t just changing how we farm; it’s also having an impact on how input markets are shaped, how agricultural policy is formed, and even how trade between countries is approached.

That said, for microbial products to really find their place in modern agriculture, they need to be backed by clear and reliable regulations. In Europe, the European Biostimulants Industry Council (EBIC), founded back in 2011, has played a major role in pushing for consistent rules for both microbial and organic-based inputs. One notable development is the refinement of the Component Material Category 7 (CMC 7), which has helped clarify things like product safety, quality control, and legal expectations. Thanks to these improvements, there’s been more room for innovation and easier access for new microbial products in the market (Castiglione et al., 2021).

To sum up, bringing microbial inputs into farming systems isn’t just about sustainability; it also opens up real economic benefits. These include lower production costs, better handling of risk, and opportunities to tap into newer markets all of which become more possible with stronger and more predictable regulatory support.

5.1. Yield and Productivity Enhancement

One of the main reasons why organic and microbial inputs are gaining popularity in agriculture is because they’re really good at improving crop yields. Different types of soil bacteria especially plant growth-promoting rhizobacteria (PGPR) help plants grow by doing a range of things like making nutrients more accessible, producing natural growth hormones, and helping plants handle stress better. As research keeps uncovering the specific roles of various PGPR strains, these microbes are becoming more common as biofertilizers in today’s farming systems (Vessey, 2003). What’s particularly interesting is that in some studies, even when chemical fertilizer use was reduced, biological inputs still kept yields at strong levels (Adesemoye et al., 2009).

Another big plus is how effective these organic and microbial inputs can be in low-input or resource-limited farming. They’re especially useful in dealing with nutrient problems like low nitrogen or phosphorus, which makes them highly valuable in sustainable production. On top of that, they help plants deal with tough environmental conditions things like high temperatures, drought, or salt in the soil (Rouphael and Colla, 2020; Rahman et al., 2025). By improving how crops handle these stresses, they don't just prevent yield losses; they also help reduce economic uncertainty and support more consistent incomes for farmers trying to adapt to a changing climate. Integrating organic and microbial amendments into agricultural systems offers a wide range of co-benefits: reducing reliance on synthetic inputs, limiting environmental harm, improving both yields and crop quality, and supporting the health of people and ecosystems alike.

In conclusion, when applied thoughtfully and strategically, these inputs can be powerful tools for advancing sustainable agriculture. They not only deliver clear environmental benefits but also support economic sustainability by boosting productivity, enhancing product quality, and improving farm profitability.

5.2. Economic Incentives and Emerging Market Developments

The European Union's Green Deal from 2019 laid out some pretty ambitious targets for agriculture including significant cuts in the use of pesticides and synthetic fertilizers by 2030. These goals are part of a wider shift toward greener and more sustainable farming across the continent. As these new rules and expectations begin to take shape, countries that export to the EU like Türkiye are starting to feel the pressure to keep up with the changing standards. In this situation, turning to organic and microbial inputs is emerging as a smart move. Not only do they help farmers comply with EU requirements, but they can also give them an edge in competitive markets both at home and abroad (European Commission, 2020; Batista and Singh, 2021).

What makes these inputs especially appealing is that they contribute to ecosystem services that also bring financial returns most notably through carbon storage. Take biochar, for example: it can hold carbon in the soil for years, which not only helps fight climate change but also links farming to the global carbon credit economy. This gives farmers a new potential income stream (Zomer et al., 2017; Smith et al., 2020). For all these reasons, rural development strategies should support the wider use of these practices not just to meet environmental goals, but to help farmers tap into climate-smart, nature-based farming that actually pays off.

Turning to microbial biostimulants and organic fertilizers isn't just good for the environment it can also help farmers qualify for sustainable agriculture certifications. These certifications open the door to high-value markets, particularly in regions like Europe, North America, and Japan where strict production standards are in place. Interestingly, even when such certifications aren't a strict requirement for export, products made with organic and microbial inputs often fetch higher prices (FAO, 2021).

On the supply side, growing global demand is opening up new market opportunities, especially for countries that produce these inputs. That said, getting into this space isn't always easy. The sector is heavily shaped by high R&D costs and complex technology, which has led to a market dominated by a few large players creating monopoly- or oligopoly-like conditions in some cases (FAO, 2021).

At present, nitrogen-fixing inoculants account for nearly 79% of the biofertilizer market worldwide a segment valued at around $1.5 billion and projected to double by 2024. North America, including the U.S., Canada, and Mexico, leads in production, holding roughly 27.7% of global output. In terms of demand, Europe and Latin America are currently the biggest consumers, with China and India following close behind (Soumare et al., 2020).

The intersection of scientific innovation and rising market interest has sparked impressive economic growth in the microbial inputs sector. With ongoing breakthroughs in biotechnology and a wider range of agricultural applications, microbial products are becoming increasingly attractive to investors and agribusinesses alike (Sessitsch et al., 2018). Industry forecasts estimate that the global market for these products will grow from approximately USD 4.5 billion in 2021 to nearly USD 12 billion by 2027 (FBI, 2021). Riding this wave of growth, several biotech startups including AgBiome, BioInnovations, Indigo, Marrone Bio Innovations, and New Leaf Symbiotics have positioned themselves at the forefront of microbial technology development.

Meanwhile, traditional giants in agriculture and food production have begun shifting capital toward biological alternatives. Since 2012, the sector has seen a surge in acquisitions, licensing deals, and partnerships worth hundreds of millions of dollars (Olson, 2015). As a result, the five largest microbial inoculant producers now hold a commanding share of the global market (Sammauria et al., 2020).

What's particularly striking is that microbial inputs are no longer viewed solely through an ecological lens. They're now seen as economically valuable assets as well. From an agricultural economics perspective, this sector represents a strategic opportunity not just for boosting high-value production and generating skilled employment, but also for driving broader economic growth. Importantly, scaling up domestic production of microbial inputs can reduce dependence on foreign chemical inputs, bolster export potential, and contribute positively to national income.

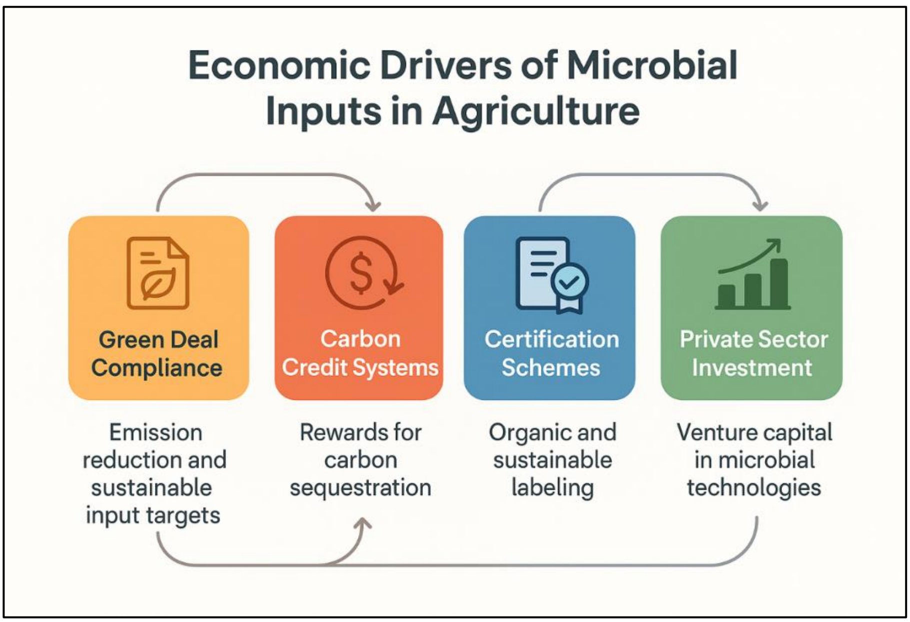

Figure 3: Key Economic Incentives for Organic and Microbial Input Adoption

5.3. The Need for Research, Development, and Extension Support

Bringing organic and microbial amendments into the heart of modern agriculture isn't just a matter of knowing the science it also demands steady support through research funding and a reliable extension network. For many small and mid-sized farmers, the decision to adopt new practices often comes down to whether they can access clear, practical information and determine if these methods will actually pay off (Feder et al., 1985). In reality, the success of any agricultural innovation hinges on the people who help deliver it: extension agents, farmer organizations, and independent advisors who act as the bridge between research and the field (Klerkx et al., 2012).

This is where the Agricultural Knowledge and Information Systems (AKIS) framework proves valuable. AKIS emphasizes the importance of turning scientific insights into actionable knowledge that farmers can use on the ground. By streamlining communication and knowledge exchange, it helps farmers make smarter, more informed decisions and adapt quickly when needed (Röling & Engel, 1991).

As Spielman and Birner (2008) pointed out, even the most promising R&D efforts need strong national coordination to truly drive innovation. And it's not just about rolling out new technologies extension services must also help farmers become more resilient in the face of rising challenges like climate change (Tambo & Abdoulaye, 2012).

Ultimately, if organic and microbial inputs are to play a lasting role in sustainable agriculture, extension models must evolve too. Success depends on collaboration between public institutions and the private sector, ensuring farmers have access to not only new ideas, but also the training, tools, and confidence to implement them effectively.

Conclusion

Climate change continues to challenge the future of agricultural systems, particularly by undermining soil health, crop stability, and long-term productivity. In light of these challenges, there has been growing interest in using organic and microbial amendments such as biochar, vermicompost, and plant growth-promoting microbes not only for their agronomic potential but also for their contributions to environmental sustainability.

What makes these inputs especially valuable is their multifaceted role: they enhance soil structure, improve nutrient efficiency, and support microbial life, while also offering a buffer against abiotic stresses like drought and salinity. Such improvements, even if sometimes modest, can make a real difference especially for farmers working in risk-prone or resource-limited environments.

On the economic side, organic and microbial inputs are gradually becoming part of a broader shift toward climate-smart agriculture. Tools like carbon credit mechanisms and sustainable certification programs are starting to reshape how these products are viewed not just as technical solutions, but as market-oriented investments. For countries exporting to high-standard markets, this shift is already creating both pressure and opportunity.

Still, wider adoption of these practices won't happen on its own. Smallholder farmers in particular often face information gaps or financial constraints that limit their ability to shift away from conventional methods. That's why investment in extension services and region-specific research remains crucial. Bridging the gap between science and practice is not just a technical issue it's also about building trust and making innovation genuinely accessible.

In short, while organic and microbial inputs are not a silver bullet, they represent a realistic and increasingly necessary step toward more resilient and sustainable agriculture. If supported by the right policies, informed advisory systems, and fair market conditions, these nature-based solutions could help shape the next generation of productive and ecologically sound farming practices.

REFERENCES

Abdo, A. I., Xu, Y., Shi, D., Li, J., Li, H., El Sappah, A. H., ... and Kuzyakov, Y. (2022). Nitrogen transformation genes and ammonia emission from soil under biochar and urease inhibitor application. *Soil and Tillage Research*, *223*, 105491.

Adesemoye, A. O., Torbert, H. A., and Kloepper, J. W. (2009). Plant growth promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial ecology, 58, 921 929.

Afzaal, M., Mukhtar, S., Malik, A., Murtaza, R., and Nazar, M. (2018). Paddy soil microbial diversity and enzymatic activity in relation to pollution. *Environmental pollution of paddy soils*, 139 149.

Al Maamori, H. A., Salman, A. D., Al Budeiri, M., Al Shami, Y. A. O., and Al shaabani, E. M. (2023, July). Effect of vermicompost production on some soil properties and nutrients in plants. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1214, No. 1, p. 012006). IOP Publishing.

Amoah Antwi, C., Kwiatkowska Malina, J., Thornton, S. F., Fenton, O., Malina, G., and Szara, E. (2020). Restoration of soil quality using biochar and brown coal waste: A review. *Science of the Total Environment*, *722*, 137852.

Asghar, N., Akram, N. A., Ameer, A., Shahid, H., Kausar, S., Asghar, A., ... and Jahangir, I. (2021). Foliar applied hydrogen peroxide and proline modulate growth, yield and biochemical attributes of wheat (Triticum aestivum L.) Under varied n and p levels. *Fresenenius Environmental Bulletin*, *30*(5), 5445 5465.

Aytenew, M., and Bore, G. (2020). Effects of organic amendments on soil fertility and environmental quality: A review. *Plant Sci*, *8*(5), 112 119.

Barutçular, C., Yıldırım, M., Koc, M., Akıncı, C., Toptaş, I., Albayrak, O., ... and El Sabagh, A. (2016). Evaluation of SPAD chlorophyll in spring wheat genotypes under different environments. *Fresenius Environmental Bulletin*, *25*(4), 1258 1266.

Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D., ... and Bhat, R. A. (2021). Soil organic matter and its impact on soil properties and nutrient status. *Microbiota and biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs*, 129 159.

Batista, B. D., and Singh, B. K. (2021). Realities and hopes in the application of microbial tools in agriculture. *Microbial Biotechnology*, *14*(4), 1258 1268.

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B. C., Munda, S., and Dari, B. (2022). A review on effective soil health bio indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology*, *13*, 938481.

Bhardwaj, D., Ansari, M. W., Sahoo, R. K., and Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microbial cell factories, 13, 1 10.

Bogati, K., and Walczak, M. (2022). The impact of drought stress on soil microbial community, enzyme activities and plants. *Agronomy*, *12*(1), 189.

Castellini, M., Bondì, C., Giglio, L., and Iovino, M. (2024). Impact of vermicompost addition on water availability of differently textured soils. *Heliyon*, *10*(15).

Castellini, M., Bondì, C., Leogrande, R., Giglio, L., Vitti, C., Mastrangelo, M., and Bagarello, V. (2025). Evaluating the Effects of Compost, Vermicompost, and Biochar on Physical Quality of Sandy Loam Soils. *Applied Sciences*, *15*(6), 3392.

Castiglione, A. M., Mannino, G., Contartese, V., Bertea, C. M., and Ertani, A. (2021). Microbial Biostimulants as Response to Modern Agriculture Needs: Composition, Role and Application of These Innovative Products. Plants, 10(8), 1533. https://doi.org/10.3390/plants10081533

Daunoras, J., Kačergius, A., and Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, *13*(2), 85.

Debicka, M. (2024). The Role of Organic Matter in Phosphorus Retention in Eutrophic and Dystrophic Terrestrial Ecosystems. *Agronomy*, *14*(8), 1688.

Despommier, D. (2024). Vertical farming: a holistic approach towards food security. *Frontiers in Science*, *2*, 1473141.

Elbasiouny, H., El Ramady, H., Elbehiry, F., Rajput, V. D., Minkina, T., and Mandzhieva, S. (2022). Plant nutrition under climate change and soil carbon sequestration. *Sustainability*, *14*(2), 914.

FAO. (2021). The State of Agricultural Commodity Markets 2020: Agricultural markets and sustainable development – Global value chains, smallholder farmers and digital innovations. Rome. https://doi.org/10.4060/cb0665en

FBI, (2021). Fortune Business Insights Market Research Report. https://www.fortunebusinessinsights.com/industry reports/agricultural microbial market 100412 Erişim Tarihi: 29.05. 2025

Feder, G., Just, R. E., and Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. Economic development and cultural change, 33(2), 255 298.

Filipović, L., Romić, M., Sikora, S., Huić Babić, K., Filipović, V., Gerke, H. H., and Romić, D. (2020). Response of soil dehydrogenase activity to salinity and cadmium species. *Journal of Soil Science and Plant Nutrition*, *20*, 530 536.

Hellequin, E.; Monard, C.; Chorin, M.; Le Bris, N.; Daburon, V.; Klarzynski, O.; Binet, F. Responses of active soil microorganisms facing to a soil biostimulant input compared to plant legacy effects. Sci. Rep. 2020, 10, 13727.

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., ... and Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*, 379 420.

Igbinosa, E. O. (2015). Effect of cassava mill effluent on soil microbial activity. *Environmental Monitoring and Assessment*, 187, 4651.

Iqbal, A., Khan, R., Hussain, Q., Imran, M., Mo, Z., Hua, T., ... and Tang, X. (2024). Vermicompost application enhances soil health and plant physiological and antioxidant defense to conferring heavy metals tolerance in fragrant rice. *Frontiers in Sustainable Food Systems*, *8*, 1418554.

Jacoby, R.; Peukert, M.; Succurro, A.; Koprivova, A.; Kopriva, S., (2017). The role of soil microorganisms in plant mineral nutrition—Current knowledge and future directions. Front. Plant Sci, 8, 1–19.

Jeffery, S., Verheijen, F. G., van der Velde, M., and Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta analysis. Agriculture, ecosystems and environment, 144(1), 175 187.

Kabir, E., Kim, K. H., and Kwon, E. E. (2023). Biochar as a tool for the improvement of soil and environment. *Frontiers in Environmental Science*, *11*, 1324533.

Kamal, A., Mian, I. A., and Tariq, M. (2023). Sustainable maize farming: organic soil amendments boost maize production and soil quality. *Plant Bulletin*, *2*(1), 41 58.

Karamina, H., and Fikrinda, W. (2020). Soil amendment impact to soil organic matter and physical properties on the three soil types after second corn cultivation. *AIMS Agriculture and food*, *5*(1), 150 168.

Klerkx, L., Van Mierlo, B., and Leeuwis, C. (2012). Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. Farming Systems Research into the 21st century: The new dynamic, 457 483.

Kumar, S., Dhar, S., Barthakur, S., Rajawat, M. V. S., Kochewad, S. A., Kumar, S., ... and Meena, L. R. (2021). Farmyard manure as K fertilizer modulates soil biological activities and yield of wheat using the integrated fertilization approach. *Frontiers in Environmental Science*, *9*, 764489.

Kumar, S., Meena, R. S., Sheoran, P., Jhariya, M. K., and Ghosh, S. (2024). *Regenerative Agriculture for Sustainable Food Systems*. Springer.

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*(5), 3265 3277.

Latkovic, D., Maksimovic, J., Dinic, Z., Pivic, R. (2020). Case study on biofertilizer effects on enzyme activity. *Biology*, 9(12), 452.

Le Mire, G.; Nguyen, M.L.; Fassotte, B.; Du Jardin, P.; Verheggen, F.; Delaplace, P.; Haissam Jijakli, M. Implementing plant biostimulants and biocontrol strategies in the agroecological management of cultivated ecosystems. A review. Biotechnol. Agron. Soc. Environ. 2016, 20, 299–313.

Li, Z., Li, Y., Yao, B., and Carmona, C. (2024). Optimising management practices to secure grassland agroecosystems' sustainability. *Frontiers in Sustainable Food Systems*, *8*, 1507692.

Lishan, T., and Alemu, F. (2024). Elucidating sole application of farmyard manure and blended NPSB fertilizer effects on soil properties at Bench Shako and West Omo zone, South West Ethiopia. *Heliyon*, *10*(1).

Liu, S., Cen, B., Yu, Z., Qiu, R., Gao, T., and Long, X. (2025). The key role of biochar in amending acidic soil: reducing soil acidity and improving soil acid buffering capacity. *Biochar*, *7*(1), 52.

Liu, Z., Dugan, B., Masiello, C. A., and Gonnermann, H. M. (2017). Biochar particle size, shape, and porosity act together to influence soil water properties. *Plos one*, *12*(6), e0179079.

Louis, B. P., Maron, P. A., Menasseri Aubry, S., Sarr, A., Lévêque, J., Mathieu, O., ... and Viaud, V. (2016). Microbial diversity indexes can explain soil carbon dynamics as a function of carbon source. *PLoS One*, *11*(8), e0161251.

Malik, L., Sanaullah, M., Mahmood, F., Hussain, S., Siddique, M. H., Anwar, F., and Shahzad, T. (2022). Unlocking the potential of co applied biochar and plant growth promoting rhizobacteria (PGPR) for sustainable agriculture under stress conditions. *Chemical and biological technologies in agriculture*, *9*(1), 58.

Masud, M. M., Abdulaha Al Baquy, M., Akhter, S., Sen, R., Barman, A., and Khatun, M. R. (2020). Liming effects of poultry litter derived biochar on soil acidity amelioration and maize growth. *Ecotoxicology and Environmental Safety*, *202*, 110865.

Matisic, M., Dugan, I., and Bogunovic, I. (2024). Challenges in sustainable agriculture—the role of organic amendments. *Agriculture*, *14*(4), 643.

Mbarki, S., Skalicky, M., Talbi, O., Chakraborty, A., Hnilicka, F., Hejnak, V., ... and Abdelly, C. (2020). Performance of Medicago sativa grown in clay soil favored by compost or farmyard manure to mitigate salt stress. *Agronomy*, *10*(1), 94.

Millán, R., Schröder, P., and Sæbø, A. (2019). Options for Transition of Land Towards Intensive and Sustainable Agricultural Systems. *Frontiers in Plant Science*, *10*, 346.

Mosa, A. A., Taha, A., and Elsaeid, M. (2020). Agro environmental applications of humic substances: A critical review. *Egyptian Journal of Soil Science*, *60*(3), 211 229.

Mulatu, G., and Bayata, A. (2024). Vermicompost as Organic Amendment: Effects on Some Soil Physical, Biological Properties and Crops Performance on Acidic Soil: A Review. *Frontiers*, *10*(4), 66 73.

Naamala, J., and Smith, D.L. (2020) Relevance of plantgrowth promoting microorganisms and their derived com pounds, in the face of climate change. Agron 10: 1179.https://doi.org/10.3390/agronomy10081179

Nandi, A., Yan, L. J., Jana, C. K., and Das, N. (2019). Role of catalase in oxidative stress-and age-associated degenerative diseases. *Oxidative medicine and cellular longevity*, *2019*(1), 9613090.

Nikitin, D. A., Semenov, M. V., Chernov, T. I., Ksenofontova, N. A., Zhelezova, A. D., Ivanova, E. A., ... and Stepanov, A. L. (2022). Microbiological indicators of soil ecological functions: a review. *Eurasian Soil Science*, *55*(2), 221 234.

Olson, S. (2015) An analysis of the biopesticide market now and where it is going. Outlooks Pest Manag 26: 203–206. https://doi.org/10.1564/v26_oct_04

Paz-Ferreiro, J., and Fu, S. (2016). Biological indices for soil quality evaluation: perspectives and limitations. *Land Degradation and Development*, *27*(1), 14 25.

Peterson, C. W., Li, T., Jiang, W., Hughes, T. L., and Bahl, G. (2021). Trapped fractional charges at bulk defects in topological insulators. *Nature*, *589*(7842), 376 380.

Philippot, L., Chenu, C., Kappler, A., Rillig, M. C., and Fierer, N. (2024). The interplay between microbial communities and soil properties. *Nature Reviews Microbiology*, *22*(4), 226 239.

Phillips, M.W.A. (2020) Agrochemical industry development,trends in RandD and the impact of regulation. Pest ManagSci 76: 3348–3356. https://doi.org/10.1002/ps.5728

Pokharel, P., Ma, Z., and Chang, S. X. (2020). Biochar increases soil microbial biomass with changes in extra and intracellular enzyme activities: a global meta analysis. *Biochar*, *2*, 65 79.

Rahman, S. U., Han, J. C., Yasin, G., Imtiaz, M. T., Zhao, X., Alharbi, S. A., ... and Alarfaj, A. A. (2025). Synergetic effects of potassium and biochar on morphological, physiological, and biochemical attributes of maize crop grown under different levels of drought stress. *BMC Plant Biology*, *25*(1), 402.

