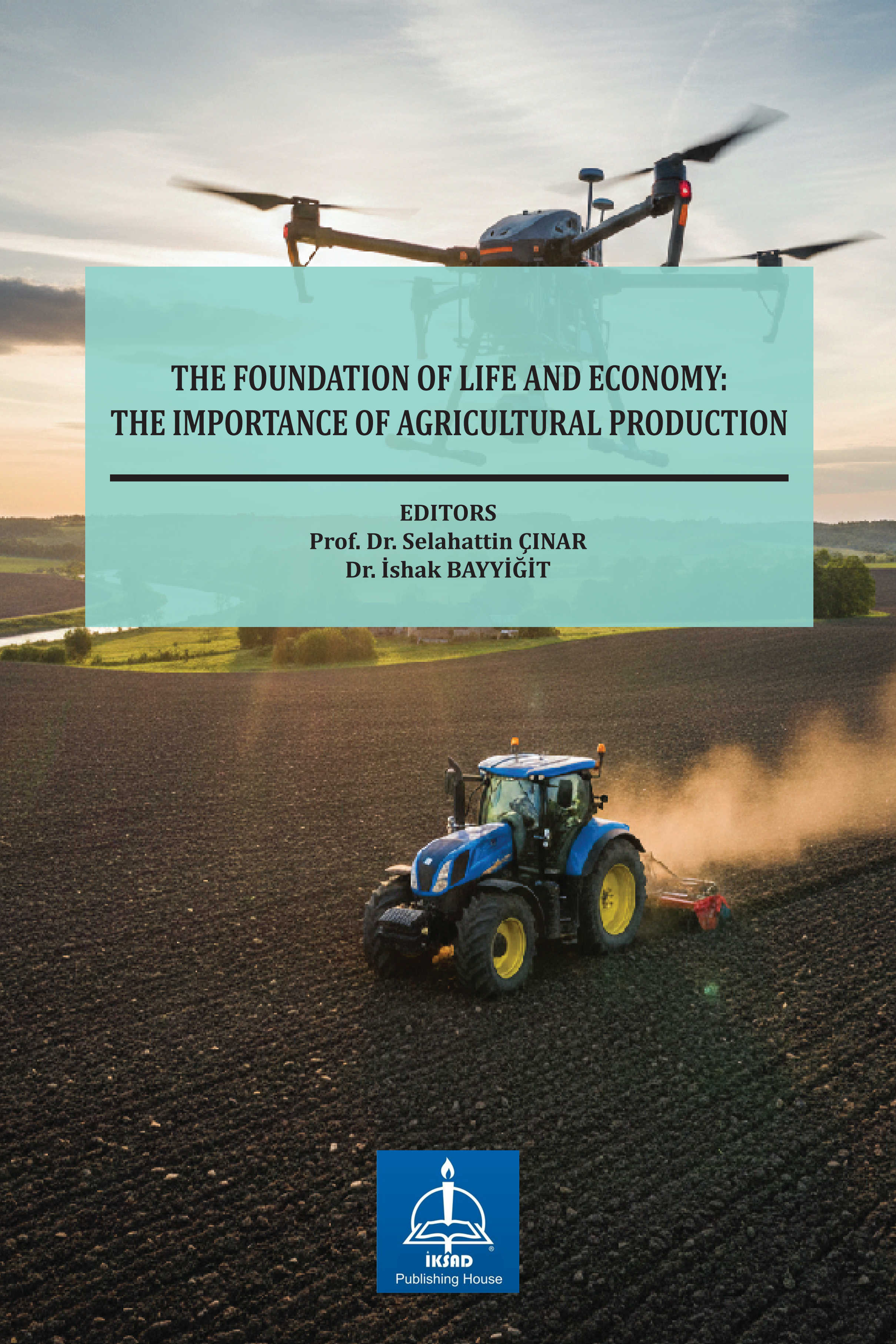

THE FOUNDATION OF LIFE AND ECONOMY: THE IMPORTANCE OF AGRICULTURAL PRODUCTION

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Institution of Economic Development and Social Researches Publications®
(The Licence Number of Publicator: 2014/31220)
TÜRKİYE TR: +90 342 606 06 75
USA: +1 631 685 0 853
E mail: iksadyayinevi@gmail.com
www.iksadyayinevi.com

ISBN: 978-625-378-527-7
Cover Design: İbrahim KAYA
December / 2025
Ankara / Türkiye
Size: 16x24cm

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PREFACE

Agriculture, the greatest revolution in human history, has been the main carrier of civilization since the transition to settled life. Today, no matter how much technology advances, agricultural production remains indispensable for maintaining our basic life functions and preserving global prosperity. The importance of agriculture can be examined under three main headings: food security, economic development, and environmental sustainability.

The primary duty of agricultural production is to feed the rapidly growing world population. Food security means more than just a nation feeding itself; it also means protecting its political and economic independence. Societies that cannot produce their own food become dependent on the outside world and are directly affected by global crises. Therefore, agriculture is a matter of national security beyond being just a sector.

Agriculture is the largest supplier of raw materials for the industrial and service sectors. Many fields, from textiles to pharmaceuticals and from cosmetics to energy, depend directly on agricultural outputs. Especially in developing countries, agriculture remains the most important source of livelihood and employment for a large part of the population. Supporting rural development not only prevents overcrowding in cities but also brings about balanced economic growth.

The biggest threat to agricultural production in the future is climate change. Decreasing water resources and degrading soil fertility are forcing us to move from "traditional methods" to "smart farming" applications.

- Precision Farming: Preventing the waste of water and fertilizers by using satellite data and sensors.
- Sustainability: Organic and regenerative farming practices carried out without disturbing the biological structure of the soil.
- Technology Integration: Achieving higher yields in smaller areas thanks to drones, artificial intelligence, and automation.

In conclusion, agricultural production is not just a "farming activity"; it is a multi-dimensional structure where ecology, economy, and technology intersect. Protecting the soil and supporting agricultural production with modern methods is the most valuable legacy we can leave to future generations. Ensuring sustainability in agriculture is not just a preference, but a necessity for the continued existence of humanity.

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CHAPTER 1

THE INFLUENCE OF CLIMATE CHANGE ON SOIL PHYSICAL PROPERTIES

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DOI: https://www.doi.org/10.5281/zenodo.18093168

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Introduction

Rising air temperatures; elevated atmospheric carbon dioxide, sudden and significant changes in daily, seasonal, and interannual temperatures, changes in wet and dry cycles, heavy precipitation events, extended drought periods, extreme frost; and hot and dry periods that increase fire danger levels are defined as climate change (Patterson, Lutz, & Doyle, 2013). Climate change alters soil physical, chemical, and biological processes, with cascading environmental consequences. Climate change lead profound effects on soil physical properties, causing through alterations in temperature, precipitation, and vegetation dynamics (Shoumik et al. 2025a; Shoumik et al., 2025b). The implications are far-reaching, impacting soil structure, moisture retention, and nutrient availability, which collectively influence soil health and agricultural productivity (Figure.1). The sustainability of agriculturally productive arid and semiarid areas depends on timely knowledge of the geographical effects of changes in climate patterns on soil properties that affect crop yields, because of the projected susceptibility of arid regions to prolonged and recurring droughts (Corwin & Yemoto, 2017). Climate change creates significant threats to soil physical properties, influencing water retention, erosion resistance, and overall soil health. It is known that soil moisture and temperature jointly regulate soil organic carbon storage and transformation, soil respiration, microbial communities and nutrient cycling. Soil texture is important in determining the depth and thickness of the critical zone, which has serious effects on soil moisture retention in changing climatic conditions Groh et al. (2016). Rabbi et al., (2015) reported that regional aridity linked to climate change directly affects carbon input into soils, influencing microbial processes and nutrient cycling critical components of soil health. Similarly, it has been reported that decreased rainfall can lead to lower aggregate stability, which in turn can increase susceptibility to erosion. This is a critical issue for land management strategies aimed at combating the negative impacts of climate change on soil (Ziadat & Taimeh, 2013). Additionally, the impact of climate change on soils can significantly alter moisture dynamics and salinity gradients, particularly in arid and semi-arid regions. Soil physical changes in such areas can lead to ecological shifts, emphasizing the vulnerability of wetland systems influenced by soil chemical and physical alterations (Wang et al., 2021).

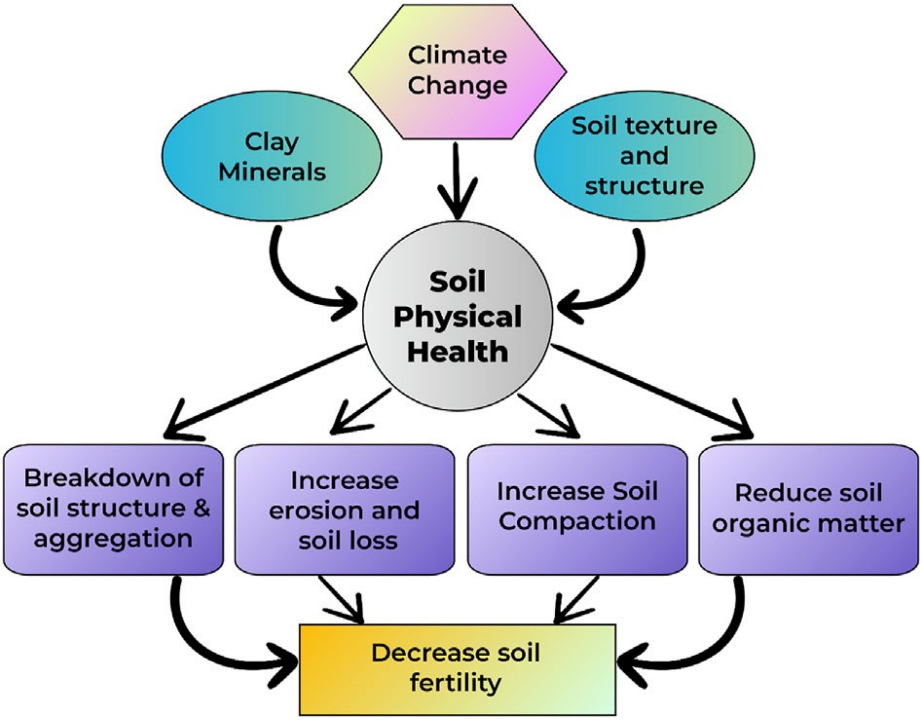

Figure 1. Effects of climate change on soil physical health and productivity (Oishy et al., 2025).

Brevik (2013) reported that soil organic matter plays a critical role in maintaining physical properties essential for sustainable agriculture, leading that climate-induced changes could lead to declines in soil organic matter, impairing decreasing soil productivity. Furthermore, soil nitrogen mineralization, a process critical for soil fertility, is influenced not solely by climatic changes but also by microbial biomass, which interacts with physical soil properties. This relationship is important as it redefines traditional understandings of nutrient cycling in regard of climate impact (Li et al., 2019). The objective of this paper is to explore the intricate relationship between climate change and soil physical properties. This review integrates current research findings to elucidate how climate-induced alterations impact soil characteristics, influencing ecological balance and agricultural productivity. Soil physical properties and processes affect soil health by altering water movement, root penetration, and water retention. Climate change directly and indirectly affects soil properties. Some of the direct effects include surface runoff, water filtration, and impaired raindrop function, particularly during heavy rains and storms, whose intensity and frequency are characteristic of climate change. Climate change has an indirect impact on the entire biosphere, which in turn affects soil properties and development. Important soil physical properties that affect soil health under the influence of climate change as follow.

Soil Texture and Structure

Changes in soil texture occur very slowly on geological timescales, making it less susceptible to change over time and therefore less relevant for climate change studies. However, it remains an important determinant of soil sensitivity to climate change. Agricultural and ecological management strategies should consider soil texture to predict drought vulnerability and tailor irrigation and conservation practices under climate change. Texture-aware approaches improve soil moisture availability estimates; provide information for drought mitigation, and guide land management decisions in grasslands, croplands, and forests facing changing precipitation and warming (Kumari et al., 2024). Shrinkage and cracking of clay soil due to increased drying and wetting cycles have made this soil type vulnerable to climate change. This leads to significant cracking in the soil. The direct and rapid movement of water flow through the soil surface via bypass flow is a result of deep cracks, which can weaken the soil's filtering mechanism and increase the risk of nutrient loss and water pollution. These processes are common in clay soils, material and water loss are amplified when frequent droughts follow heavy rainfall events (Tripathi et al., 2021).

A good soil structure is defined as an arrangement of soil fractions into stable larger units, and of the pore spaces between those units, that allows movement of water and air through the soil, ease of penetration by roots and decreases the soil erodibility (Gülser 2006). Soil aggregate is directly affected by raindrops to some extent. Soil structural parameters such as aggregate stability, mean weight diameter, mass and fragmentation fractal dimensions generally are influenced by the amount of soil organic carbon content (Gülser, 2006; Candemir and Gülser 2010; Parent et al., 2012; Gülser et al. 2015). Increased temperature and reduced water availability result in a decrease in soil aggregate stability and size, and a decrease in soil organic and biomass content. A decline in soil organic matter levels lead to a decrease in soil aggregate stability, infiltration rates and increase in susceptibility to compaction, run-off furthermore susceptibility to erosion (Gülser and Candemir, 2015; Bot and Benites, 2005; Karmakar et al., 2016). The change in soil form, structure and spatial distribution of soil aggregate stability due to climatic change is a very complex process. Soil structures are directly impacted with the increase in temperature and changes in the temporal distribution and volume of precipitation through processes of dispersion, slaking, compaction, and mechanical disruption (Tripathi et al., 2021). As reported by Kumari et al. (2024), varying climate scenarios (humid, sub-humid, semi-arid, and arid) are generating shifts in soil texture, thereby influencing the physical stability of soils. Increased frequency of heavy rainfall can lead to soil compaction, which adversely affects soil aeration and root growth. Extreme weather events exacerbate the inherent properties of low productivity soils, underscoring the importance of organic matter in stabilizing soil structure. The interplay between climatic conditions and soil physical properties is crucial, determining water holding capacity and erosion resistance, which are critical under changing climate regimes (Madena et al., 2012; , Gelybó et al., 2018)

Bulk Density and Porosity

It is known that **bulk density,** which is closely related to soil texture properties and organic matter quality, depends on climate (Tripathi et al., 2021). Amount of soil organic carbon stock depends on climate change as well as different land uses and managements (Gülser et al. 2021; Shoumik et al. 2025a; Shoumik et al., 2025b). The positive effects of soil organic matter on soil structural properties such as bulk density, porosity and compaction are known (Gülser and Candemir 2015; Gülser et al., 2017). Gülser and Candemir (2012) reported that increasing soil organic matter content by incorporating of different organic wastes into soil decreases soil bulk density and compaction with increasing soil total porosity.

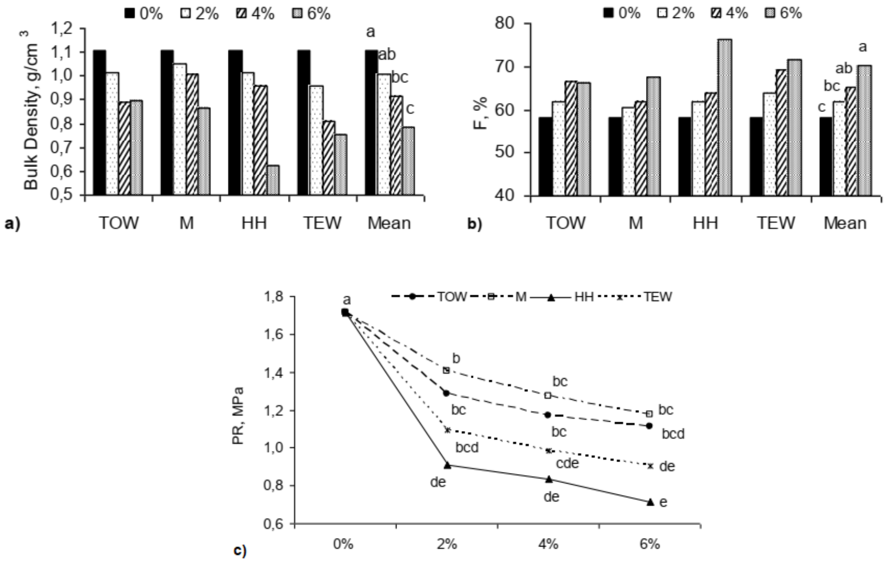

Figure 2. Effects of organic waste treatments (TOW:tobacco waste, M:manure, HH: hazelnut husk, TEW:tea waste) on a) bulk density, b) total prosity (F) and c) penetration resistance (PR) (Gülser and Candemir 2012).