Rahul, R., Sharma, P., Singh, A., Singh, J., and Kumar, M. (2022). Soil enzymes and their role in soil health improvement. In *Advances in Agricultural and Industrial Microbiology: Volume 1: Microbial Diversity and Application in Agroindustry* (pp. 39 61). Singapore: Springer Nature Singapore.

Rao, P. L., Jayasree, G., Pratibha, G., and Prakash, T. R. (2017). Effect of soil amendments on physical properties of soil in maize (zea mays L.). *International Journal of Current Microbiology and Applied Sciences*, *6*, 2082 2091.

Rehman, S. U., De Castro, F., Aprile, A., Benedetti, M., and Fanizzi, F. P. (2023). Vermicompost: Enhancing plant growth and combating abiotic and biotic stress. *Agronomy*, *13*(4), 1134.

Riddle, M. (2018). Phosphorus leaching from Swedish arable organic soils. *Acta Universitatis Agriculturae Sueciae*, (2018: 50).

Rivier, P. A., Jamniczky, D., Nemes, A., Makó, A., Barna, G., Uzinger, N., ... and Farkas, C. (2022). Short term effects of compost amendments to soil on soil structure, hydraulic properties, and water regime.

Röling, N and Engel, P. (1991). "The development of the concept of agricultural knowledge information systems (AKIS): implications for extension." 125 137.

Rouphael, Y., and Colla, G. (2020). Biostimulants in agriculture. Frontiers in plant science, 11, 40.

Rusu, M., Filip, M., Cara, I. G., Țopa, D., and Jităreanu, G. (2025). Soil Nutrient Dynamics and Farming Sustainability Under Different Plum Orchard Management Practices in the Pedoclimatical Conditions of Moldavian Plateau. *Agriculture*, *15*(5), 509.

Sachdev, S., Ansari, S. A., Ansari, M. I., Fujita, M., and Hasanuzzaman, M. (2021). Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms. *Antioxidants*, *10*(2), 277.

Saltalı, K., and Kara, Z. (2022). Effects of gyttja applications on some chemical properties of acidic soils. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi*, *25*(2), 374 379.

Saltalı, K., Solak, S., Özdoğan, A., Kara, Z., and Yakupoğlu, T. (2023). Gyttja as a soil conditioner: changes in some properties of agricultural soils formed on different parent materials. *Sustainability*, *15*(12), 9329.

Sammauria, R., Yadav, A., Sharma, P., and Singh, J. (2020). Microbial inoculants: A boon for sustainable agriculture. Environmental Sustainability, 3(3), 287–298. https://doi.org/10.1007/s42398 020 00107 x

Semenov, M. V., Zhelezova, A. D., Ksenofontova, N. A., Ivanova, E. A., Nikitin, D. A., and Semenov, V. M. (2025). Microbiological Indicators for Assessing the Effects of Agricultural Practices on Soil Health: A Review. *Agronomy*, *15*(2), 335.

Sessitsch, A., Brader, G., Pfaffenbichler, N., Gusenbauer, D., and Mitter, B. (2018) The contribution of plant microbiota to economy growth. Microb Biotechnol 11: 801. https://doi.org/10.1111/1751 7915.13290

Shu, X., He, J., Zhou, Z., Xia, L., Hu, Y., Zhang, Y., ... and Wang, C. (2022). Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta analysis. *Science of the Total Environment*, *829*, 154627.

Sikdar, A., Hossain, M. S., and Feng, S. (2020). Heavy metal pollution of environment by mine tailings and the potential reclamation techniques: a review. *J. Biol. Agric. Health*, *10*, 33 37.

Singh, M., Kumar, J., Singh, S., Singh, V. P., and Prasad, S. M. (2015). Roles of osmoprotectants in improving salinity and drought tolerance in plants: a review. *Reviews in environmental science and bio/technology*, *14*, 407 426.

Sivaram, A. K., Abinandan, S., Chen, C., Venkateswartlu, K., and Megharaj, M. (2023). Microbial inoculant carriers: Soil health improvement and moisture retention in sustainable agriculture. *Advances in Agronomy*, *180*, 35 91.

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., ... and Keesstra, S. (2019). Land management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annual Review of Environment and Resources, 44(1), 255 286.

Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., and Kouisni, L. (2020) Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. Plants 9: 1011. https://doi.org/10.3390/plants9081011

Spielman, D. J., and Birner, R. (2008). How innovative is your agriculture? Using innovation indicators and benchmarks to strengthen national agricultural innovation systems. Washington, DC, USA: World Bank.

Srivastava, P., Singh, R., Tripathi, S., Singh, H., and Raghubanshi, A. S. (2016). Soil carbon dynamics and climate change: current agro environmental perspectives and future dimensions. *Energy, Ecology and Environment*, *1*, 315 322.

Szpunar Krok, E., Bobrecka Jamro, D., Pikuła, W., and Jańczak Pieniążek, M. (2023). Effect of nitrogen fertilization and inoculation with *Bradyrhizobium japonicum* on nodulation and yielding of soybean. *Agronomy*, *13*(5), 1341.

Takács, T., Cseresnyés, I., Kovács, R., Parádi, I., Kelemen, B., Szili Kovács, T., and Füzy, A. (2018). Symbiotic effectivity of dual and tripartite associations on soybean (Glycine max L. Merr.) cultivars inoculated with *Bradyrhizobium japonicum* and AM Fungi. *Frontiers in Plant Science*, *9*, 1631.

Tambo, J. A., and Abdoulaye, T. (2012). Climate change and agricultural technology adoption: the case of drought tolerant maize in rural Nigeria. Mitigation and Adaptation Strategies for Global Change, 17, 277 292.

Ullah, S., Ali, I., Yang, M., Zhao, Q., Iqbal, A., Wu, X., ... and Jiang, L. (2023). Partial substitution of urea with biochar induced improvements in soil enzymes activity, ammonia nitrite oxidizers, and nitrogen uptake in the double cropping rice system. *Microorganisms*, *11*(2), 527.

Utobo, E. B., and Tewari, L. (2015). Soil enzymes as bioindicators of soil ecosystem status. *Applied Ecology and Environmental Research*, 13(1), 147–169.

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and soil*, *255*, 571 586.

Wang, G., Liu, F., Tariq, M., Wan, J., Liang, W., Zhang, W., ... and Yang, J. (2022). A comparative study on various indicators for evaluating soil health of three biochar materials application. *Journal of Cleaner Production*, *343*, 131085.

Wang, P., Liu, W. C., Han, C., Wang, S., Bai, M. Y., and Song, C. P. (2024). Reactive oxygen species: multidimensional regulators of plant adaptation to abiotic stress and development. *Journal of Integrative Plant Biology*, *66*(3), 330 367.

Yakupoğlu, G., Saltalı, K., Rodrigo Comino, J., Yakupoğlu, T., and Cerda, A. (2022). Manure effect on soil–plant interactions in capia pepper crops under semiarid climate conditions. *Sustainability*, *14*(20), 13695.

Zomer, R. J., Bossio, D. A., Sommer, R., and Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. Scientific reports, 7(1), 15554.

Župunski, V., Jevtić, R., Grčak, M., Lalošević, M., Orbović, B., Živanov, D., and Knežević, D. (2022). Effectiveness of Species and Trichothecene Specific Primers in Monitoring Fusarium graminearum Species Complex in Small Grain–Pea Intercropping Systems. *Agriculture*, *12*(6), 834.

CHAPTER 11

SOIL MICROBIAL ACTIVITY IN PLANT NUTRITION: FUNCTIONS AND ADVANCES IN NEXT-GENERATION BIOFERTILIZERS

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INTRODUCTION

Soil is not only a physico-chemical environment consisting of mineral particles, but also a dynamic living ecosystem consisting of microorganism communities such as bacteria, fungi, actinomycetes, protozoa and nematodes (Schneider et al., 2025). These microbial communities, which contain 10^8–10^9 cells per gram, sustain complex biochemical cycles by feeding on dead plant residues, root secretions and organic matter residues. In order to meet the needs of the increasing world population, soil nutrients play a critical role in terms of sustainable and high-yield production of agricultural products and access to healthy food. In agricultural production, fertilizer use is needed to increase yield. The fertilizers used can be of chemical, organic or microbial origin. These types of fertilizers provide significant contributions both in terms of supporting plant growth and improving soil quality. Chemical fertilizers are preferred to provide the necessary nutrients to plants quickly and to achieve results in a short time. However, the high nutrient content of these fertilizers can cause environmental problems, especially negative effects such as pollution of water resources (Mahdi et al., 2010). In this context, biofertilizers stand out as a sustainable alternative that increases agricultural productivity without harming the environment.

Plant growth-promoting microorganisms (PGPMs) are naturally found in the nutrient-rich soil region called the rhizosphere, which surrounds plant roots. These microorganisms help plants absorb nutrients more efficiently through functions such as nitrogen fixation and phosphate solubilization. In addition, PGPMs produce various plant hormones, siderophores, cyanide compounds, and lytic enzymes, which act as biopesticides and rhizomediators by promoting plant growth. These microorganisms, which live naturally in the rhizosphere, support plant development while also increasing plant resistance to diseases (Mrkovacki et al., 2012). PGPMs can be divided into two main groups: bacteria and fungi. Prominent microorganisms belonging to these groups include Azospirillum, Azotobacter, Rhizobium, Pseudomonas, Enterobacter, Bacillus, Penicillium, and Trichoderma. While some of these microorganisms directly increase plant growth and yield, others can be used as biological control agents against harmful organisms and plant pathogens.

1. Definition And Importance Of Soil Microbial Activity

Soil microbial activity refers to the activities of microorganisms (bacteria, fungi, actinomycetes, algae, etc.) living in the soil in biochemical processes. These activities include basic soil functions such as decomposition of organic matter, mineralization of nutrients, nitrogen fixation, phosphorus dissolution, and humus formation (Nannipieri et al., 2003). Microbial activity is an important indicator of soil health and plays a critical role in processes that directly affect plant growth and productivity.

Soil microorganisms release carbon dioxide and inorganic nutrients by decomposing organic matter. This process enables nutrients to be provided to plants in a usable form (Sylvia et al., 2005). For example, free-living or symbiotic bacterial species (Rhizobium, Azotobacter, Azospirillum) contribute to the soil nitrogen cycle by converting atmospheric nitrogen into a form usable by plants (Zaidi et al., 2009). Mycorrhizal fungi are particularly effective in the transport and uptake of phosphorus to plant roots (Smith & Read, 2008). Another important aspect of microbial activity is the improvement of soil structure. Polysaccharides and other adhesive substances secreted by microorganisms promote the formation of soil aggregates, which positively affects soil aeration, water retention capacity and root development (Tisdall & Oades, 1982). In addition, some microorganisms can suppress pathogenic microorganisms and increase plant resistance to diseases. This situation becomes especially important in biofertilizer and biopesticide applications (Glick, 2012).

Soil microbial activity is directly related to agricultural practices. Applications such as excessive use of chemical fertilizers, pesticides, intensive tillage and monoculture can negatively affect microbial diversity and activity (Lupwayi et al., 2001). On the other hand, sustainable methods such as organic matter addition, rotation, minimum tillage and biological fertilization protect the biological balance of the soil by increasing microbial activity (Hartmann et al., 2015). Soil microbial activity is one of the main determinants of soil fertility and health. The continuity of biological processes in the soil is directly related to the functional diversity and metabolic capacities of these microorganisms. Therefore, supporting microbial activity in sustainable agricultural systems is of great importance both in terms of increasing product productivity and ensuring environmental sustainability.

2. Microbial Role In Plant Nutrition

Plant nutrition involves the provision of macro and micro nutrients that plants need for growth, development and product yield from the soil or external sources. In this process, soil microorganisms play a fundamental role in plants accessing nutrients and using them effectively. Microorganisms such as bacteria, fungi and actinomycetes in the soil biota regulate the plant nutrient cycle and increase bioavailability through both direct and indirect mechanisms (Glick, 2012). One of the most obvious functions of microorganisms is the conversion of macro nutrients (especially nitrogen, phosphorus and sulfur) into forms that plants can absorb by decomposing organic matter (Richardson et al., 2009). For example, nitrogen-fixing bacteria (Rhizobium, Azospirillum, Azotobacter) convert atmospheric nitrogen into ammonium form and provide it to the soil. This biological nitrogen fixation supports sustainable agriculture by reducing dependence on synthetic fertilizers (Bhattacharyya & Jha, 2012). Likewise, phosphate-solubilizing microorganisms (Pseudomonas, Bacillus species) dissolve insoluble phosphorus compounds in the soil and make them available for plants (Khan et al., 2007).

Mycorrhizal fungi play a critical role in the transport of low-mobility elements, especially phosphorus and zinc. These fungi establish a symbiotic relationship with roots, expanding the root surface area and allowing more nutrients to be taken from the soil (Smith & Read, 2008). In addition, the uptake of micronutrients such as iron is increased by siderophores secreted by microorganisms. This increases the resistance of plants to nutrient deficiencies (Compant et al., 2010). Microorganisms also produce phytohormones (auxin, cytokinin, gibberellin, etc.) that directly stimulate plant growth. These substances stimulate root development, allowing the plant to take in more nutrients and water (Vessey, 2003). In addition, some microorganisms develop biocontrol mechanisms against pathogens, promoting healthy root development and thus indirectly supporting nutrient uptake (Lugtenberg & Kamilova, 2009). Soil microorganisms are decisive actors not only in the decomposition of organic matter, but also in the conversion of nutrients into suitable chemical forms for the plant to absorb them more efficiently. The active use of these microorganisms in agricultural production increases both product quality and yield, while also supporting environmental sustainability. For this reason, microbial fertilizers and biological applications are becoming increasingly important in modern plant nutrition strategies.

3. New Generation Biopertifiers And Their Microbial Contents

Biofertilizers are environmentally friendly, sustainable and economical agricultural inputs containing microorganisms that support plant growth. While traditional biofertilizers generally show limited properties such as nitrogen fixation or phosphorus solubility, new generation biofertilizers (NNBGs) increase both bioavailability and plant stress tolerance thanks to multifunctional microorganisms and advanced carrier systems (Rouphael et al., 2015; Vassilev et al., 2020). The main difference of new generation biofertilizers is that they contain microorganisms that are not only limited to providing nutrients but also reduce biotic and abiotic stresses, increase root development in the plant, synthesize phytohormones and suppress pathogens (Lugtenberg & Kamilova, 2009). The microorganisms used in these fertilizers are genetically selected or developed with engineering techniques and can perform a wide range of functions.

3.1. Microbial Contents

Microorganisms frequently found in the content of new generation biofertilizers are as follows:

3.1.1. Nitrogen Fixing Bacteria: Bacteria such as Rhizobium, Azospirillum, Azotobacter meet the nitrogen needs by converting atmospheric nitrogen into a form that plants can use (Bhattacharyya & Jha, 2012).

Table 1: Effect of Azotobacter on crop yield (Bhattacharjee & Dey, 2014).

Crop	Yield Increase with Chemical Fertilizers (%)
Cereals	
Wheat	8–10
Rice	5
Maize (Corn)	15–20
Sorghum	15–20
Others	
Potato	13
Carrot	16
Cauliflower	40
Tomato	2–24
Cotton	7–27
Sugarcane	9–24

3.1.2. Phosphate-Solving Microorganisms: Bacillus, Pseudomonas and Penicillium species dissolve phosphorus that is not dissolved in the soil with the help of organic acids and enzymes and present it to the plants (Khan et al., 2007).

3.1.3. Mycorrhizal Fungi (Glomus spp.): They establish a symbiotic relationship with plant roots and increase the uptake of phosphorus, zinc and water. They also increase the root surface area and facilitate the transportation of micronutrients (Smith & Read, 2008).

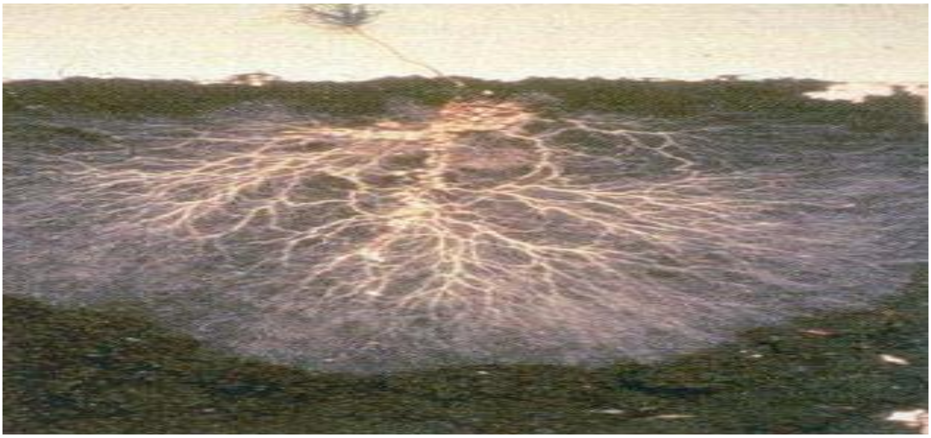

Figure 1: Mycorrhiza (Peters, 2002).

3.1.4. Plant Growth-Promoting Rhizobacteria (PGPR): Species such as Pseudomonas fluorescens, Bacillus subtilis, and Enterobacter cloacae synthesize hormones such as auxin, gibberellin, and cytokinin, increasing root development and nutrient uptake (Glick, 2012).

3.1.5. Silicate-Solving Bacteria: Species such as Bacillus mucilaginosus enhance plant resistance by increasing potassium and silicon solubility (Etesami et al., 2017).

3.1.6. Biocontrol-Effective Microorganisms: Trichoderma, Streptomyces, and some Bacillus species protect plant health by suppressing pathogens and indirectly support productivity (Compant et al., 2010). The use of specific microorganisms to combat plant diseases and pests is defined as biological control. This method offers a nature-sensitive, ecologically based solution to the environmental and economic problems caused by plant protection practices (Harman et al., 2004). Bacterial and fungal groups, in particular, play an active role in this control. Among these, Trichoderma species are highly valuable for biological control. Trichoderma species are free-living, beneficial microorganisms that can inhabit soil, leaves, and roots, and are highly adaptable to environmental conditions. Thanks to their antifungal properties, these species provide effective defense against plant pathogens.

Trichoderma is frequently preferred both as a biofertilizer and as a biocontrol agent by forming mycorrhizal-like symbiotic interactions with plants (Harman et al., 2004). These species have been shown not only to suppress pathogenic fungi but also to promote plant growth and contribute to increased yields (Doni et al., 2013). Trichoderma spp. has been scientifically confirmed to produce siderophores, phosphate-solubilizing enzymes, and plant growth hormones (phytohormones) (Doni et al., 2013). Some Trichoderma species colonize plant roots, triggering various morphological and biochemical changes in the plant. This effect leads to systemic plant-wide resistance responses. Trichoderma competes with other microorganisms in the root zone for both nutrients and habitat, while inhibiting disease development by inhibiting enzymes such as pectinase, which play a role in the activity of plant pathogens. With the increasing interest in alternative and environmentally friendly agricultural practices, the use of microbial fertilizers as an alternative to chemical fertilizers is rapidly expanding. Biofertilizers formulated with beneficial microorganisms like Trichoderma have become indispensable components of sustainable agricultural systems.

Additionally, new-generation biofertilizers are formulated with advanced technologies such as nanocarriers, biochar-supported structures, and controlled-release polymers to maintain microbial viability for long periods (Malusá & Vassilev, 2014). These formulations increase the effectiveness of microorganisms in the soil and make them more resilient to environmental conditions.

Conclusion

New-generation biofertilizers represent a significant paradigm shift in agricultural production in terms of both increased yields and environmental sustainability. Considering the long-term negative effects of traditional chemical fertilizers, such as deteriorating soil structure, polluting water resources, and reducing microbial diversity, biofertilizers, especially new-generation formulations with enriched microbial content, stand out as a strong alternative for sustainable agricultural practices.

New-generation biofertilizers not only provide nutrients such as nitrogen and phosphorus, but also produce phytohormones that promote plant root growth, synthesize pathogen suppressing substances, and enhance plant adaptability under biotic/abiotic stress conditions. Functional microorganisms such as mycorrhizal fungi, rhizobacteria, and phosphate-solubilizing bacteria provide the multifaceted effects of these products. Furthermore, the use of advanced carrier systems (nanomaterials, biochar, controlled-release polymers) enhances bioavailability by allowing microorganisms to remain active in the soil for longer periods and increasing their interaction with the target plant. Considered in this context, the use of new-generation biofertilizers offers not only short-term yield increases but also long-term benefits such as maintaining soil health, maintaining microbial balance, and minimizing environmental impacts. Promoting these biological inputs is of strategic importance for the future of agricultural production, reducing chemical dependence, and preserving ecosystem services. Therefore, new-generation biofertilizers should be the focus of both scientific research and agricultural policies, and they should be expanded as an integral component of integrated nutrition strategies.

REFERENCES

Bhattacharjee, R., & Dey, U. (2014). Biofertilizer, a way towards organic agriculture: A review. African Journal of Microbiology Research, 8(24), 2332-2343.

Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World Journal of Microbiology and Biotechnology, 28(4), 1327–1350.

Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World Journal of Microbiology and Biotechnology, 28(4), 1327–1350.

Compant, S., Clément, C., & Sessitsch, A. (2010). Plant growth-promoting bacteria in the rhizo- and endosphere of plants: Their role, colonization, mechanisms involved and prospects for utilization. Soil Biology and Biochemistry, 42(5), 669–678.

Compant, S., Clément, C., & Sessitsch, A. (2010). Plant growth-promoting bacteria in the rhizo- and endosphere of plants: Their role, colonization, mechanisms involved and prospects for utilization. Soil Biology and Biochemistry, 42(5), 669–678.

Doni, F., Al-Shorgani, N., Tibin, E., Abuelhassan , N., Anizan, I., Wan, M.W. And Che, R. C. (2013). Microbial involvement in growth of paddy. 5(6):285–290.

Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth, and future prospects -a review. Journal of Soil Science and Plant Nutrition, 17(4), 897–911.

Glick, B. R. (2012). Plant Growth-Promoting Bacteria: Mechanisms and Applications. Scientifica, 2012, 963401.

Glick, B. R. (2012). Plant Growth-Promoting Bacteria: Mechanisms and Applications. Scientifica, 2012, Article ID 963401.

Harman, G., Lorito, M. And Lynch, J. (2004). Uses of Trichoderma spp. to remediate soil and waterr pollution. Ady Appl Microbiol 56:313-330.

Hartmann, M., Frey, B., Mayer, J., Mäder, P., & Widmer, F. (2015). Distinct soil microbial diversity under long-term organic and conventional farming. The ISME Journal, 9(5), 1177–1194.

Khan, M. S., Zaidi, A., & Wani, P. A. (2007). Role of phosphate-solubilizing microorganisms in sustainable agriculture—A review. Agronomy for Sustainable Development, 27(1), 29–43.

Khan, M. S., Zaidi, A., & Wani, P. A. (2007). Role of phosphate-solubilizing microorganisms in sustainable agriculture—A review. Agronomy for Sustainable Development, 27(1), 29–43.

Lugtenberg, B., & Kamilova, F. (2009). Plant-Growth-Promoting Rhizobacteria. Annual Review of Microbiology, 63, 541–556.

Lugtenberg, B., & Kamilova, F. (2009). Plant-Growth-Promoting Rhizobacteria. Annual Review of Microbiology, 63, 541–556. https://doi.org/10.1146/annurev.micro.62.081307.162918

Lupwayi, N. Z., Rice, W. A., & Clayton, G. W. (2001). Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. Soil Biology and Biochemistry, 33(7-8), 1021–1030.