The loss of organic carbon from increased decomposition due to elevateted temperature (Davidson and Janssens, 2006) can lead to increased bulk density and hence soil compaction, making it more susceptible to land management activities and climate change stresses from variable and high intensity rainfall and drought events (Birkas et al., 2009). There is increase in bulk density with the soil erosion or decomposition rate which results in the loss of organic matter present in the soil and leads to the soil compaction with all of the implications like root growth inhibition due to formation of compact layer and decrease in soil porosity (Tripathi et al., 2021). Hirmas et al. (2018) reported that soil macroporosity can change rapidly in response to climate change, and associated changes in soil hydraulic properties at the continental scale can create unexplored feedbacks between climate and the land surface, thus intensifying the water cycle.

Moisture Dynamics under Climate Change

Soil moisture content is greatly affected by changing precipitation patterns and increasing temperatures brought about by climate change. Changes in moisture availability due to erratic precipitation and drought cycles can disrupt microbial communities and the biogeochemical cycling of vital nutrients, further affecting soil structure, function, fertility, and ultimately crop productivity (Furtak and Wolińska, 2023). Soil water supply and water conservation, which have a strong impact on the functioning of soil ecosystems, depend on the inflation rate against the possible effects of climate change. Infiltration can be one of the most critical soil determinants, helping to improve soil water storage and minimize the risk of soil erosion, flash floods, and drought. Therefore, the soil hydrothermal regime (water mode, heat mode) is a key determinant of the soil moisture system and a key soil climate determinant (Várallyay, 2010). The changes in climatic conditions can lead to altered soil moisture dynamics, significantly affecting agricultural viability in various regions. Research demonstrates varying sensitivities of soil moisture across different textural classes, emphasizing the need for nuanced understanding in water resource management. The rise in global temperatures and changing precipitation patterns critically influence soil thermal regimes, vital for nutrient cycling and microbial activity. This effect is particularly pronounced in arid and semi-arid landscapes, where soil water retention becomes increasingly crucial (Gelybó et al., 2018). In a study about determination of soil moisture constants with pedotransfer functions, Gülser, 2004a) indicated that field capacity and permanent wilting point values had statistically significant relations with soil organic matter content. Shoumik et al. (2025b) reported that mean annual temperature increased and precipitation decreased between 2009 and 2018 in the central Europe. They found that there was no relationship between precipitation and soil organic C stock in woodland, but soil organic C stocks in woodland and shrubland areas significantly decreased with rising temperature (Figure 3). They concluded that climate warming can significantly affect soil organic C stock. Climate change also significantly affects soil moisture dynamics, with soil texture and vegetation cover playing pivotal roles. Soil texture governs soil-specific hydraulic properties (pore size distribution, porosity, and saturated hydraulic conductivity), which determine how precipitation is partitioned between evaporation, infiltration, and drainage. This relationship has been demonstrated in studies focusing on the climate-soil-vegetation relationship. In these studies, soil texture has been identified as a critical determinant of water stress and vegetation productivity under changing climate conditions (Fernandez-Illescas et al., 2001). Furthermore, regional drought assessments that consider soil moisture as an important mediator between climate forcing and water balance stress highlight texture as a determinant of moisture retention and release properties under changing precipitation patterns (Wu et al., 2022). Soil texture can lead to different responses in shallow and deep soil moisture pools under warming and changing precipitation. Therefore it was emphasized that multilayer moisture dynamics in soil horizons should be considered when examining the effects of climate change on soil moisture Dierauer and Zhu (2020). Bell et al. (2010) reported that variations in precipitation and temperature reshape soil water dynamics and soil moisture frequency distributions in tallgrass prairie, illustrating how climate-driven changes in rainfall and temperature translate into altered soil moisture regimes relevant for probabilistic modeling and ecosystem responses. The rising temperatures often interact with evapotranspiration to reduce soil moisture, thereby affecting soil respiration and carbon turnover indirectly, as discussed in broader climate-soil frameworks (Falloon et al., 2011).

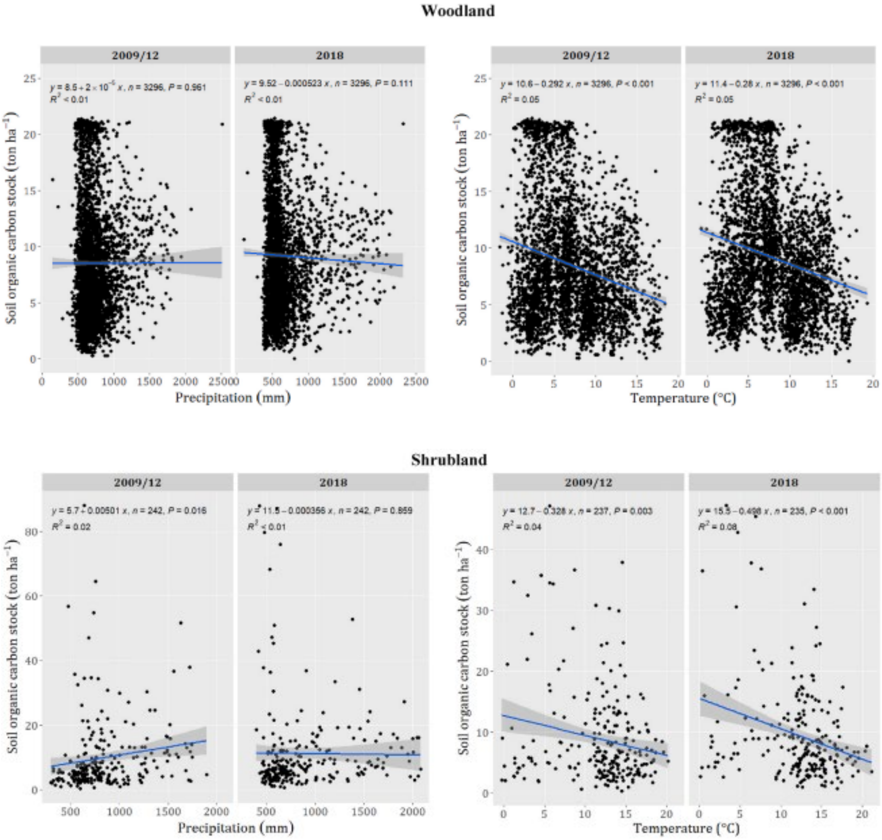

Figure 3. Relationship between soil organic C stock with precipitation and temperature changes in 2009/12 and 2018 in woodland shrubland areas in Europe (Shoumik et al., 2025b).

Alteration of Soil Thermal Properties

One of the key factors affecting soil thermal properties is its moisture content, which is closely linked to climate variability. The studies have shown that soil thermal conductivity varies with moisture content, affecting its ability to conduct heat (Ekberli et al., 2021). In general, soil heat capacity depends on the mineralogical and organic composition, bulk density and moisture content of the soil (Ekberli et al., 2005). The changes in vegetation composition associated with climate change also contribute to altering soil thermal behavior. Gong et al. (2018) reported how changes in vegetation caused by climate warming affect microbial activity and decomposition rates, altering the energy and thermal balance in the soil. Another important factor influencing soil thermal dynamics is the state of soil organic carbon (SOC) and its decomposition under increasing temperatures. Studies have shown that warmer conditions can accelerate SOC decomposition, potentially leading to higher rates of CO_2 and methane emissions from permafrost regions, where large stores of carbon are present (Standen & Baltzer, 2021, Briones et al., 2024). It has been reported that increasing temperatures may activate microbial processes and further affect soil structure and thermal properties (Schipper et al., 2014). Permafrost degradation, influenced by climate warming, alters the moisture regime in the soil, which in turn affects the thermal properties and dynamics of the soil (Pradhan et al., 2024). Qin et al., (2017) demonstrated that the Qinghai-Tibetan Plateau experiences significant changes in thermal states and active layer dynamics due to pronounced global warming effects, indicating that permafrost on the Qinghai-Tibetan Plateau has a higher soil temperature and greater susceptibility to degradation compared to other regions.

Strategies to Mitigate the Adverse Effects of Climate Change on Soil Physical Properties

Expected changes in soil physical properties have direct implications for food production and sustainability. Brevik (2013) reported that soil fertility may decrease due to changes in physical, chemical, and biological properties resulting from climate change. Since combat the negative impacts of climate change on soil structure and fertility, adaptive management strategies are essential. Potential strategies include increasing soil organic matter and implementing sustainable agricultural practices (Figure 4). These may include practices that enhance soil health and resilience, such as maintaining soil cover, reducing tillage, and implementing integrated nutrient management. (Anteneh & Assen, 2019, Nurmalasari et al., 2022).

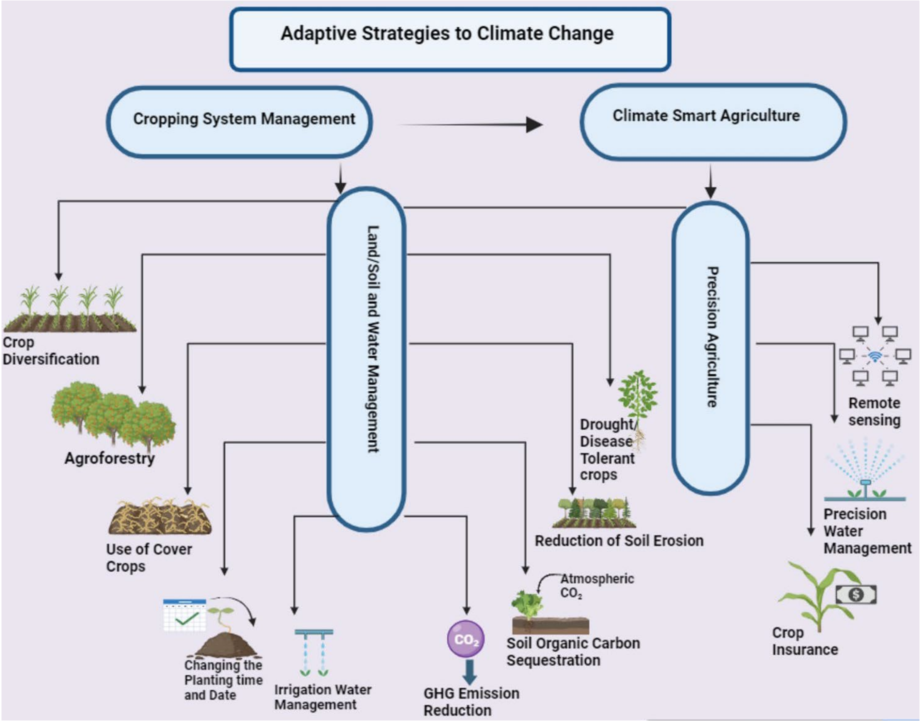

Figure 4. Mitigate strategies to climate change (Saleem et al., 2025).

The conservation tillage practices have been shown to increase water retention and alter thermal conductivity, playing a critical role in the dynamics of soil warming and cooling under changing climatic conditions (Dec et al., 2009). Particularly in regions vulnerable to climate extremes, strategies focused on increasing organic matter content through green manuring or cover crop cultivation can create more resilient soil systems that can with stand climate variability (Zahoor, 2016, Pandey and Srivastava, 2021). Moreover, the use of soil amendments such as biochar can affect thermal properties by improving soil structure and moisture retention capacity, which can positively affect thermal conductivity under certain humidity conditions (Dobrokhotov and Kozyreva, 2023). Strategic application of both organic and inorganic fertilizers plays a key role in improving soil structure and fertility under climate stress. Research shows that combining farmyard manure with chemical fertilizers improves soil organic content and physical properties such as porosity and permeability (Guo and Wang, 2013; Mahmood et al., 2017, Thakur et al., 2022;). The synergistic effects of these nutrient sources can help increase soil fertility while also insulating soils against climate-related challenges. Monitoring soil parameters such as soil density, porosity, soil organic matter and nutrient status is critical for effectively managing soil health and quality (Gülser, 2004b, Candemir and Gülser, 2010; Doğan and Gülser, 2019, 2020) especially under climate stress (Fu et al., 2004, Utami, 2019 Demenois et al., 2020). Continuous assessment allows for timely adjustments to management practices to suit changing soil conditions, thereby promoting sustainable agricultural practices in a changing climate.

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CHAPTER 2

ECOLOGY OF LEECHES AND THEIR RESPONSE TO TRADITIONAL AND EMERGING CONTAMINANTS

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DOI: https://www.doi.org/10.5281/zenodo.18093190

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1. INTRODUCTION

Leeches are significant components of freshwater ecosystems, functioning either as abundant predators of invertebrates or ecto-parasites feeding on vertebrates (Sawyer, 1974; Tessler and Fahmy, 2025). Their subclass Hirudinea is characterized by defining features such as anterior and posterior suckers, a segmented body with external annular divisions, and the absence of chaetae (Sawyer, 1986; Kuo and Lai, 2019). Recent advancements in molecular systematics have refined the understanding of medicinal leeches (genus *Hirudo*), clarifying that the group previously considered a single species is, in fact, a complex of several distinct taxa (Siddall et al., 2007; Kutschera and Elliott, 2014).

Currently, five species are recognized in the Western Palaearctic: *Hirudo medicinalis*, *Hirudo verbana*, *Hirudo orientalis*, *Hirudo sulukii* and *Hirudo troctina* (Utevsky and Trontelj, 2005; Utevsky et al., 2010; Saglam et al., 2016). This reclassification is crucial, as the Mediterranean medicinal leech, *H. verbana*, is now recognized as the most widely traded species globally for medical applications (Siddall et al., 2007; Popa et al., 2024). Due to their wide distribution, sensitivity to environmental changes, and tendency to bioaccumulate a wide array of contaminants, ranging from heavy metals to microplastics, leeches are recognized as important bioindicator organisms for monitoring the ecological health of aquatic systems (Petrauskienė, 2004; Macova et al., 2009; Kazancı et al., 2015).

The present study reviews the ecological characteristics of leech species and evaluates their physiological and molecular responses to both traditional and emerging anthropogenic stressors. This study aims to contribute to a deeper understanding of the ecological roles, distribution patterns, and environmental sensitivities of leech species. It also enhances their reliability as bioindicators, thereby improving the accuracy of freshwater ecosystem assessments and supporting effective conservation and management strategies.

2. TAXONOMIC BACKGROUND AND GENERAL MORPHOLOGY

Leeches belong to the phylum Annelida, sharing common ancestry with oligochaetes, which is supported by phylogenetic analyses (Tessler et al., 2018;

Bolotov et al., 2025). The order Hirudinida is traditionally categorized based on feeding morphology: Rhynchobdellida use proboscis to penetrate hosts, whereas Arhynchobdellida, which includes the Hirudinidae family, typically possess toothed jaws (Sawyer, 1986; Graf et al., 2006). Within the medically significant genus *Hirudo*, species are differentiated by subtle pigment patterns on their dorsal and ventral sides (Kutschera and Elliott, 2014; Arias et al., 2021). For instance, *H. medicinalis* and *H. verbana* possess species-specific pigment patterns. The external morphology of an adult *H. medicinalis* includes five pairs of eyes arranged in a crescent shape on the head, five annuli per complete midbody segment, and a small anterior sucker equipped with muscular ridges and cuticular teeth in the buccal cavity (Kutschera and Elliott, 2014).

3. HABITAT ECOLOGY AND ENVIRONMENTAL DETERMINANTS

Leech distribution patterns are primarily driven by the fundamental difference between lotic (flowing) and lentic (stagnant) aquatic habitats, as well as by the availability of prey (Mann, 1955; Sawyer, 1974; Kubová et al., 2013).

3.1. Key environmental predictors

Several factors interact to determine leech assemblage patterns.

- Prey availability: The density of benthos, representing food availability, is considered the best predictor of leech species composition in both lotic and lentic systems (Sawyer, 1974; Kubová et al., 2013; Kubová and Schenková, 2014). For instance, the prevalence of *Erpobdella octoculata* in soft waters is linked to its diet of chironomid and trichopteran larvae (Mann, 1955).

- Temperature and flow: Leeches are generally described as thermophilic organisms (Kubová et al., 2013). Water temperature is a critical factor influencing distribution (Mann, 1955; Sawyer, 1974). For instance, the optimal temperature range for the growth of *H. verbana* is between 18.7 °C and 19.7 °C (Ceylan et al., 2025). In fast-flowing (lotic) habitats, species like *E. octoculata* typically seek shelter under stones to avoid being washed away (Mann, 1955).