Mahdi, S. S., Hassan, G. I., Samoon, S. A., Rather, H. A., & Dar, S. A. (2010). Bio-fertilizers in organic agriculture. Journal of Phytology, 2(10), 42–54.

Malusá, E., & Vassilev, N. (2014). A contribution to set a legal framework for biofertilisers. Applied Microbiology and Biotechnology, 98, 6599–6607.

Mırkovacki, N., Jarak, M., Ivica, D. And Jockovic, D. (2012). Importance of PGPR application and its effect on microbial activity in maize rhizosphere. 49 (3): 335-344.

Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G., & Renella, G. (2003). Microbial diversity and soil functions. European Journal of Soil Science, 54(4), 655–670.

Richardson, A. E., Barea, J. M., McNeill, A. M., & Prigent-Combaret, C. (2009). Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant and Soil, 321(1–2), 305–339.

Rouphael, Y., Colla, G., et al. (2015). Biostimulant activity of a protein hydrolysate-based product in lettuce plants. Journal of Plant Nutrition and Soil Science, 178(5), 792–799.

Schneider, J., Müller, A., Becker, C., & Hoffmann, T. (2025). Soil biodiversity and ecosystem functionality: Integrating microbial communities into sustainable soil management. Springer Nature.

Smith, S. E., & Read, D. J. (2008). Mycorrhizal Symbiosis (3rd ed.). Academic Press.

Sylvia, D. M., Fuhrmann, J. J., Hartel, P. G., & Zuberer, D. A. (2005). Principles and Applications of Soil Microbiology (2nd ed.). Pearson Prentice Hall.

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. Journal of Soil Science, 33(2), 141–163.

Vassilev, N., Vassileva, M., & Nikolaeva, I. (2020). Novel biotechnological strategies for the formulation and application of biofertilizers. Springer Nature Applied Sciences, 2(2), 1–6.

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. Plant and Soil, 255(2), 571–586.

Zaidi, A., Khan, M. S., Ahemad, M., Oves, M., & Wani, P. A. (2009). Recent advances in plant growth promotion by phosphate-solubilizing microbes. Microbial Strategies for Crop Improvement, 23–50.

CHAPTER 12

MONITORING AND MANAGEMENT OF NITROGEN USE EFFICIENCY (NUE) IN AGRICULTURAL PRACTICES

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INTRODUCTION

Soil is not only a physical-chemical environment consisting of mineral particles, but also a dynamic living ecosystem consisting of microorganism communities such as bacteria, fungi, actinomycetes, protozoa and nematodes (Schneider et al., 2025). The world population is expected to reach approximately 9 billion by 2050. In order to meet the nutritional needs of this rapid population growth, agricultural lands should be used more efficiently, modern agricultural technologies should be disseminated, genetic improvement studies should be carried out, agricultural productivity should be increased through effective irrigation and balanced fertilization practices (Blanco, 2011). As of 2013, global chemical fertilizer consumption was estimated at around 183.4 million tons, with a market value of 59.2 billion USD. Nitrogen-based fertilizers account for approximately 60% of this total usage (Mikkelsen, 2009; FAO, 2011).

Nitrogen is the most commonly limiting nutrient in crop production and plays a crucial role in promoting plant growth and productivity (Kara, 2006). (Kara, 2006). Globally, nitrogen use efficiency averages around 50%, depending on the application method and fertilizer type. The economic value of nitrogen that remains unused by plants is estimated to be approximately 17.7 billion USD annually (Brentrup and Palliere, 2011; Karaşahin, 2014). This unutilized nitrogen negatively affects soil microorganisms responsible for biological nitrogen fixation, is transported through precipitation and irrigation, and contributes to eutrophication and nitrate accumulation in both surface and groundwater resources. Moreover, nitrogen losses through denitrification result in the emission of greenhouse gases, which contribute to atmospheric warming, acid rain, and the depletion of the ozone layer (Gupta and Khosla, 2014).

Nitrate, which enters the human body through drinking water and nitrate-rich foods, first turns into nitrite and then reacts with secondary amines to form harmful compounds called nitrosamines. These compounds are known for their toxic, mutagenic, teratogenic and carcinogenic effects (Ekici, Alişarlı and Sancak, 2008). As of 2012, annual chemical fertilizer consumption in Turkey was approximately 5.3 million tons and 39% of this amount was met through imports (Gübretaş, 2013). The ratio of nitrogenous fertilizers in the total fertilizers used in our country is approximately 65%. High amounts of nitrogenous fertilizer imports cause a significant loss of foreign exchange and high amounts of fossil fuels are consumed in the production of these fertilizers. The low absorption of nitrogenous fertilizers produced and applied by plants both puts pressure on these limited resources and brings additional costs to producers and consumers. Nitrogen losses; gas emission, nitrification, denitrification, surface runoff, evaporation and leaching from the root zone to groundwater. Increasing nitrogen uptake efficiency is a basic requirement to ensure adequate plant production to feed the increasing population and to reduce the negative effects of nitrogen fertilizer use on the environment and human health.

Nitrogen Uptake Efficiency in Plant Production

Nitrogen uptake efficiency is defined as the ratio of plant-absorbed nitrogen to the total available nitrogen in the soil. As a key determinant of plant productivity, nitrogen is often regarded as a primary limiting factor in crop growth. However, research has shown that nitrogen uptake efficiency tends to decline as the amount of applied nitrogen increases (Staley and Perry, 1995; Presterl et al., 2003). Once plants reach their optimal nitrogen requirement, any additional nitrogen is susceptible to leaching losses and does not contribute to further yield improvements (Jokela and Randall, 1997; Lambert, Esgar, and Joos, 2000). Furthermore, exceeding the optimal nitrogen application rate reduces nitrogen use efficiency and significantly increases nitrate losses (Karam et al., 2002). When excessive nitrogen application is combined with poor agricultural management practices, the risk of nitrate contamination in surface and groundwater is substantially heightened.

In order to make nitrogen use more efficient, it is very important to consider the amount of mineral nitrogen in the root zone. The plant's nitrogen uptake capacity from the soil depends on the planting date, the amount of available mineral nitrogen (especially the nitrate form) and the amount of nitrogen released from the mineralization of organic matter during the growth period (Sarımehmetoğlu, 2007). In increasing nitrogen use efficiency and effectively taking the nitrogen the plant needs, the correct nitrogen dose is a determining factor. It is emphasized that the amount of fertilizer to be applied depends directly on the plant's nitrogen need and indirectly on the nitrogen uptake efficiency; the amount of mineral nitrogen in the soil and the residual nitrogen from the previous period should be taken into consideration before fertilization (Büyük, 2006). It has been determined that only the necessary amount of nitrogen should be provided to the plant in order for nitrogen to be used with maximum efficiency, and that the plant's nitrogen uptake depends on temperature and humidity conditions; nitrogen uptake is more effective at high temperatures and humidity (Muchow, 1994).

Irregular fertilization practices can negatively impact nitrogen uptake efficiency by causing imbalances and antagonistic interactions among plant nutrients. For instance, potassium deficiency during the early stages of plant development is known to restrict nitrogen absorption (Swain et al., 2006). Conversely, the application of sulfur has been shown to enhance nitrogen uptake efficiency and reduce nitrogen losses from the soil (Brown et al., 2000). Conducting soil nutrient analysis prior to fertilization is essential—not only to ensure balanced nutrient application, but also to optimize nutrient use efficiency and minimize environmental risks and economic losses (Kılıç and Korkmaz, 2012). The development of slow-release and long-lasting fertilizers can help mitigate nutrient losses and reduce the risk of seed damage caused by fertilizers applied during sowing. Such innovations are expected to further enhance nitrogen uptake efficiency. In maize, insufficient nitrogen application during the early growth stages significantly reduces nitrogen uptake and utilization. Approximately 73% of the total nitrogen absorbed by maize at maturity is stored in the grains, with about half of this nitrogen translocated from vegetative tissues such as leaves and stems (Plenet and Lemaire, 2000). Therefore, suboptimal nitrogen availability during early growth can substantially limit both yield and nitrogen use efficiency. It has also been reported that nitrogen uptake efficiency tends to increase with longer plant growth durations.

Species with a long vegetative period have the capacity to take more nitrogen from the soil thanks to their more developed root systems, which increases nitrogen uptake efficiency. The period when nitrogen uptake is most intense in plants is the full leafing stage. It has been determined that most of the factors affecting nitrogen uptake reach their highest levels during this period; the amount of nitrogen taken after flowering meets only 12-18% of the total grain nitrogen requirement, and high nitrogen doses given before planting do not increase nitrogen uptake after flowering. It is also stated that net nitrate uptake in spring wheat varieties increases until the flowering period and then experiences a sudden decrease (Cengiz, 2007).

In order to increase nitrogen uptake efficiency, the nitrogen fertilization method, application time and the nitrogen needs of the plant at different growth stages should be taken into consideration (Zotarelli et al., 2008; Karnez, 2010). In addition to the amount of fertilizer, the irrigation program is also a determining factor in nitrogen leaching. Proper irrigation management can significantly increase nitrogen uptake from the plant's root zone. Especially in soils with low water holding capacity, excessive irrigation leads to the loss of these elements by leaching before the plant nutrients are fully taken up (Zotarelli et al., 2008). When flood irrigation is applied to sandy and low water holding capacity soils, nitrogen leaching becomes inevitable due to the effect of excess water (Perrin et al., 1998). In order to prevent nitrogen losses in such soils, a careful and controlled irrigation program should be applied.

Irrigation should be started when approximately 10-50% of the usable water between the field capacity and the wilting point is depleted. The amount of water to be given should be at a level that will bring the root zone back to field capacity. For example, while nitrogen uptake efficiency increases with regular and correct irrigation applications in lettuce cultivation, water shortages have negatively affected both yield and nitrogen use efficiency. Under full irrigation conditions, nitrogen uptake efficiency reaches 77%, while this rate drops to 48% in water shortage (Battilani et al., 2008). Studies show that high nitrogen use efficiency can be achieved by using low amounts of nitrogen with appropriate irrigation and agricultural care (French et al., 2014). Nitrogen uptake varies significantly depending on the availability of water in the soil. The plant provides the highest efficiency under conditions where sufficient water and nitrogen are present together in the soil. If nitrogen is applied when there is a lack of water in the soil, the plant's cell water is drawn by the fertilizer due to osmotic pressure, which can lead to plant death. On the other hand, nitrogen applied as a result of excessive irrigation is easily removed from the plant root zone with water (Martin et al., 1982). In general, only approximately 50% of applied nitrogenous fertilizers can be taken up by plants. Effective irrigation and fertilization methods contribute to the prevention of environmental damage by increasing nitrogen use efficiency (Karnez, 2010).

In the dynamic fertigation system, water and nutrients are applied by adjusting them precisely according to the daily dry matter increase and root volume of the plant (Battilani et al., 2008). Giving nitrogen in the period when the plant needs it and in the right amount increases fertilizer uptake efficiency while also reducing environmental damage. When preparing fertilization plans, soil analyses and nutrient uptake trends observed in plants for many years should be taken into account. It is also known that annual and regional climate differences have an effect on nitrogen uptake efficiency. Nitrogen uptake by plants varies according to ecological conditions, temperature and humidity levels (Staley and Perry, 1995). Nitrogen and water uptake by plants is closely related to temperature. While nitrate uptake slows down at low temperatures, nitrogen uptake increases at high temperatures and humidity conditions (Muchow, 1994). While suitable temperature and humidity encourage plant development, low temperatures encountered during the flowering period reduce the transfer of nitrogen from leaves and stems to grains and reduce the uptake rate of soil nitrogen, increasing losses through evaporation and leaching. In addition, when nitrogen fertilizer is applied when the soil temperature is low, nitrogen uptake efficiency remains low because the roots are not active enough (Brown et al., 2000).

There are differences in nitrogen use efficiency among plant species and even varieties. Studies show that hybrid varieties use nitrogen more efficiently than synthetic varieties. The difference in root length and morphology also affects nitrogen uptake capacity. It has been stated that nitrogen application positively affects the root development of corn plants and that root development supports nitrogen uptake (Büyük, 2006).

Nitrogen uptake depends on the uptake capacity of roots, the storage capacity of shoots and the growth rate of these structures. In general, nitrogen uptake in plants varies depending on factors such as dissolved carbohydrate levels in roots, environmental temperature, water status and nitrogen availability in the soil. It has been reported that nitrogen use efficiency in wheat varieties varies according to genetic differences, while nitrogen uptake and usage times differ among varieties in corn genotypes. These differences are generally related to changes in root structure or nitrogen transport within the plant. When there is high nitrogen in the soil, uptake is related to growth rate, and in low nitrogen conditions, it is related to the morphological and physiological characteristics of the roots (Khalilzadeh, Mozaffari and Azizov, 2011).

In no-till farming practices, leaving plant residues in the soil increases grain and straw yields, water and nitrogen use efficiency, and soil organic matter in wheat production (Mohammad et al., 2012). There is an inverse relationship between root depth and nitrate leaching. Therefore, growing deep-rooted plants after shallow-rooted plants in rotation reduces nitrogen loss and increases nitrogen uptake efficiency. Deep-rooted plants act as a biological filter in the soil, regaining nitrate from groundwater and preventing nitrate loss. Especially in sandy soils, including deep-rooted plants such as alfalfa in rotation is an effective method to reduce the leaching problem by increasing water and nitrogen use efficiency (Zhaohui et al., 2014).

Although nitrogen uptake efficiency varies for different plant species and ecosystems, it generally does not exceed 50%. For example, this rate varies between 29-42% for cereals. In order to increase nitrogen uptake efficiency, it is necessary to establish a correct relationship between nitrogen application method, time and nitrogen requirements of plants at different growth stages. Nitrogen uptake efficiency is affected by many factors such as applied nitrogen dose, nitrogen source, application time and method (Karnez, 2010). In addition, low temperature, inadequate soil and water conditions also reduce nitrogen utilization rates (Muchow, 1994). The main factors affecting nitrate leaching are applied nitrogen dose, time, fertilizer source and application method, use of nitrification inhibitors, plant density, nitrogen uptake, soil profile and structure, rainfall amount, distribution and amount of irrigation water. In order to reduce nitrogen losses in the soil-plant system and increase nitrogen uptake efficiency, crop rotation, inclusion of legume plants in production, preference of hybrid or cultivar varieties, appropriate soil tillage, use of ammonium-based fertilizers, foliar nitrogen application and appropriate irrigation techniques are recommended as basic strategies (Raun et al., 2002; Das, Munda, & Patel, 2005).

What is NUE and How Can It Be Managed?

Nitrogen use efficiency (NUE) is an important concept that needs to be addressed comprehensively. The first definition of NUE refers to the ability of plants to take nitrogen from the soil and retain it in their bodies (Daigger et al., 1976). The reason for preferring this definition is that plants tend to release some of the nitrogen they take in to the atmosphere in the form of nitrogen oxide (N_2O) instead of keeping it fixed in their structures. On the other hand, legume plants generally have higher NUE values because they fix nitrogen by atmospheric means and store it in their bodies (Vinod et al., 2016; Hocking & Reynolds, 2012). However, due to nitrogen losses that occur during the decomposition of these plants, it is still debated whether net nitrogen efficiency is really higher compared to other species (Volpe et al., 2016). NUE allows the evaluation of the extent to which nitrogen is used effectively by revealing the amount of nitrogen taken in by a plant and how much of it is lost as nitrogen oxide. While nitrogen taken up by plants is considered as available nitrogen; nitrogen oxides released into the atmosphere are assumed to be from the soil before plants absorb this nitrogen. Because plants can take nitrogen in the forms of ammonium (NH_4^+) and nitrate (NO_3^-) from the soil through their roots (Choi et al., 2009). This approach also overlaps with the basic definition of NUE. The second definition of NUE refers to an efficiency level in which nitrogen applied to the soil by organic or synthetic means is used only by the plant and is not consumed by other processes such as denitrification (Koffi et al., 2016).

Nitrogen solubility in the soil is mostly related to factors such as excessive fertilization, poor drainage (usually caused by lack of organic matter) or sloping lands (Daniel et al., 2010). On the other hand, denitrification is mostly caused by excess water in the fields (Matejek et al., 2010). With soil samples taken at the beginning of the season and analyses, the amount of available nitrogen, the amount of fixed nitrogen (Choi et al., 2009), the amount of nitrogen lost through leaching and denitrification, and the amount of nitrogen remaining in the soil can be calculated. The efficiency of the system is determined by how much nitrogen the plant can take up and use compared to the nitrogen lost as a result of these processes and remaining in the soil. When considered particularly in terms of fertilizer applications, the goal is for the plant to take in all of the applied nitrogen and to minimize losses (Peltonen et al., 1995).

In general terms, NUE is the level of effective and beneficial use of nitrogen. This efficiency is expressed as the ratio of the nitrogen taken up and retained by the plant until harvest to the total available nitrogen in the soil and is usually evaluated in comparison with the applied fertilizer nitrogen (Raun &

Johnson, 1999). NUE is a common indicator showing the relationship between the amount of nitrogen applied and the amount of nitrogen taken up by the plant. A typical example of this is the ratio of the biomass of the harvested crop to the amount of nitrogen applied. Considering the nitrogen losses that occur in field conditions, the variability in yield potential, and the fluctuations in both nitrogen fertilizer and product prices, the development of practices to optimize fertilizer use is of great importance. Globally, nitrogen use efficiency (NUE) in cereal production is low, and it is estimated that only an average of 33% of the applied fertilizer is recovered by the plant (Raun & Johnson, 1999). The main reasons for these losses are leaching nitrate with precipitation and denitrification. The time between the time nitrogen is applied and the time the plant actively absorbs this nitrogen prepares the ground for various losses. During these processes, losses such as leaching, clay retention, immobilization, denitrification, and transition to the gas phase may occur (Scharf & Lory, 2002).

Globally, nitrogen use efficiency (NUE) in cereal production is low, with an estimated average of only 33% of applied fertilizer being recovered by the plant (Raun & Johnson, 1999). The main causes of these losses include leaching of nitrate with precipitation and denitrification. The time between when nitrogen is applied and when the plant actively absorbs it, creates the ground for various losses. These processes can include leaching, clay retention, immobilization, denitrification and gaseous phase losses (Scharf & Lory, 2002).

One of the main reasons why current nitrogen management practices lead to low NUE is the lack of synchronization between when nitrogen is applied and when the plant needs it (Raun & Johnson, 1999; Cassman et al., 2002; Abebe & Feyisa, 2017). High doses of nitrogen applied before planting further increase this synchronization problem. Depending on the weather and soil conditions, nitrogen applied early can seep below the root zone before the plant reaches the period when it needs nitrogen the most (Cameron et al., 2013). This leads to a high level of usable nitrogen accumulation that can be lost in the soil in a short time. In addition, it is observed that productivity decreases as the amount of nitrogen applied increases (Reddy & Reddy, 1993). In contrast, nitrogen applications made during the growing season provide higher NUE than pre-applications (Olson et al., 1986). Nitrogen provided during the period when the plant needs it can increase productivity (Keeney, 1982).

Another important factor causing low NUE is the application of the same amount of nitrogen to areas with different yield potential in the fields. Studies show that variable nitrogen applications specific to the area are more beneficial from an environmental and economic perspective (Scharf & Lory, 2002; Mamo et al., 2003). Soil nitrogen availability, plant nitrogen uptake and nitrogen response vary spatially within fields (Inman et al., 2005). Therefore, fixed-rate nitrogen applications applied throughout the field may be excessive in some regions and inadequate in others.

Soil Test Approach

Soil and plant analyses are widely employed as essential tools in nitrogen management strategies (Cameron et al., 2013). To account for spatial variability within agricultural fields, several studies advocate for variable nitrogen application based on spatial management zones (MZs) (Franzen et al., 2002). Management zones are defined as areas that exhibit similar soil and landscape characteristics. Regions with comparable attributes such as electrical conductivity (EC), historical crop yield data, and farmer knowledge are considered to be homogeneous units (Flowers et al., 2005; Kitchen et al., 2005). Fertilizer applications within these zones are expected to produce uniform crop responses and comparable environmental impacts due to their similar agronomic potential.

Various methods have been developed to determine MZ boundaries. Spatial data such as soil color, EC, topography and yield are analyzed and classified with the help of geographic information systems (GIS) (Schepers et al., 2004). In addition, information such as soil mapping units (Wibawa et al., 1993), remote sensing techniques (Schepers et al., 2004), topographic analyses (Alexandra et al., 1949), yield maps and EC measurements (Franzen et al., 2002) have been successfully used in MZ definitions. However, since most of these determinations are based on yield potential that varies over time, they may have limited reliability (Jaynes & Colvin, 1997; Lambert et al., 2006). Therefore, this data alone may not adequately reflect the differences in nitrogen requirements within the field. In commercial crop production, nitrogen requirements are usually calculated with a formulation based on target yield, soil nitrate measurements up to 60 cm depth and nitrogen remaining from the previous crop. This system is important in terms of increasing both economic gain and reducing environmental losses by encouraging efficient use of nitrogen. NUE is widely used to show the relationship between applied nitrogen and the amount of nitrogen taken up by the plant. The ratio of the amount of harvested products to the amount of nitrogen applied is an important indicator of this efficiency.

When the variability in yield and nitrogen loss potential observed in different fields is combined with the annual fluctuations in nitrogen and product prices, the development of fertilization strategies that allow the determination of seasonal nitrogen doses can increase both efficiency and the producer's profitability. In crop cultivation, climatic conditions such as temperature and precipitation affect the uptake of nitrogen by the plant and the rate of mineralization of residues. In addition, characteristics such as soil structure, pH and organic matter levels can increase nitrogen losses through denitrification and leaching, especially in rainy years. Therefore, it is ideal to plan nitrogen applications in a way specific to the region and climatic conditions (Bibi et al., 2016).

In some cases, especially in C4 crops, the amount of nitrogen to be applied is determined by the biomass yield of the crop. For example, C4 crops such as maize have lower nitrogen requirements for the same biomass than C3 crops such as wheat (Gastal & Lemaire, 2002). However, in arid climate conditions, precipitation and temperature variability make yield estimation difficult. Therefore, nitrogen requirements can be calculated based on average yield data from past years; however, this does not necessarily reflect future yields. For more reliable estimates, it is recommended to consider yield values from years with good growing conditions. However, in adverse conditions, nitrogen either remains in the soil or is lost during off-season periods. Therefore, when determining target yield, it is recommended to take the average of the last 5 to 7 years and add 5–10% to it (Gastal & Lemaire, 2002).

Use of Tissue Analysis for N Management

One method used to assess nutrient levels is to use highly sensitive plant species as indicators of soil conditions. Some plants are reliable reflections of general development status because of their direct relationship to environmental conditions and tillage practices (Inada, 1965). In general, increased nitrogen in plants leads to higher nitrogen concentration in leaf tissue, resulting in increased chlorophyll (Inada, 1965) and increased photosynthetic capacity (Sinclair & Horie, 1989). The chlorophyll level in maize leaves, as determined by a chlorophyll meter, is strongly correlated with both yield and leaf nitrogen content (Schepers, Blackmer & Francis, 1992).