- Substrate and vegetation: In lentic environments, species composition is significantly influenced by morphological characteristics like substrate type and the presence of macrophytes, which can compensate for the lack of a coarse substrate (Sawyer, 1986; Kubová et al., 2013; Kubová and Schenková, 2014). Conversely, macrophyte cover is an important predictor in both lotic and lentic sites, affecting thermal conditions and possibly providing cold-water refuges (Kubová et al., 2013; Drinkwater et al., 2020).

- Water chemistry: Water conductivity, total nitrogen, and orthophosphate phosphorus are significant predictors of leech composition, reflecting the chemistry and trophic status of the water (Kubová et al., 2013; Kazancı et al., 2015).

3.2. Salinity and specialized habitats

Most freshwater leech species are adapted to live in oligohaline waters. However, members of the Piscicolidae family are the only group known to penetrate mesohaline waters, suggesting a specialized tolerance related to their marine-derived ancestry (Jueg and Zettler, 2015).

A specialized habitat type is the waterfowl nest, which is used by species such as *H. verbana* and *Haemopis sanguisuga* both as habitat and, crucially, for cocoon deposition. Leeches are found more frequently in nests during the bird's reproductive period (April-June) (Ceylan et al., 2021a). The preference for moist, terrestrial-like substrates, such as peat, over fully aquatic environments is essential for viability, as water immersion can compromise embryo survival (Kutschera and Roth, 2006; Ceylan et al., 2021a).

4. FEEDING AND REPRODUCTIVE STRATEGIES

4.1. Diverse feeding modes

Leeches exhibit highly specialized feeding behaviors, ranging from predation to specific sanguivory (Sawyer, 1974).

- Predatory leeches: Species like *H. sanguisuga* are macrophagous predators that typically swallow small, soft-bodied invertebrates, such as oligochaetes, snails, and insect larvae (Šyvokienė et al., 2008). *E. octoculata* primarily feeds on chironomid, simuliid, and trichopteran larvae (Mann, 1955).

- Sanguivorous leeches: In this groups, juvenile leeches initially feed predominantly on amphibians (frogs, toads, newts) because they are often too small to pierce mammalian skin (Kutschera and Elliott, 2014; Merilä and Sterner, 2002). Adults opportunistically feed on mammals, birds, reptiles, and fish (Davies and McLoughlin, 1996; Ceylan et al., 2023). The scarcity of large mammalian hosts may lead remaining leech populations to rely more heavily on amphibians, potentially increasing predation pressure on amphibian communities (Merilä and Sterner, 2002).

4.2. Specialized parasitism on turtles

The Glossiphoniid leech *Placobdella costata* is an obligate ectoparasite of freshwater turtles, such as the European pond turtle (*Emys orbicularis*) and the Balkan turtle (*Mauremys rivulata*) (Ceylan and Çetinkaya, 2023). In sampled Turkish wetlands, the overall leech infection prevalence on these turtles was high, with infestation intensity and abundance being higher in female turtles and correlating positively with host body size (Ceylan and Çetinkaya, 2023; Readel et al., 2008; Rocha et al., 2025). Leeches typically attach to the host's plastron or hind limbs, regions that offer sheltered attachment sites (Ceylan and Çetinkaya, 2023; Rocha et al., 2025).

4.3. Life history strategies (R/K selection)

Reproductive strategies vary significantly within the *Hirudo* genus and are closely linked to habitat stability. *H. verbana* is classified as an r-strategist, characterized by the highest fecundity, rapid growth rate, and high juvenile mortality, making it well-suited for unstable, temporary habitats typical of steppe landscapes. *H. medicinalis* and *H. orientalis* are K-selected species, producing fewer but heavier hatchlings, leading to lower juvenile mortality rates. These species are generally adapted to more stable and predictable environments, such as static ponds and lakes (Petrauskienė et al., 2011; Ceylan et al., 2021b).

5. LEECHES AS BIOINDICATORS FOR ECOTOXICOLOGICAL ASSESSMENT

Leeches are effective monitors of aquatic pollution, often termed time integrators of contaminant levels, meaning their tissues reflect long-term exposure rather than transient spikes in water concentration (Hall and Jacob, 1988; Petrauskienė, 2004; Grzelak et al., 2012).

5.1. Pollutant accumulation

Leeches exhibit a remarkable capacity for bioaccumulation. Studies have shown that species like *Dina dubia* and *Erpobdella punctata* concentrate chlorophenols at levels 1-3 orders of magnitude greater than those found in crustaceans and other benthic invertebrates (Metcalfe et al., 1984; Grzelak et al., 2012). Contaminants, such as polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs), accumulate in both the internal dermato-muscular sac tissue and the external mucous coat, with the latter serving as a primary defense mechanism (Grzelak et al., 2012; Saleh et al., 2015). For instance, *Limnatis nilotica* is considered a useful tool for biomonitoring OCPs and PCBs (Saleh et al., 2015).

Bioaccumulation capacity and retention times are species-specific and compound-dependent. A comparative study on *D. dubia*, *E. punctata*, and *Helobdella stagnalis* exposed to 16 organic compounds revealed that while *D. dubia* had the highest uptake, residues persisted longest in *E. punctata*. Crucially, half-lives for Chlorophenols and DDT exceeded one month, validating leeches as effective biomonitors for intermittent contamination. In contrast, the rapid depuration of Lindane (1 day) and benzothiazoles (1-7 days) limits their utility to chronically polluted sites (Metcalfe et al., 1988)

5.2. Heavy metal toxicity

Exposure to heavy metals induces specific behavioral and physiological stress responses in leeches:

- **Cadmium (Cd):** Acute exposure to Cd resulted in a 96-hour LC_{50} of 4.02 mg/L for *H. verbana*. Exposure triggered uncontrolled swimming, excessive mucus secretion, localized edema, and penis prolapse, alongside morphological changes quantifiable using the newly developed Body Flexion

Ratio (BFR), indicating neuromuscular stress (Çelik et al., 2026). Susceptibility to cadmium also varies by life stage and species. In the freshwater predatory leech *Nephelopsis obscura*, the 96-h EC_{50} for cocoons was determined as 832.6 µg/L. High exposure concentrations (1,000-4,000 µg/L) during the cocoon stage significantly reduced post-hatchling survivorship. Interestingly, resistance to acute toxicity increased with leech biomass. Behaviorally, *N. obscura* exhibited significantly decreased activity at concentrations of 100-200 µg/L. This reduced motility likely explains the counter-intuitive results in preference-avoidance tests, where leeches spent more time in contaminated zones, effectively failing to escape due to toxicity-induced lethargy (Wicklum et al., 1997).

- Zinc (Zn): *H. verbana* showed moderate sensitivity to zinc, with a 96-hour LC_{50} of 14.12 mg/L (Ceylan et al., 2021c). Responses included defecation, reduced attachment strength, body curling, and regurgitation of digested blood (Ceylan et al., 2021c).

- Copper (Cu) and mixtures: Comparative long-term assays (30 days) on *H. verbana* revealed that leeches are remarkably more sensitive to copper than to zinc. When exposed to a binary mixture (Zn+Cu), a partially additive interaction was observed, particularly during acute phases (Petrauskienė, 2008). At the cellular level, this high sensitivity is linked to severe structural degeneration. Transmission electron microscopy (TEM) analysis of leeches exposed to 0.2 mg/L Cu for 96 hours revealed profound histopathological alterations, including irregular and disorganized muscle fibers, degenerated epithelial cells and fibroblasts, and compromised body wall integrity evidenced by short, scattered microvilli (Kutlu et al., 2010). Crucially, unlike fish, mortality in leeches continued throughout the entire 30-day period. This prolonged lethal response suggests that standard acute tests may underestimate toxicity, necessitating long-term experimental designs for accurate risk assessment (Petrauskienė, 2008).

- General Responses: Leeches display avoidance responses to heavy metal mixtures, which can be utilized as an express method for water quality assessment. Chronic exposure often leads to impaired physiological functions, such as decreased feeding activity and altered excretion rates (Petrauskienė, 2004).

Heavy metal accumulation in the saliva of *Hirudinaria manillensis* poses clinical risks. However, a recent study demonstrated that maintaining leeches in deionized water for three weeks effectively depurates these contaminants. This protocol significantly reduced metal loads, specifically lowering salivary Cd by 99.7% and tissue Pb by 92.38%, thereby ensuring safer biomedical utilization (Alaama et al., 2021).