The nitrogen level in the plant, especially at critical times, can provide information about nitrogen status. Critical nitrogen refers to the lowest amount of nitrogen required for maximum growth at that time (Ulrich, 1952). Nitrogen concentration is high in the early stages of plant development, while this rate decreases as development progresses. The curve showing this decrease is called the 'critical nitrogen dilution curve' (Lemaire & Salette, 1984). The Nitrogen Nutrition Index (NNI) is calculated as the ratio of plant available nitrogen to a predetermined critical nitrogen level (Gastal & Lemaire, 2002). NNI greater than or less than 1 indicates sufficient or insufficient nitrogen levels, respectively. This method has been used successfully in wheat (Justes et al., 1994), sorghum (Van Oosterom, Carberry & Muchow, 2001), rice (Sheehy et al., 1998) and various grasses (Lemaire & Salette, 1984). However, in some crops such as maize and potato, assessments based on critical nitrogen levels at early developmental stages do not give reliable results (Binford, Blackmer & Cerrato, 1992); this may be due to competition between plants (Binford et al., 1992). Furthermore, as the crop grows, nitrogen concentration may decrease as biomass increases, a dilution effect (Greenwood et al., 1990). The critical nitrogen curve for maize remains valid up to the silage stage (Herrmann & Taube, 2004). This approach is generally considered unsuitable for large-scale commercial production, although it is more applicable in small-scale agricultural systems.

Spatial Variability

Production areas in commercial agriculture are differentiated by spatial differences in soil types, history of use, farming techniques, and nutrient and water movement. This variation can affect plant nitrogen requirements, stress sensitivity, and yield potential from one region to another. Differences in the slope of the land can cause significant fluctuations in grain yield (Alexandra, Kravchenko & Bullock, 1949). In addition, soil depth and drainage characteristics have significant effects on maize and potato yields (Kravchenko et al., 2005). Accumulation of elements such as organic matter and clay content in depressions can lead to increased nitrogen productivity in these areas. This is more pronounced in upper slope areas with low organic matter (Ginting, Moncrief & Gupta, 2003). Although phosphorus (P) and potassium (K) levels are higher in foothill areas, intensive cropping in the past may have caused these nutrients to be less available than expected (Ginting et al., 2003). Therefore, the distribution of P and K may not be directly related to the slope (Ginting et al., 2003). Topography is one of the important factors affecting the spatial variability in grain yield. For example, in corn and soybean (Glycine max L.) production, topographic structure and slope differences explain 30% to 85% of the yield variation (Kravchenko et al., 2005). However, these two factors only partially explain the yield difference; there are many other factors that affect productivity. When plants are under stress, growth performance and crop yield decrease. Seasonal climatic conditions affect plants differently, especially in areas with different slopes.

In dry seasons, soils with high water holding capacity and rich organic matter feel less drought effects, while excessive rainfall can cause ponding and yield loss in depression areas (Alexandra et al., 1949; Kravchenko et al., 2005). In addition, deterioration in soil structure can deepen these differences by causing a decrease in organic matter and water content. Field tillage methods and agricultural techniques used also play a decisive role in growth and yield. In areas where the use of chemical inputs and the amount of soil tillage are reduced, an increase in spatial variability has been observed (Alexandra et al., 1949; Kravchenko et al., 2005).

Fertilizer Application Method and Timing

Nitrogen, one of the most extensively utilized nutrients by plants, is highly susceptible to various soil processes that influence its availability and efficiency. These processes occur both at the surface and within the soil profile, directly affecting nitrogen use efficiency (NUE). Significant nitrogen losses commonly occur through mechanisms such as leaching, surface runoff, and volatilization, all of which can substantially reduce the amount of nitrogen available for plant uptake.

For efficient nitrogen use, nitrogen must be applied in a highly accessible manner. For example, surface-spread urea-ammonium nitrate (UAN) solutions may result in lower yields than subsoil-applied UAN, especially in areas with plant residue (Fox et al., 1986; Bandel et al., 1980). Surface-applied UAN can cause losses such as ammonia volatilization from the urea compound in solution and nitrogen fixation in surface residue (Bandel et al., 1980). Therefore, subsoil application of nitrogenous fertilizers is generally more effective.

Leaf Area Index (LAI)

Leaf Area Index (LAI) is defined as the ratio of leaf surface area to unit soil area (Whittaker and Marks, 1975). This ratio is an indicator that directly reflects the photosynthetic capacity of the vegetation (Cowling and Field, 2003). In some plant species, there is a strong relationship between LAI and biological productivity, while in other species this relationship depends on other variables such as light intensity, canopy density, nitrogen use efficiency (NUE) and the amount of light reaching the canopy (Anten et al., 1995). C4 plants generally exhibit higher nitrogen productivity in denser vegetation, while they produce more leaf area than C3 plants under the same conditions (Anten et al., 1995).

Various methods have been developed to determine LAI by remote sensing. The most common methods include inversion of radiative transfer models (Fang et al., 2003) and empirical relationships between LAI and spectral vegetation indices (Weiss and Baret, 1999). However, these methods have some limitations. For example, calculations based on vegetation indices are difficult to generalize to different types of sites or large geographies (Wiegand et al., 1979). In addition, variables such as atmospheric conditions, ground properties, vegetation architecture, and sensor-sun-target geometry can affect the accuracy of measurements, especially at high LAI levels (Curran, 1983).

When plants are exposed to environmental stress factors, changes occur in the spectral properties of their leaves. Carter (1993) stated that stresses such as competition between plants, the effect of diseases, inadequacy of ectomycorrhizal infections, aging, herbicide damage, increased ozone levels, drought and soil salinity cause similar changes in spectral responses. These responses are generally associated with a decrease in chlorophyll levels. Chlorophyll a has limited light absorption in the red and green wavelengths. Therefore, even small changes in chlorophyll levels can cause increased reflectance in these spectral ranges (Carter and Knapp, 2001). Zhao et al. (2003) reported that the amount of chlorophyll a in plants decreased by more than 60% 42 days after emergence, and as a result, increased reflectance was observed between 550 and 710 nm. Estimation of Vegetative Indices

Nutritional Status

Soil quality directly affects corn growth, and this growth can be optimized by supplementing deficient nutrients with fertilizer (Belay et al., 2002). While traditional methods for assessing the nutrient status of plants include soil analyses and destructive plant analyses, non-destructive sensor-based technologies have recently become increasingly used (Schepers et al., 2003). Such sensor applications are mostly aimed at determining the nitrogen status of plants (Shanahan et al., 2001). Nitrogen deficiency reduces the photosynthetic capacity of leaves in corn plants, leading to a decrease in kernel dry weight, a decrease in yield components, and overall yield losses (Wolfe et al., 1988). Therefore, determining appropriate spectral wavelengths is of great importance in monitoring the nitrogen status of corn (Belay et al., 2002; Shanahan et al., 2001). Shanahan et al. (2001) suggested the use of the Green NDVI (GNDVI) index along with conventional NDVI. GNDVI is calculated based on the reflections obtained from the green bands in the near infrared (NIR) range of 500–600 nm. These results are based on a comprehensive study in which four different corn hybrids were evaluated at five different nitrogen levels under irrigation conditions.

The active optical sensors used in the study can measure by reflecting light at four different wavelengths: blue (460 nm), green (555 nm), red (680 nm) and near infrared (800 nm). It was determined that the obtained NDVI values were significantly related to the applied nitrogen doses and sampling dates. It was also determined that the increase in chlorophyll content showed a high level of positive correlation with nitrogen applications ($r^2 \geq 0.96$) (Ma et al., 1996). Hansen et al. (2003) showed that NDVI is an effective indicator for monitoring growth and development, especially in small grain plants. Similarly, a study by Eminoğlu (2019) aimed to estimate yield and some yield variables in corn using NDVI images obtained from an unmanned aerial vehicle (UAV) flown at low altitude. Within the scope of the study, a general increase in NDVI values was observed as the vegetative development of the plants progressed

This finding supports the strong relationship between NDVI and plant biomass, indicating that NDVI is an effective spectral indicator for monitoring plant growth (Figure 1).

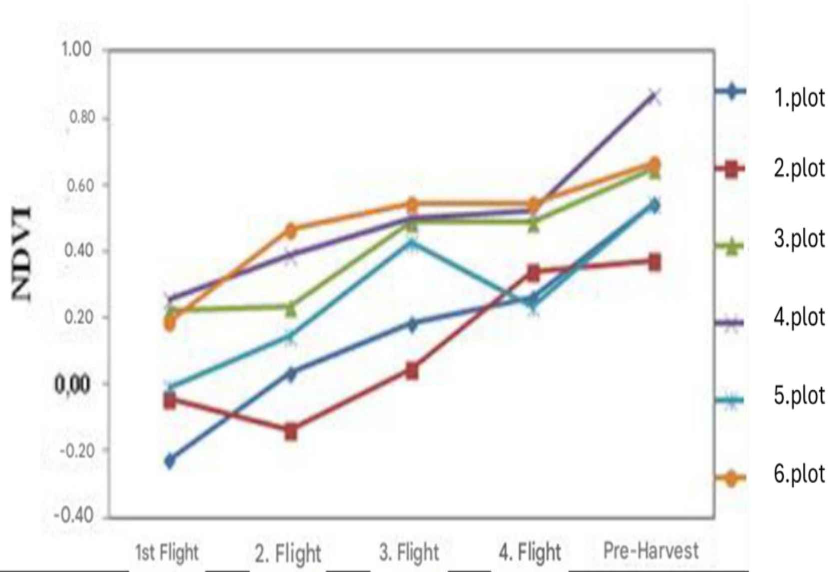

Figure 1. Variation in NDVI Values of Plots Depending on Plant Growth Eminoğlu (2019)

Yield Estimation

Although vegetative indices can be related to green leaf biomass, sensor-based yield estimation is complex (Gitelson et al., 2003). Sensor measurements taken at the Feekes 5 stage of wheat have shown a stronger relationship with grain yield than at other stages (Moges et al., 2005). Estimates based on sensor data can explain 83% of the variation in grain yield (Raun et al., 2001). However, this relationship varies over time and space; factors such as sampling time, hybrid differences, seasonal fluctuations, local conditions, and nitrogen fertilization create uncertainty (Inman et al., 2007).

Use of Sensors and NDVI

Farmers often base nitrogen application on past experience and soil conditions and rarely use season-specific decision support tools (Kitchen and Goulding, 2001). They often target maximum yield by using nitrogen above the recommended dose (Scharf et al., 2006). Sensors close to the canopy plant help determine nitrogen requirements (Schepers et al., 2003). SPAD chlorophyll meters are widely used to assess plant nitrogen status and allow balancing nitrogen to use with optimum yield (Schepers et al., 2003; Scharf et al., 2006). However, samples taken from different hybrids and leaves may affect the instrument calibration (Schepers et al., 2003). A reference strip fertilized with sufficient nitrogen in the field is usually needed (Schepers et al., 1992). When nitrogen carrier is used in the irrigation system, nitrogen recommendations can be made by comparing the measurements in the reference strip and the fields (Scharf et al., 2006). Nitrogen application can be made in cases where the SPAD value falls below the critical threshold (Scharf et al., 2006). Relative SPAD measurements provide better estimates of grain yield than absolute measurements (Scharf et al., 2006). In drought systems, it may be difficult to establish a precise relationship with a single nitrogen application (Scharf et al., 2006). However, in irrigated systems, SPAD measurement is more effective in these systems because constant low rates of nitrogen application can be repeated when necessary.

Conclusions

This review has determined that it is not a single method that can be used alone, but a combined approach can help improve NUE. In long-term prospecting, the use of optical sensors can help improve NUE and farmer profits only when accurate data are collected from multiple sites, considering soil, climate and cultural practice variability, and then a robust yield prediction model is developed. Sensor-based in-season nutrient management combined with a soil test approach at the beginning of crop planting and a split application may be the answer to improving nitrogen use efficiency. Improvement in sensor technology and algorithm development requires further research to develop more reliable and stable models.

REFERENCES

Abebe, Z., & Feyisa, H. (2017). Effects of nitrogen rates and time of application on yield of maize: Rainfall variability influenced time of N application. *International Journal of Agronomy*, 2017, Article ID 1–10.

Alexandra, N., Kravchenko, D. G. B., & Bullock, D. G. (1949). Correlation of corn and soybean grain yield with topography and soil properties. *Agronomy Journal*, *92*(1), 75–83.

Anten, N. P. R., Schieving, F., Medina, E., Werger, M. J. A., & Schuffelen, P. (1995). Optimal leaf area indices in C3 and C4 mono- and dicotyledonous species at low and high nitrogen availability. Physiologia Plantarum, 95(3), 541–550.

Bandel, V. A., Dzienia, S., & Stanford, G. (1980). Comparison of N fertilizers for no-till corn. Agronomy Journal, 72(3), 337.

Battilani, A., Plauborg, F. L., Hansen, S., Dolezal, F., Mazurczyk, W., & Bizik, Z. (2008). Nitrogen uptake and nitrogen use efficiency of fertigated potatoes. Vth IS on Irrigation of Horticultural Crops, 61–67.

Belay, A., Claassens, A., & Wehner, F. (2002). Effect of direct nitrogen and potassium and residual phosphorus fertilizers on soil chemical properties, microbial components and maize yield under long-term crop rotation. Biology and Fertility of Soils, 35(5), 420–427.

Bibi, S., Saifullah, Naeem, A., & Dahlawi, S. (2016). Environmental impacts of nitrogen use in agriculture, nitrate leaching and mitigation strategies. In *Soil Science: Agricultural and Environmental Perspectives* (pp. 131–157). Springer International Publishing.

Binford, G. D., Blackmer, A. M., & Cerrato, M. E. (1992). Relationships between corn yields and soil nitrate in late spring. Agronomy Journal, 84, 53–59.

Blanco, M. (2011). Supply of and access to key nutrients NPK for fertilizers for feeding the world in 2050. Agronomos Etsiaupm. We Engineer Life Food and Environment.

Brentrup, F., & Palliere, B. (2011). Nitrogen use efficiency as an agro-environmental indicator. Yara International Research Centre.

Brown, L., Scholefield, D., Jewkes, E. C., Preedy, N., Wadge, K., & Butler, M. (2000). The effect of sulphur application on the efficiency of nitrogen use in two contrasting grassland soils. Journal of Agricultural Science, 135(2), 131–138.

Büyük, G. (2006). Çukurova koşullarında mısır çeşitlerinde değişik dönemlerde uygulanan farklı azot dozlarının azot kullanım etkinliğine, tane verimine ve kaliteye etkisi (Doktora tezi). Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, Adana.

Cameron, K. C., Di, H. J., & Moir, J. L. (2013). Nitrogen losses from the soil/plant system: A review. *Annals of Applied Biology*, *162*(2), 145–173.

Carter, G. A. (1993). Responses of leaf spectral reflectance to plant stress. American Journal of Botany, 80(3),

Carter, G. A., & Knapp, A. K. (2001). Leaf optical properties in higher plants: Linking spectral characteristics to stress and chlorophyll concentration. American Journal of Botany, 88(4), 677–684.

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO*, *31*(2), 132–140.

Cengiz, M. (2007). Güncel ekmeklik buğday çeşitlerinde azot alım ve kullanımının yüksek sıcaklıktan etkilenişi (Yüksek lisans tezi). Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, Adana.

Choi, J.-H.; Maruthamuthu, S.; Lee, H.-G.; Ha, T.-H.; Bae, J.-H. Nitrate removal by electro-bioremediation technology in Korean soil. J. Hazard. Mater. 2009, 168, 1208–1216.

Cowling, S. A., & Field, C. B. (2003). Environmental control of leaf area production: Implications for vegetation and land-surface modeling. Global Biogeochemical Cycles, 17(1), 7-1–7-14.

Curran, P. J. (1983). Multispectral remote sensing for the estimation of green leaf area index. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 309(1131), 257–270.

Daigger, L.A.; Sander, D.H.; Peterson, G.A. Nitrogen content of winter wheat during growth and maturation. Agron. J. 1976, 68, 815–818.

Daniel, F. B., Griffith, M. B., & Troyer, M. E. (2010). Influences of spatial scale and soil permeability on relationships between land cover and baseflow stream nutrient concentrations. *Environmental Management*, *45*(2), 336–350.

Das, A., Munda, G. C., & Patel, D. P. (2005). Technological options for improving nutrient and water use efficiency.

Ekici, K., Alişarlı, M., & Sancak, Y. C. (2008). Peynir çeşitlerinde nitrit ve nitrozaminler. YYÜ Veteriner Fakültesi Dergisi, 2, 71–72.

Eminoğlu, M. A. (2019). Mısırda verim ve bazı verim değişkenlerinin NDVI kameralı alçak irtifa insansız hava aracı kullanılarak tahmin edilmesi (Yüksek lisans tezi, Harran Üniversitesi, Fen Bilimleri Enstitüsü).

Fang, H., Liang, S., & Kuusk, A. (2003). Retrieving leaf area index using a genetic algorithm with a canopy radiative transfer model. Remote Sensing of Environment, 85(3), 257–270

FAO. (2011). Current world fertilizer trends and outlook to 2015. Rome, Italy.

Flowers, M., Weisz, R., & White, J. G. (2005). Yield-based management zones and grid sampling strategies. *Agronomy Journal*, *97*(4), 968–982.

Fox, R. H., Kern, J. M., & Piekielek, W. P. (1986). Nitrogen fertilizer source, and method and time of application effects on no-till corn yields and nitrogen uptakes. Agronomy Journal, 78(5), 741–746.

Franzen, D. W., Hopkins, D. H., Sweeney, M. D., Ulmer, M. K., & Halvorson, A. D. (2002). Evaluation of soil survey scale for zone development of site-specific nitrogen management. *Agronomy Journal*, *94*(2), 381–389.

French, R., Bowling, R., Abbott, A., & Stewart, M. (2014). High yield irrigated corn: Implementing research and adapting for profitable production. Great Plains Soil Fertility Conference, 15, 78–83.

Gastal, F., & Lemaire, G. (2002). N uptake and distribution in crops: An agronomical and ecophysiological perspective. *Journal of Experimental Botany*, *53*(370), 789–799.

Ginting, D., Moncrief, J. F., & Gupta, S. C. (2003). Performance of a variable tillage system based on interactions with landscape and soil. Precision Agriculture, 4, 19–34.

Gitelson, A. A., Viña, A., Arkebauer, T. J., Rundquist, D. C., Keydan, G. P., Leavitt, B., & Rundquist, D. C. (2003). Remote estimation of leaf area index and green leaf biomass in maize canopies. *Geophysical Research Letters*, 30(1), 51–52.

Greenwood, D. J., Lemaire, G., Gosse, G., Cruz, P., Draycott, A., & Neeteson, J. J. (1990). Decline in percentage N of C3 and C4 crops with increasing plant mass. Annals of Botany, 66, 425–436.

Gupta, M. L., & Khosla, R. (2014). Precision nitrogen management and global nitrogen use efficiency. Retrieved from https://www.ispag.org/.../abstract_1013.docx

Gübretaş. (2013). Türkiye gübre sanayi 2012 yılı değerlendirmesi.

Hansen, P. M., & Schjoerring, J. K. (2003). Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sensing of Environment, 86(5), 542–553.

Herrmann, A., & Taube, F. (2004). The range of the critical nitrogen dilution curve for maize (Zea mays L.) can be extended until silage maturity. Agronomy Journal, 96(4), 1131–1138.

Hocking, M.D.; Reynolds, J.D. Nitrogen uptake by plants subsidized by Pacific salmon carcasses: A hierarchical experiment. Can. J. For. Res. 2012, 42, 908–917.]

Inada, K. (1965). Studies for a method for determining the deepness of green color and chlorophyll content of intact crop leaves and its practical application. 2. Photoelectric characters of chlorophyll meter and correlation between the reading and chlorophyll content in leaves. Proceedings of the Crop Science Society of Japan, 33, 301–308.

Inman, D., Khosla, R., Reich, R. M., & Westfall, D. G. (2007). Active remote sensing and grain yield in irrigated maize. *Precision Agriculture*, 8(4), 241–252.

Jaynes, D. B., & Colvin, T. S. (1997). Spatiotemporal variability of corn and soybean yield. *Agronomy Journal*, *89*(1), 30–37.

Jokela, W. E., & Randall, G. W. (1997). Fate of fertilizer nitrogen as affected by time and rate of application on corn. Soil Science Society of America Journal, 61, 1695–1703.

Justes, E., Mary, B., Meynard, J.-M., Machet, J.-M., & Thelier-Huche, L. (1994). Determination of a critical nitrogen dilution curve for winter wheat crops. Annals of Botany, 74, 397–407.

Kara, B. (2006). Çukurova koşullarında değişik bitki sıklıkları ve farklı azot dozlarında mısırın verim ve azot kullanım etkinliğinin belirlenmesi (Doktora tezi). Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, Adana.

Karam, F., Mounzer, O., Sarkis, F., & Lahoud, R. (2002). Yield and nitrogen recovery of lettuce under different irrigation regimes. Journal of Applied Horticulture, 4(2), 70–76.

Karaşahin, M. (2014). The effects of different irrigation methods and plant densities on nitrogen and irrigation water use efficiency in silage corn production. Crop Research-Hisar, 47(1,2&3), 33–39.

Karnez, E. (2010). Aşağı Seyhan Ovasında buğday ve mısır üretim alanlarında azot bütçesine ilişkin girdi ve çıktıların irdelenmesi (Doktora tezi). Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, Adana.

Keeney, D. R. (1982). Nitrogen management for maximum efficiency and minimum pollution. In *Farmed soils, fertilizer, agro-ecosystems* (pp. 215–229). American Society of Agronomy.

Khalilzadeh, G. H., Mozaffari, J., & Azizov, E. (2011). Genetic differences for nitrogen uptake and nitrogen use efficiency in bread wheat landraces (Triticum aestivum L.). International Journal of AgriScience, 1(4), 232–243.

Kılıç, R., & Korkmaz, K. (2012). Kimyasal gübrelerin tarım topraklarında artık etkileri. Biyoloji Bilimleri Araştırma Dergisi, 5(2), 87–90.

Kitchen, N. R., & Goulding, K. W. T. (2001). On-farm technologies and practices to improve nitrogen use efficiency. In R. F. Follett & J. L. Hatfield (Eds.), *Nitrogen in the environment: Sources, problems, and management* (pp. 335–369). Elsevier.

Kitchen, N. R., Sudduth, K. A., Myers, D. B., Drummond, S. T., & Hong, S. Y. (2005). Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. *Computers and Electronics in Agriculture*, *46*(3), 285–308.

Koffi, D.; Vincent, B.; Valere, M. Yield and nitrogen use efficiency of aromatic rice varieties in response to nitrogen fertilizer. Emir. J. Food Agric. 2016, 28, 126–135.

Kravchenko, A. N., Robertson, G. P., Thelen, K. D., & Harwood, R. R. (2005). Management, topographical, and weather effects on spatial variability of crop grain yields. Agronomy Journal, 97(2), 514–523.

Lambert, D. M., Lowenberg-DeBoer, J., & Malzer, G. L. (2006). Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus. *Agronomy Journal*, *98*(1), 43–54.

Lambert, R. J., Esgar, R. W., & Joos, D. K. (2000, January 24–26). Factors affecting the removal of soil nitrogen by corn hybrids. Illinois Fertilizer Conference Proceedings.

Lemaire, G., & Salette, J. (1984). Relation entre dynamique de croissance et dynamique de prélèvement d'azote pour un peuplement de graminées fouragères: I. Étude de l'effet du milieu. Agronomy Journal, 74(4), 423–430.

Ma, B. L., Morrison, M. J., & Dwyer, L. M. (1996). Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agronomy Journal, 88(6), 915–920.