Leeches also serve as reliable indicators in establishing natural baseline levels in relatively unpolluted ecosystems. A study conducted in Kara Lake (Türkiye) on the endemic species *H. sulukii* revealed that heavy metal accumulation followed the order Fe>Zn>Cu>Pb>Mn>Cr>Ni>Cd. Although sediment metal concentrations peaked during the summer stagnation due to evaporation, the levels in *H. sulukii* and co-occurring macrophytes remained below US EPA risk thresholds. This suggests that in the absence of anthropogenic input, leech tissue burden accurately reflects the geological characteristics of the habitat (Keser et al., 2020).

5.3. Organic pollutant toxicity

Toxicity of organic compounds represents another critical dimension of aquatic pollution. Chronic exposure to BTEX (25 µg/L) induces severe reproductive toxicity in the freshwater leech *Erpobdella johanssoni*. Cytological analysis revealed degenerative changes in ovarian cells, including cytoplasmic vacuolization and mitochondrial alterations. Furthermore, the Comet assay confirmed significant DNA fragmentation, indicating that BTEX-induced genotoxicity directly compromises oogenesis and reproductive success (Khaled et al., 2017).

6. EMERGING CONTAMINANTS (MICRO AND NANOPLASTICS)

Leeches are highly vulnerable to micro- and nanoplastics (MNPs). Exposure of *E. johanssoni* to polyethylene (PE) microplastics induced severe histopathological damage, including cuticle detachment and muscle disorganization, alongside significant oxidative stress (Ben Ahmed et al., 2025). In the medicinal leech *H. verbana*, investigations into Polypropylene (PP) and Polyethylene Terephthalate (PET) nanoplastics revealed sophisticated immune responses beyond physical damage. Both polymer types were internalized by macrophages, triggering a time-dependent inflammatory cascade characterized by significant angiogenic remodeling (neovascularization) and endothelial activation evidenced by CD31 expression. At the molecular level, this response involves the upregulation of pro-inflammatory markers (HmAIF-1, HvRNASET2) and altered expression of oxidative stress genes (SOD, GST), demonstrating that MNPs activate conserved innate immune pathways in medicinal leeches (Baranzini et al., 2022; Bon et al., 2026).

7. CONCLUSION

Leeches represent a biologically diverse and functionally critical group within freshwater food webs. Their distribution is governed by a complex interplay of abiotic factors, temperature, water chemistry, and substrate, and biotic pressures like prey availability. The divergence in life-history strategies, particularly between the r-selected *H. verbana* and K-selected congeners, underscores their evolutionary adaptation to varying habitat stabilities.

Beyond their ecological role, leeches serve as robust bioindicators, capable of reflecting environmental quality through the bioaccumulation of heavy metals and persistent organic pollutants. Crucially, recent evidence of metal accumulation in saliva highlights potential clinical risks for hirudotherapy, though newly developed depuration protocols offer a viable mitigation strategy. Toxicological assessments reveal that leeches exhibit distinct sensitivities, particularly to Copper and metal mixtures, with damage manifesting at cellular levels through severe histopathological alterations and mortality extending beyond standard acute test durations. Furthermore, their response to emerging contaminants like micro- and nanoplastics goes beyond physical abrasion, eliciting conserved innate immune pathways involving angiogenesis, macrophage recruitment, and oxidative stress gene regulation. Consequently, leeches act as comprehensive sentinels for aquatic health, integrating physiological, behavioral, and molecular responses to assess both traditional and emerging anthropogenic threats in threatened freshwater ecosystems.

DECLARATION OF AI USE

During the preparation of this paper, the author used Google Gemini Pro for translation the text from Turkish to English and to improve the grammatical flow and clarity of the manuscript. The author reviewed the final text and takes full responsibility for the accuracy and integrity of the work.

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CHAPTER 3

EFFECTS OF ORGANIC AND CHEMICAL FERTILIZERS ON YIELD TRAITS OF CHICKPEA

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DOI: https://www.doi.org/10.5281/zenodo.18093259

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1. INTRODUCTION

Legumes play an important role in the diets of millions of people in developing countries (Temba et al., 2016). They are multipurpose crops that can be used directly as food, in processed forms or as fodder in agriculture (Kassie et al., 2009; Akibode & Maredia, 2012; Cömert-Acar et al., 2019). Chickpea, in particular, has an important place in nutrition and soil improvement as a vegetable protein source (Gogoi et al., 2018). Legumes contain protein, minerals such as calcium (Ca), iron (Fe), phosphorus (P), dietary fibre and complex carbohydrates, and are also rich in vitamins (Latham, 1997; Roy et al., 2010). Legumes are usually grown as rotation crops with cereals due to their role in nitrogen (N) fixation, chickpea is an ancient self-pollinating legume plant, thought to originate from south-eastern Turkiye and Syria (Singh, 1997). Chickpea provides great health benefits with its high protein content and potential to reduce cardiovascular, diabetic and cancer risks (Merga & Haji, 2019). As a low-cost protein source, it plays an important role in regions where animal protein sources are inadequate and expensive (Egesel et al., 2006; Acharya et al., 2006). Chickpea can be used in various areas such as edible, snack and animal feed and can be easily cultivated in arid climates with low irrigation requirements (Üstün & Gülümser, 2003; Gül et al., 2006; Kayan et al., 2014). Chemical fertilisers and pesticides used in agriculture cause environmental pollution, pollute groundwater and cause soil degradation (Norse, 2005; Mózner et al., 2012; Wang et al., 2018). Therefore, the use of organic fertilisers is becoming increasingly important as an environmentally friendly agricultural method by improving soil structure (Timsina, 2018; Uçar, 2019; Uçar et al., 2020a). Leonardite, which has a brown and coal-like appearance, is an oxidised form of lignite. Leonardite, which contains between 30-80% humic acid (HA), offers important opportunities for soil improvement and positively affects growth and crop yield (Ayuso et al., 1996; Akinremi et al., 2000; Muscolo et al., 2013; Qian et al., 2015; Barone et al., 2019). Vermicompost (VC) is obtained by digesting and composting organic wastes by earthworms (*Eisenia Foetida* and *Lumbricus Rubellus*) (Domínguez, 2004; Mısırlıoğlu, 2011). The positive effects of vermicompost on plant growth have been proven (Atiyeh et al., 2001). Moreover, vermicompost promotes plant growth and improves soil properties, providing positive results in both organic and conventional agriculture (Singh & Chauhan, 2009). Vermicompost humus is rich in microbial metabolites, which function as plant growth regulators by stimulating root development, enhancing nutrient uptake, and promoting overall plant growth (Huerta et al., 2010). Vermicompost applications can increase nutrients such as N, P and K in soil by 42, 29 and 57 per cent (Sharma & Banik, 2014). Compared to other organic fertilisers, vermicompost contains micronutrients (Fe, Zn, Cu and Mn) as well as nutrients (Tognetti et al., 2005; Suthar, 2009; Beykkhormizi et al., 2016).

This study aimed to determine the effects of different doses of leonardite, vermicompost, and chemical fertilizers on the growth and yield parameters of chickpea plants.

2. MATERIAL AND METHOD

Characteristics of chickpea (*Cicer arietinum* L.) plant used in the experiment: Azkan chickpea variety is 41.0-46.3 cm tall and the first pod height is 35 cm and it is an upright growing variety. Grain colour is cream, 100 grain weight varies between 46-49 g and it has ram's head grain type. Harvest maturity period varies between 100-105 days. Yield level varies between 131.0-190.3 kg da^{-1} depending on climate and soil structure. It is tolerant to anthracnose, root rot and wilt diseases and cold (Anonymous, 2021).

Fertiliser material used in the experiment: Leonardite and vermicompost are two important sources of organic matter that offer different properties in improving soil health. Leonardite, with its 20% organic matter and 20% total humic+fulvic acid content, helps to lower soil pH and ensure more efficient nutrient utilisation. However, it has a low moisture content of 20%, pH 4.5 and an acidic structure. Vermicompost fertiliser has a richer structure with 55% organic matter and 42% ash content. The properties of leonardite and vermicompost fertiliser used in the experiment are given in Table 1. Fertilizer analyses were carried out in the central research laboratory of Mardin Artuklu University.

Table 1. Properties of leonardite and vermicompost fertilizers used in the experiment

Property	Leonardite	Vermicompost
Organic Matter (%)	20.0	55.0
Total Humic + Fulvic Acid (%)	20.0	12.0
Moisture (%)	20.0	40.0
pH	4.50	7.20
Ash Content (%)	-	42.0
Total N (%)	2.00	1.60
P_2O_5 (%)	0.35	2.20
Ca (%)	0.28	5.00
Mg (%)	0.19	1.20
Fe (%)	-	1.50
Mn (mg kg^{-1})	65.2	73.0
Pathogenic Microflora	-	-
Parasites	-	-
Heavy Metals	-	-

Organic fertilisers are substances that naturally supply plant nutrients and improve soil health. The effects of organic fertilisers such as vermicompost and leonardite on soil fertility are based on factors such as nutrients, organic components and chemical composition. However, how efficient these effects will be depends on the soil conditions (soil pH value, moisture status, organic matter content, etc.) and the specific needs of the plants grown (macro and micronutrient demands). In order to understand the effects of these organic fertilisers in agricultural studies, it is important to examine the physical and chemical properties of each of them in detail. Some physical and chemical properties of organic fertilisers commonly used in agricultural studies are given in Table 2.

Table 2. Some properties of organic fertilizers commonly used in agricultural studies

Fertilizer Type	Physical Properties	Chemical Properties
Leonardite	- Leonardite is a substance formed by the oxidation of lignite coal, typically black, shiny, and brittle.	- Leonardite contains a high amount of humic substances and fulvic acid, which increase the organic matter content of the soil.
	- It is commonly found in granular or powdered form, making it easy to use.	- Its high organic carbon content improves soil structure and increases water retention capacity.
	- The particle size varies depending on the processing method; it is more homogeneous in granular form and finer in powdered form.	- Leonardite also contains hormone-like compounds and trace minerals that promote plant growth.
Vermicompost	- Vermicompost is a dark, crumbly, soil-scented material created by earthworms digesting organic matter.	- Vermicompost is rich in humus, which enhances soil water retention and supports microbial activity.
	- It has a fine, soil-like texture, which facilitates its integration with soil.	- It contains essential macro nutrients such as N, P, and K, as well as micronutrients like S, Fe, and Zn.
	- Typically well-aerated and has high water retention capacity, helping to maintain soil moisture in dry conditions.	- The pH level is generally neutral or slightly acidic (around pH 6.00-7.00), providing an optimal environment for most plants.

Trial area: The experiment was conducted in the farmer's field in Yukarı Aydınlı neighbourhood, Artuklu District, Mardin province during the 2019-2020 growing period. The results of some physical and chemical analyses of the test area are given in Table 3.

Table 3. Some chemical and physical properties of the experimental soil

Property	Test Soil	References
pH	7.65	Kacar, 1995
Texture	Clay-Loam	Bouyoucus, 1952
Salt (%)	0.21	Soil Survey Staff, 1951
$CaCO_3$ (%)	36.2	Loeppert & Suarez, 1996
Organic Matter (%)	1.25	Kacar, 1995
Available P (mg P_2O_5 kg^{-1})	13.6	Olsen et al., 1954
Available K (mg K_2O kg^{-1})	74.7	Richards, 1954
Fe (mg kg^{-1})	22.3	Lindsay & Norvell, 1978 (extracted with DTPA)
Cu (mg kg^{-1})	2.95	
Mn (mg kg^{-1})	65.1	
Zn (mg kg^{-1})	7.19	

Climatic characteristics of the research area: In the 2019/2020 production season in Mardin province, the average temperature in October was 18.6°C, which was cool, while in June it was as high as 32.0°C, indicating a hot and dry climate in summer and a cool climate in winter. The humidity was 11.8% in October and decreased to 27.0% in June, while in the winter months, especially in January and February, humidity levels were as high as 71.0%. Rainfall was high in October, November and December with 37.0 mm, 66.0 mm and 99.0 mm, respectively, while only 2.0 mm fell in June. The climatic data of Mardin province in the 2019/2020 production season are given in Table 4.

Table 4. Climate data of Mardin province in the 2019/2020 production season

	Oct. 2019	Nov. 2019	Dec. 2019	Jan. 2020	Feb. 2020	Mar. 2020	Apr. 2020	May. 2020	Jun. 2020
Average Temperature (°C)	18.6	11.8	5.90	5.70	8.60	13.3	18.6	25.0	32.0
Humidity(%)	11.8	6.20	1.50	71.0	71.0	63.0	53.0	43.0	27.0
Precipitation(mm)	37.0	66.0	99.0	66.0	53.0	61.0	70.0	44.0	2.00

Mardin Meteorology Center, 2019-2020

Experimental design: The experiment was established in three replications (30 plots) according to the split plots design in randomised blocks.

Each plot consisted of 5 rows and the distance between the rows was 20 cm and the plot area was 1 m x 5 m = 5 m^2. 350 seeds per m^2 were sown by hand. The chickpea plant used in the experiment was treated with leonardite at 50, 100, 200 and 400 kg da^{-1} and vermicompost fertiliser at 150, 200, 250 and 300 kg da^{-1} per decare. During the harvest, to minimize the edge effect, one row on each side of the five rows forming the parcel, along with plants within 50 cm from the row ends, were excluded from observation. Consequently, all measurements and observations were conducted on the central area of each parcel, measuring 0.6 m x 4 m, resulting in a total area of 2.4 m^2. The seedbed preparation was completed on 20 November 2019, coinciding with the sowing date, by creating planting lines using a marker. Weed control in the trial area was carried out twice once before flowering and once after flowering to ensure optimal growth conditions.

Statistical analyses: Analysis of variance (ANOVA) was performed to determine the significance of the differences between the responses to the combinations of fertiliser applications at different doses. The significance of the differences between means was checked by Waller-Duncan's multiple range test ($p \leq 0.05$). Statistical analysis was performed using SPSS 22.0 statistical package programme. The experimental design of split plots in randomised blocks was established in 3 parallels.

3. RESULTS AND DISCUSSION

The effect of different doses of leonardite, vermicompost and inorganic fertiliser applications on plant height, pod height, number of main branches, number of pods and number of grains in pods. The application of different doses of leonardite, vermicompost, and chemical fertilizers resulted in statistically significant effects on plant height and the number of main branches at the $p \leq 0.05$ level, while pod height, the number of pods, and the number of grains per pod were significantly affected at the $p \leq 0.01$ level (Table 5).

Table 5. Effects of different doses of leonardite and vermicompost on plant height, pod height, number of main branches, number of pods and number of grains in pods in chickpea plants

Applications	**Dose (kg da^{-1})**	**Plant height (cm)**	**Pod height (cm)**	**Number of branches (branches plant^{-1})**	**Pod Count (per plant)**	**Number seeds per pod (per plant)**
Control	0.00	56.6^{c}	29.0^{e}	2.70^{d}	24.9^{e}	22.5^{f}
$20_{(N)}$-$20_{(P)}$-$0_{(K)}$	10.0	62.3$^{a\text{-}c}$	37.6^{ab}	3.07$^{a\text{-}d}$	35.3^{ab}	35.4$^{a\text{-}c}$
Leonardite	50.0	60.9^{bc}	31.7^{de}	2.90$^{b\text{-}d}$	27.8^{de}	27.7^{e}
	100	62.8$^{a\text{-}c}$	34.2$^{b\text{-}d}$	2.87^{cd}	30.2^{cd}	30.6^{de}
	200	65.4^{ab}	36.1$^{a\text{-}c}$	3.40$^{a\text{-}c}$	33.5^{bc}	34.5$^{b\text{-}d}$
	400	68.0^{a}	38.3^{a}	3.57^{a}	39.0^{a}	38.7^{a}
Vermicompost	150	63.6^{ab}	32.7$^{c\text{-}e}$	3.27$^{a\text{-}d}$	28.3^{de}	27.9^{e}
	200	63.0$^{a\text{-}c}$	35.0$^{a\text{-}d}$	3.43$^{a\text{-}c}$	32.1^{bc}	33.1^{cd}
	250	64.7^{ab}	36.0$^{a\text{-}c}$	3.30$^{a\text{-}d}$	33.7^{bc}	34.2^{cd}
	300	67.5^{ab}	37.4^{ab}	3.50^{ab}	38.3^{a}	38.4^{ab}
F		3.02*	6.85**	2.89*	18.9**	19.7**

(**): $P \leq 0.01$, (*):$P \leq 0.05$

Plant height: In the control group, plant height showed the lowest value with 56.6 cm, while plant height increased with Leonardite applications. As the amount of Leonardite increased (from 50 kg da^{-1} to 400 kg da^{-1}), plant height also increased and the highest plant height was measured as 68.0 cm at 400 kg da^{-1}. Although a similar increase was observed in vermicompost treatments, plant height increased to 64.7 cm and 67.5 cm at 250 kg da^{-1} and 300 kg da^{-1}, respectively. Although leonardite provided higher plant heights than vermicompost, both treatments positively affected plant growth compared to the control group (Table 5). As a result, it can be said that organic fertilisers such as leonardite and vermicompost have the effect of increasing plant height and can help to improve the soil. Uçar et al. (2020a) reported that plant height increased with the increase in the dose of vermicompost fertiliser and the highest plant height was obtained at a dose of 120 kg da^{-1}. Uçar et al. (2020b) reported that leonardite applications increased plant height at doses other than 125 kg da^{-1}, and the highest increase was at a dose of 100 kg da^{-1}.