Mamo, M., Malzer, G. L., Mulla, D. J., Huggins, D. R., & Strock, J. (2003). Spatial and temporal variation in economically optimum nitrogen rate for corn. *Agronomy Journal*, *95*(4), 958–964.

Martin, D. L., Watts, D. G., Mielke, L. N., Frank, K. D., & Eisenhauer, D. E. (1982). Evaluation of nitrogen and irrigation management for corn production using water high in nitrate. Soil Science Society of America Journal, 46, 1056–1062.

Matejek, B.; Huber, C.; Dannenmann, M.; Kohlpaintner, M.; Gasche, R.; Göttlein, A.; Papen, H. Microbial nitrogen-turnover processes within the soil profile of a nitrogen-saturated spruce forest and their relation to the small-scale pattern of seepage-water nitrate. J. Plant Nutr. Soil Sci. 2010, 173, 224–236.

Mikkelsen, R. (2009). The global fertilizer situation: What is going on? Tomato Production Meeting, Woodland, California.

Moges, S. M., Raun, W. R., Mullen, R. W., Freeman, K. W., Johnson, G. V., & Solie, J. B. (2005). Evaluation of green, red, and near infrared bands for predicting winter wheat biomass, nitrogen uptake, and final grain yield. *Journal of Plant Nutrition*, 27(9), 1431–1441.

Mohammad, W., Shah, S. M., Shehzadi, S., & Shah, S. E. (2012). Effect of tillage, rotation and crop residues on wheat crop productivity, fertilizer nitrogen and water use efficiency and soil organic carbon status in dry area (rainfed) of north-west Pakistan. Journal of Soil Science and Plant Nutrition, 12(4), 715–727.

Muchow, R. C. (1994). Effect of nitrogen on yield determination in irrigated maize in tropical and subtropical environments. Field Crops Research, 38(1), 1–13.

Olson, R. A., Raun, W. R., Chun, Y. S., & Skopp, J. (1986). Nitrogen management and interseeding effects on irrigated corn and sorghum and on soil strength. *Agronomy Journal*, *78*(5), 856.

Peltonen, J.; Virtanen, A.; Haggrèn, E. Using a chlorophyll meter to optimize nitrogen fertilizer application for intensively-managed small-grain cereals. J. Agron. Crop Sci. 1995, 174, 309–318.

Perrin, T. S., Boettinger, J. L., Drost, D. T., & Norton, J. M. (1998). Decreasing nitrogen leaching from sandy soil with ammonium-loaded clinoptilolite. Journal of Environmental Quality, 27, 656–663.

Plenet, D., & Lemaire, G. (2000). Relationships between dynamics of nitrogen uptake and dry matter accumulation in maize crops. Determination of critical N concentration. Plant and Soil, 216, 65–82.

Presterl, T., Seitz, G., Landbeck, M., Thiemt, E. M., Schmidt, W., & Geiger, H. H. (2003). Improving nitrogen-use efficiency in European maize: Estimation of quantitative genetic parameters. Crop Science, 43, 1259–1265.

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Lukina, E. V., Thomason, W. E., & Schepers, J. S. (2001). In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agronomy Journal*, 93(1), 131–138.

Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W. E., & Lukina, E. V. (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94, 815–820.

Raun, W.R.; Johnson, G.V. Improving nitrogen use efficiency for cereal production. Agron. J. 1999, 91, 357–363.

Sarı mehmetoğlu, G. (2007). Farklı sulama uygulamaları altında mısır çeşitlerinin sulama suyu ve gübre kullanım etkinliği (Yüksek lisans tezi). Çukurova Üniversitesi, Fen Bilimleri Enstitüsü, Adana.

Scharf, P. C., & Lory, J. A. (2002). Calibrating corn color from aerial photographs to predict sidedress nitrogen need. *Agronomy Journal*, *94*(2), 397–404.

Scharf, P. C., Brouder, S. M., & Hoeft, R. G. (2006). Chlorophyll meter readings can predict nitrogen need and yield response of corn in the North-Central USA. *Agronomy Journal*, 98(3), 655–665. https://doi.org/10.2134/agronj2005.0119

Schepers, A. R., Shanahan, J. F., Liebig, M. A., Schepers, J. S., Johnson, S., & Ariovaldo, L., Jr. (2004). Appropriateness of management zones for characterizing spatial variability of crop production. *Agronomy Journal*, *96*(1), 195–203.

Schepers, J. S., Francis, D. D., & Schlemmer, M. R. (1992). Use of chlorophyll meters to monitor nitrogen status and predict nitrogen requirements of corn. *Journal of Plant Nutrition*, 15(11), 2379–2396.

Schepers, J. S., VanToai, T., Shanahan, J. F., Holland, K. H., Francis, D. D., Schlemmer, M. R., & Caldwell, R. (2003). Use of a crop canopy reflectance sensor to assess corn leaf chlorophyll content. In Digital Imaging and Spectral Techniques: Applications to Precision Agriculture and Crop Physiology (Vol. 66, pp. 135–150). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Shanahan, J. F., Schepers, J. S., Francis, D. D., Thompson, R. B., & Schlemmer, M. R. (2001). Use of remote-sensing imagery to estimate corn grain yield. Agronomy Journal, 93(3), 583–589.

Sheehy, J. E., Dionora, M. J. A., Mitchell, P. L., Peng, S., Cassman, K. G., Lemaire, G., & Williams, R. L. (1998). Critical nitrogen concentrations: Implications for high-yielding rice (Oryza sativa L.) cultivars in the tropics. Field Crops Research, 59(1), 31–41.

Sinclair, T. R., & Horie, T. (1989). Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. Crop Science, 29(1), 90–98.

Staley, T. E., & Perry, H. D. (1995). Maize silage utilization of fertilizer and soil nitrogen on a Hillland Ultisol relative to tillage method. Agronomy Journal, 87, 835–842.

Swain, D. K., Bhaskar, B. C., Krishnan, P., Rao, K. S., Nayak, S. K., & Dash, R. N. (2006). Variation in yield, N uptake and N use efficiency of medium and late duration rice varieties. Journal of Agricultural Science, 144, 69–83.

Ulrich, A. (1952). Physiological bases for assessing the nutritional requirements of plants. Annual Review of Plant Physiology, 3, 207–228.

Van Oosterom, E. J., Carberry, P. S., & Muchow, R. C. (2001). Critical and minimum N contents for development and growth of grain sorghum. Field Crops Research, 70(1), 55–73

Vinod, K.; Rawat, A.K.; Rao, D.L.N. Influence on soil carbon and nitrogen content in vertisols of madhya pradesh under different crop rotation. Q. Res. J. Plant Anim. Sci./Bhartiya Krishi Anusandhan Patrika 2016, 31, 108–113.

Volpe, V.; Giovannetti, M.; Sun, X.-G.; Fiorilli, V.; Bonfante, P. The phosphate transporters LjPT4 and MtPT4 mediate early root responses to phosphate status in non mycorrhizal roots. Plant Cell Environ. 2016, 39, 660–671.

Weiss, M., & Baret, F. (1999). Evaluation of canopy biophysical variable retrieval performances from the accumulation of large swath satellite data. Remote Sensing of Environment, 70(3), 293–306.

Whittaker, R. H., & Marks, P. L. (1975). Methods of assessing terrestrial productivity. In H. Lieth & R. H. Whittaker (Eds.), Primary productivity of the biosphere (Ecological Studies 14, pp. 55–118). Springer.

Wibawa, W. D., Dludlu, D. L., Swenson, L. J., Hopkins, D. G., & Dahnke, W. C. (1993). Variable fertilizer application based on yield goal, soil fertility, and soil map unit. *Journal of Production Agriculture*, *6*(2), 255–261.

Wiegand, C. L., Richardson, A. J., & Kanemasu, E. T. (1979). Leaf area index estimates for wheat from Landsat and their implications for evapotranspiration and crop modeling. Agronomy Journal, 71(3), 336–342.

Wolfe, D. W., Henderson, D. W., Hsiao, T. C., & Alvino, A. (1988). Interactive water and nitrogen effects on senescence of maize. II. Photosynthetic decline and longevity of individual leaves. Agronomy Journal, 80(5), 865–870.

Zhao, D., Reddy, K. R., Kakani, V. G., Read, J. J., & Carter, G. A. (2003). Corn (Zea mays L.) growth, leaf pigment concentration, photosynthesis and leaf hyperspectral reflectance properties as affected by nitrogen supply. Plant and Soil, 257(2), 205–217.

Zhaohui, L., Xiaozong, S., Lihua, J., et al. (2014). Strategies for managing soil nitrogen to prevent nitrate-N leaching in intensive agriculture system. In M. C. Hernandez Soriano (Ed.), Soil Health and Land Use Management.

Zotarelli, L., Scholberg, J. M., Dukes, M. D., & Muñoz-Carpena, R. (2008). Fertilizer residence time affects nitrogen uptake efficiency and growth of sweet corn. Journal of Environmental Quality, 37, 1271–1278.

CHAPTER 13

THE POTENTIAL USE OF COOL SEASON CEREALS AS SİLAGE UNDER CHANGING CLIMATE CONDITIONS

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1. INTRODUCTION

Global climate change stands as one of the most pressing and complex environmental challenges of our time, exerting profound impacts on natural ecosystems as well as on agriculture and food security. Rising temperatures, irregular precipitation patterns, drought, and the increasing frequency of extreme weather events are undermining the stability of agricultural production systems (IPCC, 2023; FAO, 2022; Smith et al., 2020). These environmental stressors reduce productivity across all components of agriculture, from crop cultivation to livestock production, and create significant vulnerabilities within food supply chains. Among the most directly affected elements are forage resources, which are critical for livestock nutrition.

Silage crops, in particular, are highly sensitive to climatic conditions and are thus among the most impacted by these changes. In semi-arid regions such as Turkey, increasing temperatures and diminishing water resources pose serious challenges to the cultivation of traditional summer forage crops. Under these circumstances, cool season cereals (e.g., wheat, barley, rye, triticale), which benefit from winter precipitation and can be harvested in early spring, have emerged as valuable alternatives (Brown et al., 2024; Rodriguez et al., 2023).

Cool season cereals offer a robust solution for sustainable agriculture in the face of climate change due to their tolerance to low temperatures and reduced water requirements, their adaptability to various soil types, and their early growth cycles (Thivierge et al., 2023; Acar & Kaya, 2023; Gökkuş & Hanoğlu Oral, 2022). Agroecological practices such as cereal legume mixtures further enhance their value, improving soil health and increasing forage quality, thereby supporting integrated production systems (Singh et al., 2023; Lopez et al., 2023).

These mixtures contribute to sustainable intensification by reducing the need for nitrogen fertilizers through biological fixation, while also enhancing crude protein content and silage digestibility. This dual effect supports both productivity and feed quality in ruminant systems (Kchaou et al., 2022; Maxin et al., 2016). Additionally, their contribution to increased carbon sequestration reinforces the role of agricultural systems in climate change mitigation (Ibáñez et al., 2020; Papanaoum et al., 2020).

In contrast, maize (*Zea mays* L.), although widely cultivated for its high yield potential, is notably sensitive to drought and heat stress. Under such adverse conditions, maize silage yields and quality may significantly decline, jeopardizing feed security in livestock systems (Babu, 2021; Bernardes et al., 2018). This underscores the need to develop more resilient and sustainable forage sources.

This study aims to evaluate the silage potential of cool season cereals in the context of climate change. Based on recent literature, it will examine the environmental adaptability, yield, and forage quality performance of these cereals, as well as their role in sustainable feed production. Furthermore, the study will explore innovative silage management strategies and identify future research needs, offering strategic recommendations to enhance climate resilience in the livestock sector.

2. Silage Potential and Adaptation Traits of Cool Season Cereals

Cool season cereals have emerged as alternative forage sources due to their ability to adapt to changing climate conditions. Compared to maize, these cereals are more tolerant to lower temperatures and reduced water availability. Their capacity to utilize winter precipitation through autumn sowing and their early spring development allowing harvest before the onset of summer drought enders them highly resilient to climate variability (Thivierge et al., 2023; Acar & Kaya, 2023).

Table 1. Cold Tolerance and Development Period of Cereals*

Cereal Type	Cold Tolerance	Spring Growth Timing	Pre Harvest Development Period (days)
Barley	High	Early	135
Triticale	Medium High	Early	140
Rye	High	Moderate	145
Maize	Low	Late	165

*(Ma et al., 2022)

Moreover, their adaptability to diverse soil types and ecological environments enables cultivation even in marginal areas, thereby enhancing the sustainability of forage production systems (Gökkuş & Hanoğlu Oral, 2022).

Cool season cereals such as barley, rye, and triticale are increasingly regarded as important alternatives in forage production due to their resilience to climate change and adaptability to a wide range of agroecological conditions. Their tolerance to lower temperatures and limited water resources, particularly in comparison to maize, makes them ideal candidates for autumn sowing systems. Poudel et al. (2023) emphasized that these cereals exhibit high dry matter yields and highlighted triticale as especially advantageous for silage use in terms of both productivity and nutritional value. Their study further demonstrated that water efficient species can be successfully cultivated even in semi-arid regions, thereby providing a sustainable forage resource for livestock systems.

3. Silage Quality and Yield Characteristics of Different Cool Season Cereals

Cool season cereals offer varying silage quality and yield potential depending on the species. Crops such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rye (*Secale cereale* L.), and triticale (× *Triticosecale* Wittm.) possess different nutritional values and digestibility characteristics, which are influenced by climatic conditions and cultivation practices. In general, cool season cereals tend to have higher crude protein content compared to maize silage, although their energy values may be somewhat lower. However, these differences can be minimized through proper harvest timing and optimized ensiling techniques (Bernardes et al., 2018).

3.1. Barley and Rye

Barley and rye exhibit high adaptability to arid and semi-arid regions and are capable of producing acceptable levels of green and dry matter yields even under water limited conditions. In a study conducted by Acar and Kaya (2023), the green and dry forage yields of barley and rye grown under drought conditions at different growth stages were evaluated, and both species were found to have significant potential as silage crops. Due to its high tolerance to cold and drought, rye stands out as a reliable forage source, especially under challenging climatic conditions. Barley, on the other hand, has a broader adaptation range and can be successfully cultivated across diverse soil types and climatic zones.

Table 2. Silage Yield and Quality of Cool Season Cereals*

Cereal Type	Dry Matter Yield (t/ha)	Crude Protein (%)	NDF (%)	Digestibility (%)
Barley	11.8	10.2	53.4	63.1
Triticale	12.5	11.0	50.1	65.7
Rye	10.3	9.5	55.8	60.2
Maize	15.2	8.7	45.2	70.3

*(Poudel et al., 2023)

3.2. Triticale

Triticale, a hybrid of wheat and rye, combines the advantageous traits of both parent species and is classified as a cool season cereal. It is characterized by high yield potential, good nutritional value, and resilience to environmental stressors. Triticale silage is particularly valued as a high quality roughage source for dairy cattle. In a doctoral dissertation by Babu (2021), which examined the effects of climate change on maize silage production, winter cereal mixtures especially triticale were highlighted for their potential as alternative forage options. Thanks to its high fiber digestibility and energy content, triticale can positively influence animal performance.

3.3. Wheat and Oats

Wheat and oats are also cool season cereals with potential for silage use. Wheat silage, especially when harvested during the grain filling stage, can offer high levels of energy and protein. Oats are noted for their rapid growth and high dry matter yield. However, the silage quality of these species can vary considerably depending on harvest timing and cultivation conditions. For instance, early harvested oat silage tends to have higher protein content and digestibility, whereas delayed harvesting increases fiber content and reduces nutritional value.

3.4. Cereal Legume Mixtures

Growing cool season cereals in combination with legumes such as forage pea (*Pisum sativum* L.), common vetch (*Vicia sativa* L.), or alfalfa (*Medicago sativa* L.) can significantly improve both silage quality and yield. Legumes contribute to nitrogen fixation, reducing the need for synthetic fertilizers and enhancing crude protein content in the silage. In a study by Kchaou et al. (2022), the forage potential of cereal legume mixtures was evaluated as a climate adaptation strategy, and these mixtures were suggested to be an important agroecological tool for sustainable farming systems. Additionally, such combinations provide environmental benefits by improving soil health and promoting biodiversity.

4. Management Practices for Silage Production from Cool Season Cereals

Climate change can affect not only plant yield but also the nutritional value and fermentation quality of silage. Elevated temperatures and drought conditions may reduce the water content of plants, leading to increased dry matter content at harvest. This can cause compaction difficulties during ensiling and negatively impact the fermentation process. Conversely, excessive rainfall may increase plant moisture levels, lowering dry matter content, which may result in undesirable butyric acid fermentation and nutrient losses (Bernardes et al., 2018). To minimize these risks, dry matter content should be continuously monitored at harvest, and adjustments such as pre wilting or controlled water addition should be considered. Moreover, the use of silage additives (e.g., inoculants, organic acids) can help optimize fermentation and reduce microbial spoilage.

4.1. Variety Selection and Sowing Time

Selecting drought and disease tolerant cultivars that are compatible with climate change conditions is a critical step for successful silage production. Regional climate projections and local conditions should be considered when choosing early maturing or stress resilient varieties. In autumn sowings, optimal use of winter precipitation and the minimization of spring frost risks depend heavily on the timing of sowing. In early spring sowings, varieties that allow harvest before the onset of summer droughts should be prioritized (Thivierge et al., 2023).

4.2. Fertilization and Soil Management

Under climate change conditions, fertilization programs must not only meet the nutritional needs of the plants but also support environmental sustainability. The timing and dosage of nitrogen fertilizers should be adjusted according to plant developmental stages and soil test results. Intercropping with legumes can enrich soil nitrogen content naturally, thereby reducing the need for synthetic fertilizers (Kchaou et al., 2022). Practices that improve soil health such as reduced tillage and the incorporation of organic matter can enhance soil water holding capacity and improve plant resilience to drought stress.

4.3. Harvest Timing and Ensiling Techniques

The quality of silage from cool season cereals is closely linked to harvest timing. Generally, cereals harvested at the milk or dough stage provide optimal dry matter content and nutritional value. Early harvesting results in higher protein content but lower dry matter, while late harvesting increases fiber content and reduces digestibility. Therefore, harvest time should be adjusted flexibly based on climate conditions. For instance, if early summer droughts are expected, harvesting should be scheduled earlier.

Silage making techniques should also be adapted to climatic conditions. In cold regions, low temperatures can slow down the fermentation process and encourage the growth of undesirable microorganisms. In such cases, the use of lactic acid bacteria based inoculants or acid based additives can accelerate fermentation and improve silage quality (Bernardes et al., 2018). Proper compaction and exclusion of air are critical for successful fermentation and high quality silage. Measures must also be taken to prevent oxygen infiltration during storage.

4.4. Water Management

Given the variability in precipitation patterns, water management strategies play a crucial role in silage production from cool season cereals. Winter sowing allows for maximum use of seasonal rainfall, potentially reducing the need for supplemental irrigation. In drought prone areas, water saving irrigation methods such as drip irrigation, or alternative sources like rainwater harvesting, should be considered. Practices such as mulching can also be effective in preserving soil moisture.

4.5. Integrated Pest and Disease Management

Climate change influences the spread and severity of plant diseases and pests. Therefore, integrated pest and disease management (IPM) strategies must be applied in the silage production of cool season cereals. The use of resistant varieties, crop rotation, biological control, and, when necessary, chemical treatment are all important for protecting plant health and minimizing yield losses. Early detection and intervention are essential to prevent potential outbreaks.

4.6. Animal Performance and Economic Feasibility

The impact of silage derived from cool season cereals on animal performance and the economic feasibility for livestock enterprises should be thoroughly investigated. Optimal ration formulations should be developed for different animal species and production systems, and the long term effects of silage on milk yield, meat quality, and animal health should be assessed. Additionally, a cost benefit analysis of silage production from cool season cereals should be conducted to determine its economic attractiveness for farmers.

5. Conclusion

Under changing climate conditions, the potential use of cool season cereals for silage is becoming increasingly important for global food and feed security. These cereals provide a more adaptable alternative to maize, showing greater resistance to drought, high temperatures, and irregular rainfall patterns. However, fully realizing this potential requires further research and development efforts.

In conclusion, cool season cereals represent a promising roughage source for the livestock sector in the context of climate change. Thanks to their adaptability, nutritional value, and flexible management practices, they can play a critical role in ensuring feed security and enhancing the sustainability of agricultural production. Through future research and policy support, this potential can be fully utilized, contributing significantly to global food security and climate change mitigation.

REFERENCES

Acar, R., Kaya, R. 2023. Fresh and dry forage yields of barley and rye at different growth stages under arid conditions. National Journal of Environmental Sciences Research, 7(2): 96-102.

Babu, A.W. 2021. Effect of climate change on global corn production: Impact on corn silage production and ensiled Italian ryegrass (*Lolium multiflorum* Lam.) and winter cereal mixtures as alternative options. Kaposvár University, PhD Thesis, Kaposvár, 1-150.

Bernardes, T.F., Daniel, J.L.P., Adesogan, A.T., McAllister, T.A., Drouin, P., Nussio, L.G., Huhtanen, P., Tremblay, G.F., Bélanger, G., Cai, Y. 2018. Silage review: Unique challenges of silages made in hot and cold regions. Journal of Dairy Science, 101(5): 4001-4019.

Brown, J., Smith, A., Lee, K. 2024. Climate change impacts on forage production a global review. Sustainability, 16(2): Article 862.

FAO. 2022. The State of Food and Agriculture 2022: Leveraging Agriculture for Climate Action. FAO, Rome.

Gökkuş, A., Hanoğlu Oral, H. 2022. An important forage source for animals: Small grain pastures. Acta Naturae Scientia, 3(1): 1-14.

Harmini, H., Fanindi, A. 2020. Adaptation strategy of forage crops to climate change. Wartazoa, 30(4): 201-210.

Ibáñez, M., Altimir, N., Ribas, À., Eugster, W., Sebastià, M. 2020. Cereal legume mixtures increase net CO_2 uptake in a forage system of the Eastern Pyrenees. Biogeosciences Discussions, 17: 1-30.

IPCC. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Jafari, A., Mirbahar, A.A. 2023. Silage performance of barley and triticale under climate resilient cropping systems. Journal of Animal and Feed Sciences, 32(2): 147-157.

Kchaou, R., Benyoussef, S., Jebari, S., Harbaoui, K., Berndtsson, R. 2022. Forage potential of cereal legume mixtures as an adaptive climate change strategy under low input systems. Sustainability, 15(1): Article 338.

Lopez, M., Garcia, F., Hernandez, J. 2023. Agroecological strategies for climate resilient forage systems. Agricultural Systems, 212: 103580.

Ma, X., Chen, X., Luo, Y. 2022. Adaptability of winter cereals to low temperature stress and forage production potential. Crop Science, 62(4): 1234-1245.

Maxin, G., Arrigo, Y., Dozias, D., Andueza, D., Morvan, A., Baumont, R., Delaby, L. 2016. Prediction of the in vivo organic matter digestibility of cereal-legume intercrop silages. Animal, 10(1): 21-30.

Papanaoum, G., Bouloumpasi, E., Lazaridou, T. 2020. Silage yield and protein content of forage legumes intercropped with cereals. AGROFOR, 5(2): 72-80.

Poudel, P.R., Poudel, R., Islam, M. 2023. Evaluating forage yield and nutritive value of winter cereals for silage under semi-arid conditions. Agronomy Journal, 115(1): 230-243.

Rodriguez, P., Martinez, L., Chen, Y. 2023. Winter cereals for forage production in changing climates. Field Crops Research, 280: 108520.

Singh, R., Kumar, S., Patel, A. 2023. Cereal-legume intercrops for sustainable forage production. Agronomy, 13(5): Article 1219.

Smith, P., Nabuurs, G.J., Stehfest, E. 2020. Climate change and agriculture: The science of climate change impacts and adaptation in the agricultural sector. Food Security, 12(2): 271-282.

Thivierge, M.N., Bélanger, G., Jégo, G., Delmotte, S., Rotz, C.A., Charbonneau, É. 2023. Perennial forages in cold humid areas: Adaptation and resilience building strategies toward climate change. Agronomy Journal, 115(3): 1357-1372.

Turkish Food and Beverage Industry Associations Federation (TGDF). 2017. Climate Change Report. Ankara: TGDF.

CHAPTER 14

THE EFFECTS OF CLIMATE CHANGE ON SOIL HEALTH AND PLANT-SOIL INTERACTIONS

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1.INTRODUCTION

Climate change, characterized by rising greenhouse gas emissions, global temperature increases, and the intensification of extreme weather events, has emerged as one of the most critical environmental threats to agricultural ecosystems. These climatic shifts exert multifaceted impacts on soil health and plant–soil interactions, which form the foundation of agricultural productivity. Soil not only provides physical support to plants but also serves as a vital medium for water retention, nutrient cycling, and microbial activity. However, disruptions in soil moisture regimes, organic matter dynamics, microbial processes, and biochemical functions caused by climate change significantly compromise soil fertility and ecosystem resilience (Brevik, 2013).

Soil systems mediate the balance between climate, vegetation, and edaphic factors through complex mechanisms such as the carbon and nitrogen cycles, microbial diversity, root development, and symbiotic interactions. Recent studies have increasingly highlighted the vulnerability of these interactions under changing climatic conditions and the varying responses of agroecosystems to such stressors (Yang et al., 2025). For instance, elevated temperatures associated with climate change accelerate the decomposition of soil organic matter, leading to carbon losses and a consequent decline in soil quality (Pires et al., 2023). Furthermore, alterations in vegetation cover and the quantity and composition of root exudates reshape the structure of soil microbial communities and induce shifts in nutrient cycling pathways (Fetzer et al., 2024).

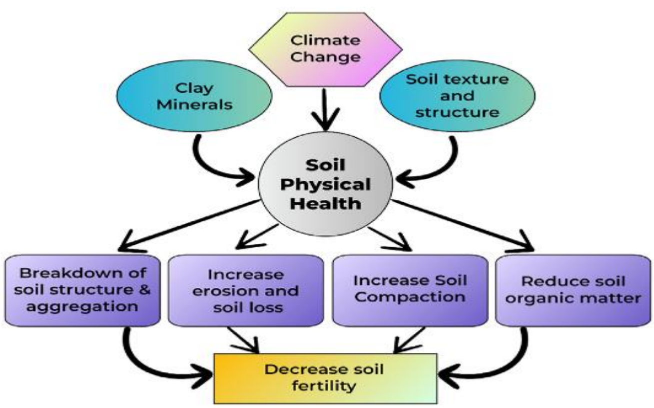

Figure.1 Pathways of climate change impacts on soil physical health and fertility (Oishy et al.,2025).

Plant–soil interactions are shaped not only by physical and chemical properties but also by intricate biological processes. Microbial activity within the rhizosphere plays a pivotal role in regulating nutrient availability and enhancing plant resilience under stress conditions (Kumar et al., 2022). Moreover, the tripartite relationship among plants, soils, and microorganisms is central to the sustainability of ecosystem services, especially under the influence of climate change (Sevanto et al., 2020). Several studies have demonstrated that the effects of plant–soil interactions on microbial communities can vary significantly under climatic stressors, and these shifts may initiate feedback loops with long-term implications for ecosystem functioning (Brigham et al., 2021). In this context, a comprehensive examination of how climate change affects soil health and plant–soil interactions is not only essential for sustaining agricultural productivity but also critical for maintaining ecosystem services and environmental balance. This chapter will provide an in-depth analysis of the effects of climatic variability on soil physical properties, organic matter content, microbial community composition, and nutrient cycling. It will also explore how reciprocal feedback mechanisms within the plant–soil system mediate and potentially amplify these changes over time.

2. IMPACTS OF CLIMATE CHANGE ON SOIL HEALTH

Soil health encompasses the integrated physical, chemical, and biological properties that sustain ecosystem functionality. However, ongoing global climate change poses a multifaceted threat to this integrity. Rising temperatures, altered precipitation patterns, and the increasing frequency of extreme weather events—such as droughts and floods—directly and indirectly affect the functioning of soil systems (Keesstra et al., 2016; Lal, 2011).

One of the most critical consequences of these changes is the decline in soil organic matter. Organic matter plays a fundamental role in maintaining soil structure, supporting biological activity, and facilitating chemical processes. Elevated temperatures and moisture loss accelerate the decomposition of organic matter and the depletion of soil carbon stocks. This not only leads to reduced soil quality but also contributes to increased atmospheric greenhouse gas concentrations (Eviner, 2008; Shah et al., 2022). As organic matter declines, the stability of soil aggregates is compromised, weakening the soil's resistance to erosion. Irregular and intense rainfall events exert further pressure on these fragile structures, resulting in severe surface runoff and the loss of fertile topsoil layers (García-Fayos et al., 2009).

The decline in soil organic matter also signifies a reduction in the primary energy source for soil biota. Microbial communities are central to the biological dynamics of soil ecosystems, functioning as key drivers of nutrient cycling and organic matter decomposition. However, fluctuations in temperature and moisture resulting from climate change adversely impact both the diversity and functionality of these communities (Classen et al., 2015; Bardgett & van der Putten, 2013). In particular, symbiotic organisms such as mycorrhizal fungi and nitrogen-fixing rhizobacteria exhibit reduced activity and colonization under stress conditions, thereby disrupting critical plant–soil interactions (Brigham et al., 2021; Fetzer et al., 2024). A loss in microbial diversity not only impairs overall ecosystem functioning but also diminishes the soil's capacity to suppress plant pathogens, which can lead to cascading negative effects on plant health.

Climate change also induces substantial degradation in the physical properties of soil. Increased rates of evaporation reduce soil moisture levels, leading to physical deformations such as compaction and cracking in drying soils (Kumar et al., 2022). These alterations restrict root development and negatively impact both the retention and movement of water within the soil profile. Concurrently, increasingly erratic precipitation patterns contribute to a dual stress scenario: prolonged droughts suppress biological activity, while intense rainfall events accelerate erosion processes. The disintegration of soil aggregates, weakening of structural integrity, and reduction in porosity diminish the soil's water infiltration capacity, thereby exacerbating water stress (Baveye et al., 2016).

From a chemical perspective, climate change disrupts the balance of essential soil nutrients, particularly the cycles of key macronutrients such as nitrogen, phosphorus, and potassium. Rising temperatures accelerate nitrogen mineralization while simultaneously promoting denitrification processes, which result in significant nitrate losses (Classen et al., 2015). Moreover, intense rainfall events facilitate the fixation of phosphorus in soil matrices and enhance potassium leaching, thereby reducing nutrient availability for plant uptake (Eviner, 2008). These nutrient losses negatively affect plant nutrition and, consequently, threaten crop productivity.

Fluctuations in soil pH and increases in salinity levels further compromise soil chemical health. Climate-induced shifts in pH can limit microbial activity and decrease the capacity of plants to absorb nutrients (Bardgett & van der Putten, 2013). In irrigated regions, elevated evaporation rates lead to the accumulation of salts at the soil surface, increasing salinity and impairing both biological and chemical soil functions (Shah et al., 2022; Lal, 2011).

These multifaceted impacts undermine the biological diversity, structural stability, and chemical balance of soils, thereby impeding their capacity to function as integral components of natural ecosystems. The effects of climate change on soil health represent not only an environmental concern but also a global threat to agricultural productivity and food security. In this context, the development of integrated policies, adaptive agricultural practices, and ecosystem-based management approaches is critical for enhancing the resilience of soil systems.

3. DISRUPTION OF PLANT–SOIL INTERACTIONS

Plant–soil interactions play a central role in the functioning of terrestrial ecosystems and are critical for the sustainability of numerous ecosystem services, including plant health, nutrient cycling, carbon sequestration, and soil fertility. However, climate change exerts multifaceted pressures on this intricate network of interactions, leading to significant disruptions. Rising temperatures, prolonged droughts, irregular precipitation patterns, and increased atmospheric carbon dioxide concentrations are profoundly altering the biochemical and physiological relationships between plants and soils (Muhammad et al., 2025; Ostle et al., 2009).

Climate change directly limits root development and functionality, particularly under drought conditions, where adaptive yet yield-reducing responses such as reduced root biomass, lower root density, and deeper root penetration are observed. These changes restrict plant access to water and essential nutrients in the soil and concurrently reduce rhizodeposition, thereby negatively impacting rhizosphere microbial communities (Classen et al., 2015). Moreover, the combined effects of elevated temperatures and water scarcity cause damage to root membranes and impair nutrient exchange between roots and soil.

Mutualistic relationships with mycorrhizal fungi, rhizobacteria, and other symbiotic organisms are highly sensitive to climate change. Elevated temperatures and drought conditions destabilize these symbiotic interactions, thereby reducing the ability of plants to uptake essential nutrients such as nitrogen and phosphorus, and diminishing the stress tolerance benefits typically conferred by symbiosis (Brigham et al., 2021; Daunoras et al., 2024). In particular, arbuscular mycorrhizal fungi (AMF) show significant declines in colony density and spore production under climate stress, which has cascading effects on plant water-use efficiency and resilience (Pritchard, 2011).

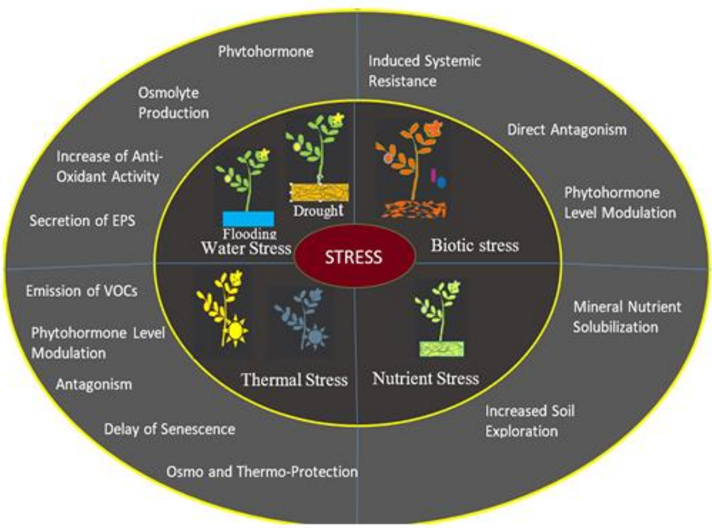

Figure.2 Climate change adaptation and soil microbiome (Shah et al.,2022).

Climate change also transforms the composition and functionality of microbial communities inhabiting the rhizosphere. Studies have shown that changes in soil temperature, moisture, pH, and organic matter availability significantly affect microbial biodiversity and enzymatic activity (Daunoras et al., 2024). In this context, declines or imbalances in the activity of key microbial enzymes involved in the carbon (C), nitrogen (N), and phosphorus (P) cycles—such as β-glucosidase, N-acetyl-glucosaminidase, phosphatases, and urease—can limit nutrient mineralization and plant nutrient uptake. Microbial enzymes are considered biological fingerprints of soil ecosystem functionality, and alterations in their activity directly impact soil health and plant development (Zhang et al., 2021).

Nutrient imbalances and disrupted microbial symbioses result in substantial deficiencies in plant nutrition. This leads to decreased photosynthetic efficiency, elevated metabolic stress, and growth inhibition, ultimately reducing crop productivity (Kumar et al., 2022). Moreover, such disruptions weaken beneficial microbial interactions that suppress pathogens, rendering plants more vulnerable to diseases.

In conclusion, climate-induced environmental stresses weaken the functional and symbiotic relationships between plants and soils, thereby threatening the sustainability of soil health, the continuity of nutrient cycles, and agricultural productivity. In this regard, promoting climate-resilient plant–microbe associations, developing adaptive agricultural practices, and implementing rhizosphere-focused sustainable management strategies are of critical importance.

4. ADAPTATION STRATEGIES AND SUSTAINABLE MANAGEMENT

One of the major challenges faced in agricultural production systems under climate change is the restoration of degraded soil health and the sustainable support of plant–soil–microbe interactions. In this context, adaptation strategies and sustainable soil management practices are essential tools for both climate change mitigation and resilience building.

At the core of these strategies lies the enhancement of soil organic matter. The application of organic amendments such as compost, farmyard manure, green manures, and cover crops plays a vital role in improving soil structure, increasing water retention capacity, and stimulating microbial activity. Moreover, organic matter enhances the soil’s buffering capacity, conferring resilience against pH fluctuations and facilitating more efficient nutrient uptake by plants (Lal, 2011; Eviner, 2008). In addition to improving soil functionality, these practices contribute to climate change mitigation by enhancing the soil's carbon sequestration potential and reducing greenhouse gas emissions.

Another critical strategy involves the use of biofertilizers and microbial inoculants. These applications commonly include beneficial microorganisms such as arbuscular mycorrhizal fungi, nitrogen-fixing rhizobacteria, phosphate-solubilizing bacteria, and potassium-mobilizing microbes, which are introduced into the plant rhizosphere. These symbiotic organisms improve nutrient availability and uptake while also enhancing plant tolerance to environmental stresses (Muhammad et al., 2025). Furthermore, such microbial agents contribute to plant health by suppressing soil-borne pathogens within the rhizosphere.

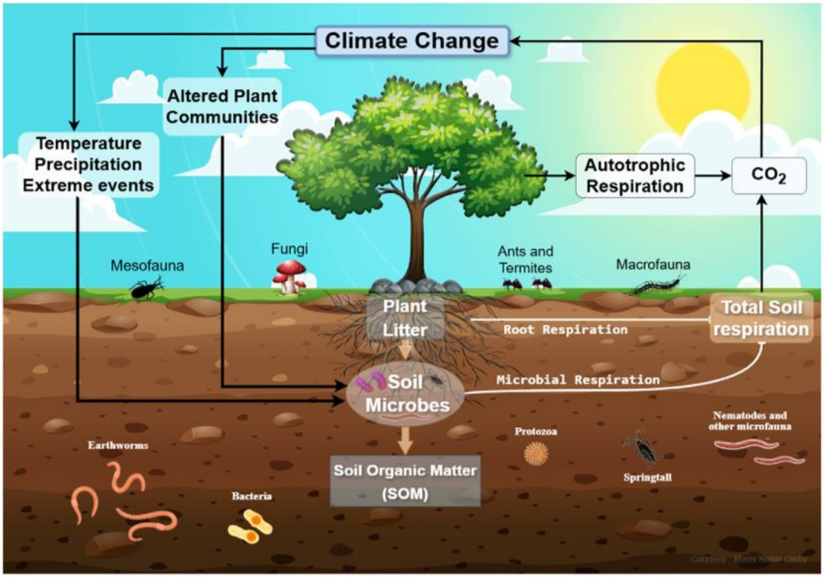

Figure.3 Impact of climate change on the interactions of soil organic matter, microbial communities, and soil biodiversity (Oishy et al.,2025).

These biological approaches are increasingly integrated into the development of "climate-smart soil management" practices, which represent a systematic and multi-component management paradigm. Climate-smart soil management encompasses a wide array of techniques, ranging from water-conserving practices and reduced tillage to integrated nutrient management, aiming not only to preserve soil structure and productivity but also to minimize environmental impacts. Such practices are particularly effective in limiting soil erosion, mitigating salinity and pH imbalances, regulating soil temperature, and enhancing microbial diversity (Keesstra et al., 2016; Brigham et al., 2021).

For soil health to be maintained in a sustainable manner, adaptive and holistic strategies must be tailored to site-specific conditions. These practices not only enhance agricultural productivity but also secure the long-term ecological functioning of soils. Therefore, building a resilient agricultural system under climate change conditions necessitates a combined consideration of organic matter management, microbially assisted biofertilization, and climate-smart agronomic techniques. Future research and policy initiatives should prioritize the field-level integration and impact assessment of these strategies to ensure both sustainable food security and ecosystem health.

5.CONCLUSION AND FUTURE DIRECTIONS

The impacts of climate change on soil health and plant–soil interactions are multifaceted and complex. The findings presented in this chapter highlight that soil organic matter, microbial diversity, nutrient cycling, and symbiotic relationships are increasingly threatened by climate change. These threats extend beyond short-term productivity losses, posing risks to long-term ecosystem resilience and agricultural sustainability. The depletion of soil organic matter leads to the contraction of microbial habitats and a decline in biological diversity, while disruptions in nutrient cycling directly impair plant development and crop quality. Moreover, the breakdown of symbiotic relationships weakens plants' defense mechanisms, particularly under drought and heat stress conditions.

Looking ahead, enhancing the resilience of soil ecosystems to climate change requires the integration of multidisciplinary and cross-scale approaches. Advanced modeling studies that evaluate the responses of various soil types and plant systems under different climate scenarios, along with long-term field trials, are essential in this context. Furthermore, elucidating the molecular mechanisms of plant–soil–microorganism interactions will enable the development of genetic and biogeochemical adaptation strategies. These insights will form a scientific foundation for the design of site-specific and locally adapted agricultural practices.

To address the impacts of climate change on agricultural productivity and soil health, it is vital to develop applicable, context-specific, and sustainable policy approaches. Farmers should be educated and incentivized to implement practices such as organic matter management, biological fertilization, and climate-smart agriculture. Agricultural support programs must go beyond the promotion of chemical inputs to also prioritize ecosystem-based solutions.

Local and national governments should establish digital soil health monitoring systems to enable early detection of risks such as erosion, salinization, and organic matter loss through decision-support tools. In addition, legal regulations and incentives for climate-resilient soil practices should be enacted, while fostering collaboration among private sectors, public institutions, academia, and farmers. This multi-stakeholder approach will not only promote environmental sustainability but also support food security and rural development.

REFERENCES

Bardgett, R. D., & van der Putten, W. H. (2013). *Belowground biodiversity and ecosystem functioning*. *Nature*, 515(7528), 505–511. https://doi.org/10.1038/nature13855

Baveye, P. C., Baveye, J., & Gowdy, J. (2016). Soil "ecosystem" services and natural capital: critical appraisal of research on uncertain ground. *Frontiers in Environmental Science*, *4*, 41.

Brevik, E. C. (2013). The potential impact of climate change on soil properties and processes and corresponding influence on food security. *Agriculture*, *3*(3), 398-417.

Brigham, L. M., et al. (2021). *Do plant–soil interactions influence how the microbial community responds to environmental change? Ecology*, 102(2), e03156. Retrieved from [PDF source]

Classen, A. T., Sundqvist, M. K., Henning, J. A., Newman, G. S., Moore, J. A., Cregger, M. A., ... & Patterson, C. M. (2015). Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: What lies ahead?. *Ecosphere*, *6*(8), 1-21.

Daunoras, J., Kačergius, A., & Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, *13*(2), 85.

Daunoras, J., Kačergius, A., & Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, *13*(2), 85.

Eviner, V. T., & Hawkes, C. V. (2008). Embracing variability in the application of plant–soil interactions to the restoration of communities and ecosystems. *Restoration Ecology*, *16*(4), 713-729.

Fetzer, J., Moiseev, P., Frossard, E., Kaiser, K., Mayer, M., Gavazov, K., & Hagedorn, F. (2024). Plant–soil interactions alter nitrogen and phosphorus dynamics in an advancing subarctic treeline. *Global Change Biology*, *30*(3), e17200.

García-Fayos, P. A. T. R. I. C. I. O., & Bochet, E. (2009). Indication of antagonistic interaction between climate change and erosion on plant species richness and soil properties in semiarid Mediterranean ecosystems. *Global Change Biology*, *15*(2), 306-318.

Keesstra, S., Pereira, P., Novara, A., Brevik, E. C., Azorin-Molina, C., Parras-Alcántara, L., ... & Cerdà, A. (2016). Effects of soil management techniques on soil water erosion in apricot orchards. *Science of the Total Environment*, *551*, 357-366.

Kumar, S. S., Wani, O. A., Krishna, J. R., & Hussain, N. (2022). Impact of climate change on soil health. *International Journal of Environmental Science*, *7*.

Lal, R. (2011). Soil health and climate change: an overview. *Soil health and climate change*, 3-24.

Muhammad, M., Wahab, A., Waheed, A., Hakeem, K. R., Mohamed, H. I., Basit, A., ... & Li, W. J. (2025). Navigating Climate Change: Exploring the Dynamics Between Plant–Soil Microbiomes and Their Impact on Plant Growth and Productivity. *Global Change Biology*, *31*(2), e70057.

Oishy, M. N., Shemonty, N. A., Fatema, S. I., Mahbub, S., Mim, E. L., Raisa, M. B. H., & Anik, A. H. (2025). Unravelling the effects of climate change on the soil-plant-atmosphere interactions: A critical review. *Soil & Environmental Health*, 100130.,

Ostle, N. J., Smith, P., Fisher, R., Ian Woodward, F., Fisher, J. B., Smith, J. U., ... & Bardgett, R. D. (2009). Integrating plant–soil interactions into global carbon cycle models. *Journal of Ecology*, *97*(5), 851-863.

Pires, D., Orlando, V., Collett, R. L., Moreira, D., Costa, S. R., & Inácio, M. L. (2023). Linking nematode communities and soil health under climate change. *Sustainability*, *15*(15), 11747.

Pritchard, S. G. (2011). Soil organisms and global climate change. *Plant Pathology*, *60*(1), 82-99.

Sevanto, S., Grossiord, C., Klein, T., & Reed, S. (2020). Plant-soil interactions under changing climate. *Frontiers in Plant Science*, *11*, 621235.

Shah, A. M., Khan, I. M., Shah, T. I., Bangroo, S. A., Kirmani, N. A., Nazir, S., ... & Biswas, A. (2022). Soil microbiome: a treasure trove for soil health sustainability under changing climate. *Land*, *11*(11), 1887.

Van der Putten, W. H., Bardgett, R. D., Bever, J. D., Bezemer, T. M., Casper, B. B., Fukami, T., ... & Wardle, D. A. (2013). Plant–soil feedbacks: the past, the present and future challenges. *Journal of ecology*, *101*(2), 265-276.

Yang, Q., Deng, Z., & Wang, R. (2025). The frontier exploration on soil-plant-climate interactions: Mechanism analysis and precision agriculture applications. *Geographical Research Bulletin*, *4*, 122-125.

Zhang, N., Nunan, N., Hirsch, P. R., Sun, B., Zhou, J., & Liang, Y. (2021). Theory of microbial coexistence in promoting soil–plant ecosystem health. *Biology and Fertility of Soils*, *57*, 897-911.

CHAPTER 15

A SILENT LIFE: SOIL

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INTRODUCTION

Soil is considered to be one of the most fundamental resources for sustaining life, yet its inherent complexity is frequently disregarded. Humans engage in a variety of activities on the land, including walking, farming, and construction, yet often neglect to consider its fundamental functions. It is vital for sustaining life, supporting agricultural practices, and regulating the climate. This article will explore the multifaceted world of soil, including the organisms that inhabit it, the ecological functions it fulfils, and the threats it faces.

Soil, which is largely invisible and silent, is the foundation of life on Earth. It is therefore vital to understand its processes if we are to ensure environmental and agricultural sustainability. The phrase "below the surface of the soil" is used to denote the entirety of that which exists beneath the Earth's uppermost layer, a realm characterised by abundant life and activity. Soil itself is a complex system of mineral particles, organic matter, microorganisms, water and air, with an even more complex environment underneath.

Although soil may appear to be a simple and unremarkable component of the Earth's surface, it in fact harbors a complex and dynamic ecosystem that supports nearly all terrestrial life. Despite its vital role in the sustainability of life, soil is often perceived merely as a medium that facilitates plant growth. However, this perspective falls short of capturing the richness and depth of the intricate processes taking place beneath the surface. From microbial activities in the rhizosphere to the interactions between soil particles and organic matter, the world below is far from "silent"—rather, it is a vibrant environment in which countless organisms are engaged in continuous cycles of life, death, and renewal.

This study seeks to explore the often-overlooked significance of soil as a living system, examining its structure, functions, and role in sustaining life on Earth. By delving into the microbial, physical, and chemical processes that define the soil environment, it aims to highlight the soil’s interconnectedness with broader ecological and environmental systems. Furthermore, understanding the biological complexity of soil has profound implications for agriculture, biodiversity conservation, and the fight against climate change. This text provides a foundation for recognizing soil as a dynamic resource that warrants careful study and protection.

Soil: The Foundation of Life

Soil, in its simplest form, is a mixture of minerals, organic matter, water, and air. Mineral components formed from the decomposition of rocks provide the soil's basic structure and contain the nutrients necessary for plant growth. However, the true life-giving element of soil is organic matter, commonly called "humus." This material, mixed with the soil through the decay of plant and animal remains, provides a rich microbial environment. Soil consists of layers that vary in composition, texture, and biological activity.

O Layer: The top layer is rich in organic matter and consists of decaying plant and animal remains.

Layer A (Topsoil): Contains a mixture of organic matter and minerals.

Layer B (Subsoil): The accumulation of minerals leached from the upper layers.

Layer C (C Layer): Made up of weathered bedrock.

R Layer: Bedrock, which is the source of soil formation.

The physical structure of soil (texture, porosity, etc.) affects plant and microbial life by determining its capacity to retain water, nutrients and gases. For example, sandy soils filter water quickly but are less fertile, while clay soils retain water and nutrients but can become compacted and inhibit root growth. These balances directly determine soil fertility and its ability to support life.

Soil Composition

Soil is a dynamic and heterogeneous medium composed of mineral particles, organic matter, air, and water. While its composition may vary across different ecosystems, all soils share a fundamental structure. These components play critical roles in soil functions such as nutrient cycling, water retention, and providing habitat for various organisms.

1.Mineral Particles

Mineral particles in the soil are primarily derived from the weathering of rocks and are classified according to their size. There are three main particle size categories: sand, silt, and clay. These particles contribute to the texture of the soil, which in turn influences its permeability, water-holding capacity, and nutrient retention ability. Sandy soils, characterized by larger particles, allow for efficient water drainage but retain fewer nutrients. In contrast, clay soils contain finer particles, which enhance the retention of water and nutrients, although they have lower permeability.

2. Organic Matter

Organic matter consists of decomposed plant and animal material. It is a vital component of soil, enhancing soil structure, supplying nutrients, and supporting the growth of soil organisms. The decomposition of organic matter releases essential nutrients such as nitrogen, phosphorus, and sulfur into the soil. Humus, a dark, stable form of organic matter, improves soil fertility by retaining water and nutrients, thus providing a favorable environment for plant growth.

3. Air and Water

Soil also contains air and water, which are essential for sustaining life. The pores within the soil provide space for gas exchange and water movement, both of which are critical for the survival of plants and microorganisms. The balance between soil moisture and air content is crucial for plant health, as excessive water can deplete oxygen and cause root rot, while insufficient water can lead to drought stress.

Soil Microbial Life: The Hidden Network

Beneath the soil surface lies an invisible yet highly diverse ecosystem of microorganisms. Soil hosts a vast array of organisms, including bacteria, fungi, protozoa, nematodes, and other microbes. These microorganisms play essential roles in nutrient cycling, organic matter decomposition, and the maintenance of overall soil health.

One of the most fascinating aspects of soil is the diversity and abundance of its microbial life. Soils are teeming with billions of bacteria, fungi, protozoa, and nematodes. These microorganisms break down organic matter to facilitate nutrient cycling, form symbiotic relationships with plant roots, and contribute significantly to soil fertility.

- Bacteria play a critical role in the nitrogen cycle by converting atmospheric nitrogen into forms usable by plants.
- Fungi form mutualistic relationships with plant roots known as mycorrhizae, enhancing water and nutrient uptake.
- Visible soil organisms, such as earthworms, enrich the soil by consuming organic matter and improving soil structure.

These processes are particularly concentrated in the rhizosphere—the region surrounding plant roots. Organic compounds secreted by roots serve as a food source for microorganisms, which in return enhance soil structure and nutrient availability.

Although modern molecular techniques have significantly advanced our understanding of soil microbiota, the complex interactions among these organisms are still not fully understood. A deeper understanding of soil ecology is essential for developing sustainable agricultural practices and addressing challenges related to climate change.

1. Decomposers

Soil decomposers, including bacteria and fungi, break down organic matter into simpler compounds. This decomposition process releases essential nutrients necessary for plant growth, thereby supporting nutrient cycling. Additionally, the activity of decomposers contributes to the formation of humus, which enhances soil structure and fertility.

2. Symbiotic Relationships

Certain soil microbes establish symbiotic relationships with plants. For example, mycorrhizal fungi form mutual associations with plant roots. These fungi extend their hyphal networks through the soil, increasing the plant's access to water and nutrients such as phosphorus. In return, the plant provides the fungi with carbohydrates produced through photosynthesis.

Certain bacteria, such as Rhizobium, form symbiotic relationships with leguminous plants, converting atmospheric nitrogen into a form that plants can utilize. This process is vital for maintaining the nitrogen cycle in soils and plays a significant role in reducing reliance on synthetic fertilizers.

Soil as a Habitat

Soil serves as a habitat for a wide range of organisms, from microscopic bacteria to larger organisms such as earthworms, insects, and small mammals. These organisms interact within complex food webs and contribute to soil health and nutrient cycling.

Soil is home to a vast array of living organisms, including earthworms, insects, bacteria, fungi, and other microorganisms. These organisms play key roles in decomposing organic matter, recycling nutrients, and supporting plant growth.

- Earthworms improve soil structure by aerating the soil.
- Fungi decompose organic matter and form symbiotic relationships with plant roots.
- Bacteria contribute to nutrient cycling by breaking down organic compounds.

1. Earthworms

Earthworms are often referred to as "ecosystem engineers" due to their significant influence on soil structure. Their burrowing and feeding activities create channels that facilitate air and water movement, thereby improving soil aeration and drainage. Furthermore, earthworms incorporate organic matter into the soil and assist in nutrient cycling.

2. Soil Invertebrates

Soil is also inhabited by a diverse group of invertebrates, including insects, ants, and nematodes. These organisms perform essential functions such as decomposing organic material, recycling nutrients, and regulating the populations of other soil organisms.

Ecological Functions of Soil

Soil performs a multitude of ecological functions that are essential for the conservation of biodiversity and the sustainability of life on Earth.

1. Nutrient Cycling

Soil is a crucial component of nutrient cycling. It stores essential nutrients required by plants, such as nitrogen, phosphorus, and potassium. Soil microorganisms facilitate the decomposition of organic matter, thereby releasing these nutrients in forms accessible to plants. Through this process, soil maintains a balanced supply of nutrients that supports plant growth.

2. Water Regulation

Soil plays a vital role in regulating water flow across landscapes. It absorbs and retains rainfall, reducing surface runoff and the risk of flooding. Moreover, soil gradually releases this stored water through evaporation and transpiration, contributing to the maintenance of groundwater levels. The water-holding capacity of soil is influenced by its texture and structure; clay-rich soils generally retain more moisture than sandy soils.

3. Carbon Storage

Soil acts as a significant carbon sink by storing large amounts of carbon in the form of organic matter. This function is critical in mitigating climate change, as it helps reduce the concentration of carbon dioxide in the atmosphere. In fact, soil can store more carbon than the atmosphere and terrestrial vegetation combined, making it a key component of the global carbon cycle. By storing atmospheric carbon as organic matter, soil can slow the progression of climate change. However, this capacity is threatened by deforestation, erosion, and unsustainable agricultural practices. Maintaining healthy soils is essential for enhancing climate resilience.

4. Plant Roots

Roots are the most prominent structures underground. They anchor plants in the soil and absorb water and nutrients from the soil. Depending on the plant species, roots can extend deep into the soil, forming a vast network that supports life above ground.

Soil: The Vital Link

Soil is not only physical support for plants but also a source of water and nutrients. Elements such as nitrogen, phosphorus, and potassium are essential for photosynthesis and growth. Plants feed soil microorganisms through their roots, and in return, the soil gains organic matter from the carbon fixed by the plants.

However, modern agricultural practices (monoculture, chemical fertilizers, etc.) disrupt this delicate balance, leading to soil degradation. Sustainable agriculture should ensure food security and environmental sustainability by focusing on soil health.

Human Impact and Soil

Human activities have a profound impact on soil health and significantly impact the soil's ability to perform its functions. Deforestation, agriculture, urbanization, and pollution have led to soil erosion and the loss of ecosystem services.

1. Soil Erosion

Soil erosion is a significant problem due to deforestation, overgrazing, and intensive agricultural practices. In areas devoid of vegetation, wind and water can easily remove the topsoil, which contains most of the soil's nutrients. Erosion leads to a loss of soil fertility and can lead to desertification in vulnerable areas.

2. Soil Compaction

Soil compaction occurs when soil particles compress each other, reducing pore space and restricting the movement of air and water. Heavy machinery used in agriculture and construction can cause soil compaction, which makes it difficult for plant roots to penetrate the soil and reduces the soil's water and nutrient retention capacity.

3. Pollution

Chemicals such as pesticides, heavy metals, and industrial wastes cause soil pollution, posing a significant threat to soil health. These pollutants can weaken soil organisms, reduce biodiversity, and contaminate the food chain. Persistent pollutants such as pesticides can also affect the soil's ability to support healthy plant growth.

The Future of Soil Management

Given the critical importance of soil, sustainable management practices are essential to maintain soil health and ensure that soil continues to provide ecosystem services. Sustainable agriculture, reforestation and soil conservation efforts are important strategies to maintain soil quality.

1. Sustainable Agriculture

Sustainable agricultural practices, methods such as crop rotation, reduced tillage and organic farming can help maintain soil fertility, prevent erosion and reduce the need for synthetic fertilizers and pesticides. These practices aim to sustain long-term productivity by focusing on working with the soil in harmony with natural processes.

2. Soil Conservation

Soil conservation includes practices that reduce erosion and protect soil from degradation. Farming on slopes, terracing and using protective vegetation can help prevent soil loss and increase water-holding capacity.

3. Tackling Climate Change

Soil management is also an important tool in the fight against climate change. By adopting practices that increase carbon storage, such as agro-forestry and no-till farming, we can increase soil's ability to store carbon and mitigate the effects of global warming.

7. Conclusion

Soil is more than just a passive environment for plant growth; it is a dynamic and living environment that supports the life of living things in ways we do not yet fully understand. The complex network of microorganisms, the physical properties of soil and the ecosystem services it provides are vital for sustaining life on Earth. As we face global challenges such as climate change, biodiversity loss and soil erosion, it is critical that we recognize the importance of soil and work on sustainable management practices to protect this precious resource. A quiet life, indeed, but one that supports and sustains the complex web of life on Earth.

REFERENCES

Bardgett, R.D., & van der Putten, W.H. (2014). *Belowground biodiversity and ecosystem functioning*. Nature, 515(7528), 505–511.

Jones, D.L., & Richards, D. (2019). *Soil microbiology: Soil biology and biochemistry*. Wiley-Blackwell.

Lal, R. (2004). *Soil carbon sequestration impacts on global climate change and food security*. Science, 304(5677), 1623–162

Pimentel, D., & Burgess, M. (2013). *Soil erosion threatens food security*. Environmental Development, 2, 47-55.

Rattan, L., & Ranjan, S. (2019). *Soil compaction and management for sustainable agricultural production*. Springer.

Smith, P., et al. (2016). *Global change and the role of soil in mitigating climate change*. Nature Sustainability, 1(5), 277-286.

Sposito, G. (2018). *The chemistry of soils*. Oxford University Press.

CHAPTER 16

THE IMPACT OF GLOBAL WARMING ON COTTON PRODUCTION: HEAT STRESS AND THE IMPORTANCE OF OSMOLYTES

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1. INTRODUCTION

Cotton (*Gossypium hirsutum*), a member of the Malvaceae family, is a critically important industrial crop. Under favorable conditions, cotton exhibits continuous growth by producing leaves, flowers, and bolls (Chalise et al., 2022). The plant has an upright, branched, and hairy stem, with lobed, heart-shaped leaves. Its taproots can reach depths of 30 to 100 cm, and the fruit—commonly referred to as the boll—is a 3- to 5-loculed capsule (Khalili, 2023).

Initially cultivated to meet clothing needs, cotton has since evolved into a globally significant economic crop (Çopur, 2018). Today, its fiber is used extensively in the textile industry; its linters are utilized in the paper, furniture, and cellulose sectors; the seed serves the oil industry; and its hulls and meal are important in the feed industry (Khalili, 2023). Furthermore, the increasing use of cottonseed oil in biodiesel production positions cotton as a potential alternative to petroleum in the long term (Khalili, 2023).

Although cotton can grow in various soil types, deep-profile alluvial soils are essential for high yield and quality fiber (Evcim & Değirmencioğlu, 2007). In Turkey, cotton cultivation dates back to 330 BC, but it flourished particularly during the Seljuk period in the 11th century and the Ottoman Empire in the 14th century (Yurtoğlu, 2020). Today, cotton farming remains a vital agricultural activity for Turkey, often referred to as “White Gold” due to its economic significance (Khalili, 2023).

As in many countries, cotton cultivation holds a prominent place within the agricultural sector in Turkey. In the 2022/2023 season, approximately 573,000 hectares were planted with cotton, yielding around 1.017 million tons of lint cotton (TÜİK, 2023). Production is concentrated in three major regions: Southeastern Anatolia, the Aegean, and Çukurova. About 55% of national production comes from Southeastern Anatolia, making it the leading region in cotton production (TÜİK, 2023).

Şanlıurfa province is the epicenter of cotton cultivation in Turkey. In the 2022/2023 season, 2,424,783 decares were planted in this province alone, producing 408,055 tons of lint cotton. These figures underscore Şanlıurfa’s dominant role in terms of both cultivation area and production volume (TÜİK, 2023).

2. Climatic Requirements of Cotton and the Impact of Temperature Fluctuations

Cotton yield, growth, and development are highly sensitive to environmental conditions. Temperature fluctuations significantly influence these processes, with yield variations reaching up to 70% (Farooq et al., 2015; Luo et al., 2014; Nasim et al., 2016; Rahman et al., 2017). When a short-term increase in temperature exceeds a plant's thermal tolerance, it results in heat stress (Gür et al., 2010). Heat stress is often accompanied by other abiotic stresses, such as drought (Rehman, 2006).

Heat stress reduces yield potential, and it is estimated that plants can only achieve about 25% of their genetic yield potential under combined environmental stress conditions (Boyer, 1982). Increased temperatures and altered precipitation patterns pose significant challenges to achieving consistent and high cotton yields (Gwimbi & Mundoga, 2010; Iqbal et al., 2016). The optimal temperature for cotton growth is around 33°C, while temperatures exceeding 36°C lead to significant reductions in boll retention (Luo, 2011; Nasim et al., 2016). Heat stress, therefore, represents a serious global threat to cotton productivity (Hall, 2001).

High temperatures affect cotton plants in various ways, inducing morphological, physiological, and biochemical changes that reduce performance and lint production. Heat stress impacts seed germination, seedling development, and root growth. Optimal temperatures for germination and early seedling development range between 28–30°C, and maximum root growth occurs at day/night temperatures of 30/22–35/27°C. However, at 40/32°C, root architecture is negatively altered, limiting root depth (Reddy et al., 1997a, b). While temperatures just above 30°C may enhance germination and early seedling growth, exceeding 40°C can have detrimental effects. Heat-tolerant genotypes may exhibit acquired thermo-tolerance between 37.7–40°C (Burke, 2001).

Although cotton has a well-defined growth pattern, this development is largely temperature-dependent (Iqbal et al., 2016). Elevated temperatures often accelerate plant growth and lead to earlier maturity, which can prevent the plant from fully expressing its genetic potential (Reddy & Zhao, 2005). Developmental processes accelerate with rising daytime temperatures (Reddy et al., 1996), although leaf expansion is more pronounced under low-light or dark conditions (Krieg & Sung, 1986). Rising temperatures during the growing season can shorten the crop cycle by up to 24 days, and a 5°C increase in global average temperature could reduce the time from germination to maturity by as much as 35 days (Reddy et al., 1997a, b). Leaves are particularly sensitive to temperature changes early in development; three weeks post-emergence, leaf expansion at 28–30°C can be 6–8 times greater than at 20–21°C (Reddy et al., 1992a, b, c; 1997a, b).

In contrast to roots, cotton shoots require higher temperatures for optimal growth (Pearson et al., 1970). Cooler temperatures slow down growth and development, leading to the accumulation of metabolites and excessive vegetative branching (Reddy et al., 1992a, b, c). As a result, higher daytime temperatures are not conducive to excessive vegetative growth. Temperatures above 30/22°C during early development support stem elongation and fruiting branch formation, with an associated increase in boll-setting nodes (Reddy et al., 1992a, b, c). Meanwhile, night temperatures play a critical role in controlling the onset of flowering. For example, a night temperature of 25°C delayed flowering and fruiting branch initiation in upland cotton (Mauney, 1966), and boll maturation was also delayed under lower night temperatures (Gipson & Joham, 1969).

Temperature fluctuations significantly impact cotton growth and potential yield (Nasim et al., 2011; Luo et al., 2014; Rahman et al., 2017). While the plant grows optimally at 33°C, fruit set drops markedly at temperatures exceeding 36°C (Luo, 2011; Singh et al., 2007). High temperatures disrupt carbohydrate production and assimilation, leading to increased boll shedding, malformed (parrot-beaked) bolls, reduced fiber quality, and overall yield losses (Hatfield et al., 2008; Oosterhuis, 2009).

Among various developmental stages, the reproductive phase—including floral development and fertilization—is the most sensitive to heat stress (Zinn et al., 2010). Adverse weather conditions can negatively affect ovule development, pollen viability, and anther dehiscence (Zinn et al., 2010; Young et al., 2004). Although viable pollen is essential for successful fertilization, it is highly susceptible to elevated temperatures (Kakani et al., 2005). Consequently, heat stress during anthesis may hinder fertilization, resulting in fewer seeds and boll formation (Kakani et al., 2005; Reddy et al., 1992a, b, c; Snider et al., 2009).

3. Effects of Temperature Variations on Fiber Quality

Since cotton fiber develops on the surface of seeds within the boll, the number of seeds per boll and the number of ovules per locule significantly influence both the quantity and quality of the resulting fiber (Stewart, 1986). Variations in seed number within a boll may indicate inadequate fertilization or post-fertilization embryo abortion, both of which are influenced by genetic factors as well as adverse environmental conditions (Stewart, 1986; Karmakar et al., 2016).

Rising temperatures accelerate plant growth and developmental processes (Ziska & Bunce, 1997); however, when temperatures exceed optimal thresholds, crop performance is adversely affected. Cotton is sensitive to heat stress at all growth stages, with the fruiting stage being the most vulnerable (Snider et al., 2009, 2010, 2011). For instance, a 1°C increase in temperature has been shown to hasten the appearance of squares, flowers, and mature bolls by 1.6, 3.1, and 6.9 days, respectively (Reddy et al., 1997a, b). Heat stress disrupts and shortens the fruit maturation period, ultimately limiting productivity and increasing fruit shedding, leading to smaller bolls and reduced yields (Reddy et al., 1999; Zhao et al., 2005).

Fruit retention is highly sensitive to elevated temperature stress, and the duration of such stress is a critical factor in determining the fruit load a plant can carry. The optimal temperature range for healthy cotton growth is 20–32°C (Mohamed & Abdel-Hamid, 2013). The ideal temperature conditions for maximum boll number and fiber yield are reported to be 30°C during the day and 22°C at night (Burke et al., 1988; Reddy et al., 1996). Reddy et al. (1992a, b, c) found that a temperature of 30/32°C was optimal for achieving the highest boll weight. When the average daily temperature reached 33°C, cotton plants retained only 50% of their bolls, while at 36°C, fruit retention ceased entirely. Young bolls are particularly sensitive to heat stress, often aborting when the daily mean temperature exceeds 32°C (Reddy et al., 1996). However, cotton can tolerate very high temperatures (43–45°C) for short periods, provided that adequate soil moisture is available. Among C3 plants, cotton exhibits relatively higher heat tolerance; nevertheless, supra-optimal temperatures promote square and boll abscission, resulting in sharp yield declines (Schlenker & Roberts, 2009). Both the intensity and duration of heat stress are critical determinants of fruit retention, and high night temperatures during the fruiting stage are especially detrimental compared to daytime heat. Research has shown that elevated night temperatures increase respiration rates, reduce soluble carbohydrate concentrations in leaves, and contribute to higher fruit drop, thus significantly reducing productivity (Loka & Oosterhuis, 2010).

Cotton is primarily cultivated for its fibers, which consist of more than 85% cellulose. Cellulose is a linear polysaccharide composed of glucose molecules linked by β-1,4-glycosidic bonds. The optimal temperature range for cellulose synthesis is reported to be 25–30°C; synthesis declines when temperatures fall below or rise above this range (Roberts et al., 1992). Sucrose, a carbohydrate produced via photosynthesis, is the primary substrate for cellulose biosynthesis (Tian et al., 2013); therefore, any fluctuations in sucrose levels directly impact cellulose production.

The photosynthetic capacity of cotton plants decreases when the average daily temperature exceeds 32°C (Crafts-Brandner & Salvucci, 2000), which in turn reduces sucrose availability. A stable photosynthetic rate under varying environmental conditions is essential for the production of high-quality fiber. Under favourable temperature conditions, a single cotton seed can produce approximately 12,000–15,000 fibers.

Adequate carbohydrate supply is critical for healthy fiber development. Adverse conditions such as high temperatures can impair carbohydrate assimilation, resulting in reductions in seed number, seed size, fiber count per seed, and fiber weight per seed, all of which contribute to yield losses (Arevalo et al., 2004; Oosterhuis, 1999). Temperature fluctuations have pronounced effects on cotton fiber properties, which can vary depending on specific environmental contexts. Fiber quality is determined by several parameters—such as fiber length, strength, and fineness (micronaire value)—that exhibit varying degrees of sensitivity to environmental conditions (Gou et al., 2007; Pettigrew, 2008). Elevated temperatures may lead to altered fiber characteristics, including higher micronaire values, increased fiber strength, and enhanced fiber maturity (Ton, 2011).

While improved fiber strength and maturity are desirable, higher micronaire values are economically unfavourable. Temperature fluctuations exert significant influence over fiber quality traits (Pettigrew, 2008), particularly affecting fiber strength during secondary cell wall thickening (Ruan, 2007). An average daily temperature of 26°C is considered optimal for fiber development (Rahman et al., 2007), whereas temperatures above 30°C or peak daytime temperatures exceeding 35°C inhibit the formation of high-quality fibers, depending on the duration of heat exposure (Pettigrew, 2001; Oosterhuis, 1999; Rahman et al., 2007). Similarly, night temperatures also influence fiber quality. Maximum fiber length occurs when night temperatures range between 15 and 21°C; lengths decline when night temperatures rise above 21°C or fall below 15°C (Pettigrew, 2008; Zhang et al., 2012). At both the upper and lower thermal limits, fiber output per boll, fiber index, and fiber percentage tend to decrease.

4. Osmolytes That Mitigate Temperature Stress in Cotton

4.1. Salicylic Acid

Plants are frequently exposed to various abiotic stress factors during their growth, development, and production phases, which prevent them from achieving optimal yield and quality. Salicylic acid (SA), a seven-carbon phenolic compound initially isolated from willow bark, is endogenously synthesized by plants and can also be applied exogenously. SA has emerged as a key plant defence hormone with critical roles in different aspects of plant immunity (Zhang & Li, 2019; Sharma et al., 2022a).

Salicylic acid enhances plant tolerance to stress conditions and is involved in mitigating a range of abiotic stress factors such as metal toxicity, drought, high salinity, cold, and heat. Once synthesized by the plant or applied externally, SA is transported through the phloem to various plant organs (Rocher et al., 2006; Culpan & Arslan, 2018). It plays a central role in the plant's tolerance to both biotic and abiotic stresses and functions as a key signalling molecule that regulates growth, development, and defence responses under stress conditions (Dong et al., 2015).

Moreover, SA plays a vital role in the functioning of guard cells, which are essential for stomatal closure, and in maintaining photosynthesis under stress (Sharma et al., 2022b). In plants subjected to abiotic stress, salicylic acid has been shown to enhance antioxidant activity and reduce the levels of reactive oxygen species (ROS), thereby alleviating oxidative damage. These properties highlight SA's importance in mitigating the adverse effects of both biotic and abiotic stresses on plants (El-Sherif, 2022).

4.2. Proline

To mitigate the adverse effects of environmental stress factors, various osmolytes are externally applied to plants; among them, the amino acid proline is particularly favoured due to its effectiveness across a wide range of plant species (Hare & Cress, 1997). Proline is an organic compound that accumulates in higher plants in response to environmental stresses and increases in concentration under such conditions (Kishore et al., 2005; Ashraf & Foolad, 2007; Verbruggen & Hermans, 2008; Ali & Ashraf, 2011). As an osmolyte, proline regulates intracellular osmotic pressure during stress, stabilizes subcellular structures such as membranes and proteins, scavenges free radicals, and contributes to the maintenance of intracellular redox homeostasis (Ashraf & Foolad, 2007; Ali & Ashraf, 2011; Moustakas et al., 2011).

4.3. Jasmonic Acid (JA)

Jasmonic acid is a phytohormone that plays a vital role in plant growth and development, and it has demonstrated strong potential in alleviating the detrimental effects of salinity stress. JA enhances plant tolerance to stress by modulating morphological, physiological, and biochemical responses (Rehman et al., 2023). Studies have shown that JA application can increase chlorophyll synthesis (Ali et al., 2022a, b), enhance antioxidant activity, promote osmolyte accumulation, and help maintain membrane stability under saline conditions (Zhu et al., 2022a, b).

4.4. Glycine Betaine (GB)

Glycine betaine is a crucial Osmo protectant actively utilized by plants, particularly in arid environments with limited water availability (Singh et al., 2015). Under drought conditions, GB helps maintain cellular water potential by compensating for loss of turgor pressure and contributes to osmotic balance (Mukarram et al., 2021). This represents a dynamic physiological response that tactically regulates water uptake. Drought leads to reduced transpiration rates, aiding in resource conservation (Ghadirnezhad Shiade et al., 2023). GB also provides long-term protection against drought-induced damage by stabilizing proteins and membranes (Upadhyaya & Panda, 2019). Plants engineered or selected for enhanced GB production exhibit competitive advantages in water-limited regions, enabling them to survive in broader ecological niches and contribute to ecosystem balance (Sá et al., 2019). In summary, the use of glycine betaine enhances plant resilience through key functions such as osmoregulation and water conservation while protecting cells from external environmental pressures (El Beltagi et al., 2022).

5. Conclusion

The increasing prevalence of heat stress due to global warming poses a significant threat to cotton production, both in terms of yield and fiber quality. Elevated temperatures negatively impact cotton plant development by reducing photosynthetic efficiency, increasing respiration rates, and disrupting critical physiological processes such as flowering and boll formation. These effects lead directly to yield losses and deterioration in fiber quality. To enhance the resilience of cotton plants against heat stress, a range of adaptive strategies have been developed. These include the adoption of appropriate agronomic practices, the development and use of heat-tolerant cultivars, the application of plant hormones (such as jasmonic acid and salicylic acid), and improved irrigation management. A multifaceted approach is essential to mitigate the adverse effects of rising temperatures on cotton production.

REFERENCES

Ali AYA, Ibrahim MEH, Zhou G, Zhu G, Elsiddig AMI, Suliman MSE, Elradi SBM, Salah EGI (2022a) Interactive impacts of soil salin ity and jasmonic acid and humic acid on growth parameters, forage yield and photosynthesis parameters of sorghum plants. South Afr J Bot 146:293–303. https:// doi. org/ 10. 1016/j. sajb. 2021.10.027

Ali AYA, Zhou G, Elsiddig AM, Zhu G, Meng T, Jiao X, Ahmed I, Salih EGI, Ibrahim MEH (2022b) Effects of jasmonic acid in foliar spray and an humic acid amendment to saline soils on for age sorghum plants' growth and antioxidant defense system. Peer J 10:e13793. https://doi.org/10.7717/peerj.13793

Ali, Q., & Ashraf, M. (2011). Exogenously applied glycinebetaine enhances seed and seed oil quality of maize (Zea mays L.) under water deficit conditions. Environmental and Experimental Botany, 71(2), 249–259. https://doi.org/10.1016/j.envexpbot.2010.12.009

Arevalo LM, Oosterhuis DM, CokerDL,Brown RS (2008). Physiological response of cotton to high night temperatures. Am J Plant Sci Biotechnol 2:63–68

Ashraf, M., & Foolad, M.R. (2007). Roles of glycine betaine and proline in improving plant abiotic stres resistance. Environmental and Experimental Botany, 60(3), 206–216. https://doi.org/10.1016/j.envexpbot.2005.12.006

Burke JJ (2001). Opportunities for improving cotton's tolerance to high temperature. In: Proceed ings of the Beltwide Cotton Conference. National Cotton Council, Memphis, TN, pp 1453–1454

Burke JJ, Mahan JR, Hatfield JL (1988). Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron J 80:553–556

Chalise, D. P., Snider, J. L., Hand, L. C., Roberts, P., Vellidis, G., Ermanis, A., ... & Lee, J. M. (2022). Cultivar, irrigation management, and mepiquat chloride strategy: Effects on cotton growth, maturity, yield, and fiber quality. *Field Crops Research*, *286*, 108633.

Crafts-Brandner SJ, Salvucci ME (2000) Rubisco activase constrains the photosynthetic potential of leaves at high temperature and CO2. Proc Natl Acad Sci U S A 97:13430–13435

Culpan, E., & Arslan, B. (2018). Salisilik asit uygulamasının aspir (Carthamus tinctorius L.) çeşitlerinin verim ve bazı kalite özelliklerine etkisinin araştırılması. Akademik Ziraat Dergisi, 7 (2), 173-178. https://doi.org/10.29278/azd.476336

Çopur, O. (2018). Güneydoğu Anadolu Projesinin Türkiye Pamuk Üretimine Etkisi: Son On Yıldaki Değişimler. Adyütayam Dergisi, 6(1) : 11-18.

Dong, Y.J., Wang, Z.L., Zhang, J.W., Liu, S., He, Z.L., & He, M.R. (2015). Interaction effects of nitric oxide and salicylic acid in alleviating salt stress of Gossypium hirsutum L. Journal of Soil Science and Plant Nutrition, 15 (3), 561-573. https://doi.org/10.4067/S0718-95162015005000024

El-Beltagi HS, Sulaiman, Mohamed MEM et al (2022) Effects of ascorbic acid and/or α-tocopherol on agronomic and physio-biochemical traits of oat (Avena sativa L.) under drought condition. Agronomy. https://doi.org/10.3390/agronomy12102296

El-Sherif, N.A. (2022). Salicylic acid and its crosstalk with other plant hormones under stressful environments. Managing Plant Stress Using Salicylic Acid: Physiological and Molecular Aspects, 304-317. https://doi.org/10.1002/9781119671107.ch16

Evcim, Ü., & Değirmencioğlu, A. (2007). Transition to Mechanical Picking "A Real Step Towards Competitiveness in Turkish Cotton Production*". *Tarım Makinaları Bilimi Dergisi*, *3*(4), 267-269.

Farooq J, Mahmood K, Akram MW, Rehman AU, Javaid MI, Petrescu-Mag IV, Nawaz B (2015) High temperature stress in cotton Gossypium hirsutum L. Extreme Life Biospeol Astrobiol 7:34–44

Ghadirnezhad Shiade SR, Fathi A, Taghavi Ghasemkheili F et al (2023) Plants' responses under drought stress conditions: effects of strategic management approaches—a review. J Plant Nutr 46:2198–2230. https://doi.org/10.1080/01904167.2022.2105720

Gipson JR, Ray LL (1969) Fiber elongation rates in five varieties of cotton (Gossypium hirsutum L.) as influenced by night temperature. Crop Sci 9:339–341

Gipson JR, Ray LL (1969) Fiber elongation rates in five varieties of cotton (Gossypium hirsutum L.) as influenced by night temperature. Crop Sci 9:339–341

Gou JY, Wang LJ, Chen SP, Hu WL, Chen XY (2007) Gene expression and metabolite profiles of cotton fiber during cell elongation and secondary cell wall synthesis. Cell Res 17:422–434

Gür A, Demirel U, Özden M, Kahraman A, Çopur O (2010) Diurnal gradual heat stress affects antioxidant enzymes, proline accumulation and some physiological components in cotton (Gossypium hirsutum L.). Afr J Biotechnol 9:1008–1015

Gwimbi P, Mundoga T (2010) Impact of climate change on cotton production under rainfed conditions: case of Gokwe. J Sustain Dev Afr 12:59–69

Hall AE (2001) Crop response to environment. CRC Press, Boca Raton, FL

Hare, P.D., & Cress, W.A. (1997). Metabolic implications of stress-induced proline accumulation in plants. Plant Growth Regulation, 21, 79–102. https://doi.org/10.1023/A:1005703923347

Hatfield JL, Boote KJ, Kimball BA, Wolf DW, Ort D, Izaurralde RC, Thomson AM, Morgan JA, Polley HW, Fay PA, Mader T, Hahn GL (2008) Agriculture. In: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC, USA, p 362

Iqbal MA, Ping Q, Abid M,Kazmi SMM,RizwanM(2016)Assessing riskperceptions and attitude among cotton farmers: a case of Punjab province, Pakistan. Int J Disaster Risk Reduct 16:68–74

Kakani VG, Reddy KR, Koti S, Wallace TP, Prasad PV, Reddy VR, Zhao D (2005) Differences in in vitro pollen germination and pollen tube growth of cotton cultivars in response to high temperature. Ann Bot 96:59–67

Karmakar R, DasI, Dutta D, Rakshit A (2016) Potential effects of climate change on soil properties: a review. Sci Int 4:51–73

Khalili, M. Y. 2023. Türkiye'de Pamuk Üretiminde Destekleme Politikalarının Üretime Olan Etkisi Ve Gelecek Öngörüsü. Harran Üniversitesi Fen Bilimleri Enstitüsü, Tarım Ekonomisi Anabilim Dalı, Yüksek Lisan Tezi, Şanlıurfa.

Kishore, K.P.B., Sangam, S., Amrutha, R.N., Laxmi, P.S., Naidu, K.R., Rao K.R.S.S., ... & Sreenivasulu, N. (2005). Regulation of proline biosynthesis, degradation, uptake and transport in higher plants: its implications in plant growth andabiotic stress tolerance. Current Science, 88(3), 424-438.

Krieg DR, Sung JFM (1986) Source-sink relations as affected by water stress. In: Mauney JR, Stewart JM (eds) Cotton physiology. The Cotton Foundation, Memphis, TN, pp 73–77

Loka DA, Oosterhuis DM (2010) Effect of high night temperatures on cotton respiration, ATP levels and carbohydrate content. Environ Exp Bot 68:258–263

Luo Q (2011) Temperature thresholds and crop production: a review. Clim Chang 109:583–598

Luo Q, Bange M, Clancy L (2014) Cotton crop phenology in a new temperature regime. Ecol Model 285:22–29

Luo Q, Bange M, Clancy L (2014) Cotton crop phenology in a new temperature regime. Ecol Model 285:22–29

Mauney JR (1966) Floral initiation of upland cotton Gossypium hirsutum L. in response to temperatures. J Exp Bot 17:452–459

Mohamed HI, Abdel-Hamid AME (2013) Molecular and biochemical studies for heat tolerance on four cotton genotypes. Rom Biotechnol Lett 18:8823–8831

Moustakas, M., Sperdouli, I., Kouna, T., Antonopoulou, C.I., & Therios, I. (2011). Exogenous proline induces soluble sugar accumulation and alleviates drought stress effects on photosystem II functioning of Arabidopsis thaliana leaves. Plant Growth Regulation, 65, 315–325. https://doi.org/10.1007/s10725-011-9604-z

Mukarram M, Choudhary S, Kurjak D et al (2021) Drought: sensing, signalling, effects and tolerance in higher plants. Physiol Plant 172:1291–1300. https://doi.org/10.1111/PPL.13423

Nasim W, Ahmad A, Wajid A, Akhtar J (2011) Nitrogen effects on growth and development of sunflower hybrids under agro-climatic conditions of Multan. Pak J Bot 43:2083–2092

Nasim W, Belhouchette H, Tariq M, Fahad S, Hammad HM, Mubeen M, Munis MF, Chaudhary HJ, Khan I, Mahmood F, Abbas T, Rasul F, Nadeem M, Bajwa AA, Ullah N, Alghabari F, Saud S, Mubarak H, Ahmad R (2016) Correlation studies on nitrogen for sunflower crop across the agroclimatic variability. Environ Sci Pollut Res 23:3658–3670

Oosterhuis DM (1999) Yield response to environmental extremes in cotton. In: Oosterhuis DM (ed) Proceeding of the 1999 cotton research meeting and summaries of cotton research in progress, vol 193. Arkansas Agricultural Experiment Station, Fayetteville, pp 30–38

Oosterhuis DM (2009) Summaries of Arkansas cotton research. Arkansas Agricultural Experiment Station, University of Arkansas Division of Agriculture, Fayetteville. 225 p

Pearson RW, Ratliff LT, Taylor HM (1970) Effect of soil temperature, strength, and PH on cotton seedling root elongation. Agron J 62:243–246

Pettigrew WT (2008) The effect of higher temperatures on cotton lint yield production and fiber quality. Crop Sci 48:278–285

Rahman HH (2005) Genetic analysis of stomatal conductance in upland cotton (Gossypium hirsutum L.) under contrasting temperature regimes. J Agric Sci 143:161–168

Rahman MH,AhmadA,WajidA,Hussain M, Rasul F, Ishaque W, Islam MA, Shelia V, Awais M, Ullah A, Wahid A, Sultana SR, Saud S, Khan S, Fahad S, Hussain M, Hussain S, Nasim W (2017) Application of CSM-CROPGRO-Cotton model for cultivars and optimum planting dates: evaluation in changing semi-arid climate. Field Crop Res 238:139–152

Rahman MH,AhmadA,WajidA,Hussain M, Rasul F, Ishaque W, Islam MA, Shelia V, Awais M, Ullah A, Wahid A, Sultana SR, Saud S, Khan S, Fahad S, Hussain M, Hussain S, Nasim W (2017) Application of CSM-CROPGRO-Cotton model for cultivars and optimum planting dates: evaluation in changing semi-arid climate. Field Crop Res 238:139–152.

Reddy KR, Davidonis GH, Johnson AS, Vinyard BT (1999) Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties. Agron J 91:851–858

Reddy KR, Hodges HF, Mckinion JM (1996) Food and agriculture in the 21st century: a cotton example. World Resour Rev 8:80–97

Reddy KR, Hodges HF, McKinion JM (1997a) A comparison of scenarios for the effect of global climate change on cotton growth and yield. Funct

Plant Biol 24:703–713 20 Heat Stress in Cotton: Responses and Adaptive Mechanisms 425

Reddy KR, Hodges HF, McKinion JM (1997b) Crop modelling and application: a cotton example. Academic, California

Reddy KR, Hodges HF, McKinion JM, Wall GW (1992a) Temperature effects on Pima cotton growth and development. Agron J 84:237–243

Reddy KR, Hodges HF, Reddy VR (1992b) Temperature effects on cotton fruit retention. Agron J 84:26–30

Reddy KR, Reddy VR, Hodges HF (1992c) Temperature effects on early season cotton growth and development. Agron J 84:229–237

Reddy KR,HodgesHF(1995)Cottoncropresponses to a changing environment. In: Rosenzweig C et al (eds) Climate change and agriculture: analysis of potential international impacts. American Society of Agronomy Special Publication no. 59. American Society of Agronomy, Madison, WI, pp 3–30

Rehman M, Saeed MS, Fan X, Salam A, Munir R, Yasin MU, Khan AR, Muhammad S, Ali B, Ali I, Khan J (2023) The multifaceted role of jasmonic acid in plant stress mitigation: An overview. Plants 12(23):3982. https://doi.org/10.3390/plants12233982

Rocher, F., Chollet, J.F., Jousse, C., & Bonnemain, J.L. (2006). Salicylic acid, an ambimobile molecule exhibiting a high ability to accumulate in https://doi.org/10.1104/pp.106.082537

Ruan YL (2007) Rapid cell expansion and cellulose synthesis regulated by plasmodesmata and sugar: insights from the single-celled cotton fibre. Funct Plant Biol 34(1):10

Sá C, Cardoso P, Figueira E (2019) Alginate as a feature of osmotolerance differentiation among soil bacteria isolated from wild legumes growing in Portugal. Sci Total Environ 681:312–319. https://doi.org/10.1016/j.scitotenv.2019.05.050

Sharma, A., Bhardwaj, R., Kumar, V., Zheng, B., & Tripathi, D. K. (Eds.). (2022a). Managing plant stress using salicylic acid: physiological and molecular aspects, John Wiley & Sons. Editor(s): Sharma, A., Bhardwaj, R., Kumar, V., Zheng, B., Tripathi, D.K. https://doi.org/10.1002/9781119671107

Sharma, N., Sharma, V., Sharma, V., & Bhardwaj, R. (2022b). Salicylic acid: A regulator of plant growth and development. Managing Plant Stress Using Salicylic Acid: Physiological and Molecular Aspects, 1-15. https://doi.org/10.1002/9781119671107.ch1

Singh RP, Vara Prasad PV, Sunita K, Giri SN, Reddy KR (2007) Influence of high temperature and breeding for heat tolerance in cotton: a review. Adv Agron 93:313–385

Singh M, Kumar J, Singh S et al (2015) Roles of osmoprotectants in improving salinity and drought tolerance in plants: a review. Rev Environ Sci Biotechnol 14:407–426. https://doi.org/10.1007/s11157-015-9372-8

Snider JL, Oosterhuis DM, Kawakami EM (2010) Genotypic differences in thermotolerance are dependent upon prestress capacity for antioxidant protection of the photosynthetic apparatus in Gossypium hirsutum. Physiol Plant 138:268–277

Snider JL, Oosterhuis DM, Kawakami EM(2011) Diurnal pollen tube growth rate is slowed by high temperature in field-grown Gossypium hirsutum pistils. J Plant Physiol 168:441–448

Snider JL, Oosterhuis DM, Skulman BW, Kawakami EM (2009) Heat stress-induced limitations to reproductive success in Gossypium hirsutum. Physiol Plant 137:125–138

Stewart JM (1986) Integrated events in the flower and fruit. In: Mauney JR, Stewart JMD (eds) Cotton physiology. The Cotton Foundation, Memphis, TN, pp 261–300

Tian J, Hu Y, Gan X, Zhang Y, Hu X, Gou L, Lou H, Zhang W (2013) Effects of increased night temperature on cellulose synthesis and the activity of sucrose metabolism enzymes in cotton f iber. J Integ Agri 12:979–988

Ton P (2011) Cotton and climate change: impacts and options to mitigate and adapt. ITC, 2011. Technical paper, Doc. No. MAR-11-200.E Technical Report, Geneva, xii, 32 p

TÜİK, 2023. Türkiye İstatistik Kurumu, Çeşitli istatistikler. https://www.tuik.gov.tr/ (Erişim tarihi: 01.01.2023

Upadhyaya H, Panda SK (2019) Drought stress responses and its management in rice. In: Adv rice res abiotic stress toler, pp 177–200 https://doi.org/10.1016/B978-0-12-814332 2.00009-5

Verbruggen, N., & Hermans, C. (2008). Proline accumulation in plants: a review. Amino acids, 35, 753–759.

Young LW, Wilen RW, Bonham-Smith PC (2004) High temperature stress of Brassica napus during flowering reduces micro- and megagametophyte fertility, induces fruit abortion, and disrupts seed production. J Exp Bot 55:485–495

Yurtoğlu, N. (2020). Atatürk Dönemi'nde Türkiye'de Pamuk Yetiştiriciliği Ve Pamuk Politikası (1923-1938). Tarih Araştırmaları Dergisi, 39(68), 504-543.

Zhang K, Zhang J, Ma J, Tang S, Liu D, Teng Z, Liu D, Zhang Z (2012) Genetic mapping and quantitative trait locus analysis of fiber quality traits using a three-parent composite population in upland cotton (Gossypium hirsutum L.). Mol Breed 29:335–348

Zhang, Y., & Li, X. (2019). Salicylic acid: biosynthesis, perception, and contributions to plant immunity. Current Opinion in Plant Biology, 50, 29-36. https://doi.org/10.2174/1570164128052 19152

Zhao D, Reddy KR, Kakani VG, Koti S, Gao W (2005) Physiological causes of cotton fruit abscission under conditions of high temperature and enhanced ultraviolet-B radiation. Physiol Plant 124:189–199

Zhu M, Liu Y, Cai P, Duan X, Sang S, Qiu Z (2022a) Jasmonic acid pre-treatment improves salt tolerance of wheat by regulating hormones biosynthesis and antioxidant capacity. Front Plant Sci 13:968477. https://doi.org/10.3389/fpls.2022.968477

Zhu M, Liu Y, Cai P, Duan X, Sang S, Qiu Z (2022b) Jasmonic acid pre treatment improves salt tolerance of wheat by regulating hormones biosynthesis and antioxidant capacity. Front in Plant Sci 13:968477. https://doi.org/10.3389/fpls.2022.968477

Zinn KE, Tunc-Ozdemir M, Harper JF (2010) Temperature stress and plant sexual reproduction: uncovering the weakest links. J Exp Bot 61:1959–1968

Ziska LH, Bunce JA (1997) Influence of increasing carbon dioxide concentration on the photosyn thetic and growth stimulation of selected C4 crops and weeds. Photosynth Res 54:199–208

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