Pod height: Compared to the control group (29.0 cm), the effect of 20-20-0 fertilizer resulted in a significant increase, reaching 37.6 cm. However, Leonardite and Vermicompost applications also showed significant increases. Leonardite, particularly at the 400 kg da^{-1} application rate, achieved the highest pod height (38.3 cm). Vermicompost applications reached values of 36.0 cm and 37.4 cm at 250 kg da^{-1} and 300 kg da^{-1} levels, respectively. These results indicate that organic fertilizers (Leonardite and Vermicompost) have a stronger effect on pod height compared to the chemical fertilizer 20-20-0 (Table 5). Specifically, the 400 kg da^{-1} application of leonardite provided the highest value for this parameter, suggesting the positive impact of organic fertilizers on plant growth. Uçar et al. (2020b) reported that under the ecological conditions of Siirt, different doses of leonardite (0, 25, 50, 75, 100, and 125 kg da^{-1}) increased plant height in chickpea compared to the control group, with the lowest plant height measured as 21.8 cm (control) and the highest as 32.2 cm at the 100 kg da^{-1} dose. Uçar et al. (2020a) reported that different doses of vermicompost increased plant height to values ranging from 30.5 cm to 33.4 cm, with the highest plant height obtained at the 120 kg da^{-1} dose. Doğan (2019) stated that organic and inorganic fertilizer applications resulted in first pod height in chickpea ranging from 29.6 cm to 45.2 cm, with the lowest value observed in the control group, and that vermicompost fertilizer increased the first pod height in plants.

Number of branches: In the control group (2.70 branches plant^{-1}), the number of main branches was the lowest, while the group treated with 20-20-0 fertilizer (3.07 branches plant^{-1}) showed a significant increase compared to the control group. Leonardite and vermicompost applications, however, resulted in even higher branch numbers. The application of leonardite at 400 kg da^{-1} achieved the highest value, with 3.57 branches plant^{-1}. Vermicompost applications also led to significant increases, particularly at 200 kg da^{-1} (3.43 branches plant^{-1}) and 300 kg da^{-1} (3.50 branches plant^{-1}). These results indicate that leonardite resulted in the highest number of main branches, but vermicompost applied at 300 kg da^{-1} produced similar outcomes (Table 5). Doğan (2019) reported that in chickpea, the number of branches varied between 2.38 branches plant^{-1} and 2.98 branches plant^{-1} as a result of organic and inorganic fertilizer applications, with the lowest number of branches recorded in the control plots. He also stated that DAP and vermicompost fertilizers had a significant positive effect on branch number. Zeidan (2007) mentioned that organic fertilizers increased the number of branches, and Saket et al. (2014) indicated that organic fertilizers (farmyard manure, chicken manure, compost, and vermicompost) had a positive effect on branch number.

Pod Count: In the control group (0.00 kg da^{-1}), the number of pods remained at the lowest value of 24.9, while the application of chemical fertilizer (20-20-0) increased the number of pods to 35.3. For leonardite applications, a rise in pod number was observed as the dose increased, with the highest value of 39.0 achieved at a dose of 400 kg da^{-1}. Similarly, with vermicompost fertilizer, pod numbers also increased as the dose rose, reaching 38.3 at 300 kg da^{-1} (Table 5). Overall, organic fertilizers (leonardite and vermicompost) were more effective at higher doses than chemical fertilizers, with the max. number of pods obtained from the 400 kg da^{-1} leonardite application. Uçar et al. (2020a) reported that vermicompost fertilizer doses in chickpea plants ranged between 33.5 and 36.0 pods $plant^{-1}$, with the lowest average pod count observed in control plots and the highest average achieved in plots treated with 120 kg da^{-1} of vermicompost fertilizer. Additionally, a positive increase in plant height was observed with increasing vermicompost fertilizer doses. Kumar et al. (2014) noted that vermicompost applications significantly enhanced pod numbers in chickpea plants. Amin & Moghadasi (2015) reported that applications of N fertilizer and vermicompost fertilizer increased pod numbers, with the lowest value recorded in control plots and the highest in plots treated with vermicompost fertilizer. Uçar et al. (2020b) found that different doses of leonardite (0, 25, 50, 75, 100, and 125 kg da^{-1}) influenced pod numbers in chickpea plants, ranging between 30.6 and 33.6 pods $plant^{-1}$. The highest value was obtained in plots treated with 100 kg da^{-1} leonardite, but pod numbers decreased when the dose exceeded 100 kg da^{-1}. Similarly, Öktem et al. (2017) reported that humic acid applications increased the number of pods in plants.

Number seeds per pod: In the control group (0.00 kg da^{-1}), the number of seeds per pod was at its lowest level with 22.5. The application of chemical fertilizer (20-20-0) increased the seed count to 35.4. Leonardite applications significantly increased the number of seeds as the dose increased, with the highest value of 38.7 obtained at a dose of 400 kg da^{-1}. Similarly, vermicompost applications showed an increase in seed count with higher doses, reaching the maximum value of 38.4 at 300 kg da^{-1} (Table 5). Overall, organic fertilizers (leonardite and vermicompost) were effective in increasing the number of seeds at higher doses, with the highest seed counts achieved through leonardite and vermicompost applications. Uçar et al. (2020a) reported that vermicompost fertilizer doses in chickpea plants resulted in seed counts ranging from 39.5 to 38.5 seeds per plant, with the lowest average seed count observed in control plots and the highest in plots treated with 120 kg da^{-1} of vermicompost fertilizer. Amin & Moghadasi (2015) examined the effects of vermicompost and N fertilizers on seed count in chickpea plants and found that the lowest values were in control plots, while the highest were in plots treated with vermicompost. Uçar et al. (2020b) noted that different doses of leonardite in chickpea plants resulted in seed counts ranging from 33.7 to 36.6 seeds per plant, with the highest value obtained at 100 kg da^{-1} leonardite. Batanay (2016) reported that humic acid applications increased seed count, and Doğan (2019) stated that vermicompost fertilizer significantly increased seed count and provided more positive contributions compared to other fertilizer sources.

The study determined that the application of different doses of leonardite, vermicompost, and chemical fertilizer had statistically significant effects on seed yield, 100-seed weight, biological yield, harvest index, and protein content in chickpea plants at the p≤0.01 significance level (Table 6).

Table 6. Effects of different doses of leonardite and vermicompost applications on seed yield, 100-seed weight, biological yield, harvest index, and protein content in chickpea plants

Applications	**Dose (kg da^{-1})**	**Seed yield (kg da^{-1})**	**100-seed weight (g)**	**Biological yield (kg da^{-1})**	**Harvest index (%)**	**Protein (%)**
Control	0.00	197^{f}	38.6^{d}	733^{d}	27.0^{e}	19.3^{e}
$20_{(N)}$-$20_{(P)}$-$0_{(K)}$	10.0	243^{cd}	40.8^{a-c}	749^{cd}	32.7^{bc}	22.0^{ab}
Leonardite	50.0	205^{f}	38.9^{cd}	736^{cd}	28.3^{e}	19.8^{de}
	100	225^{e}	40.3^{a-d}	740^{cd}	30.3^{d}	20.1^{de}
	200	238^{c-e}	40.4^{a-d}	740^{cd}	32.0^{b-d}	21.0^{b-d}
	400	265^{b}	40.0^{b-d}	783^{b}	33.7^{b}	22.0^{ab}
Vermicompost	150	229^{de}	39.4^{cd}	738^{cd}	31.0^{cd}	19.7^{de}
	200	248^{bc}	39.4^{cd}	760^{bc}	32.7^{bc}	20.3^{c-e}
	250	261^{b}	41.9^{ab}	776^{b}	33.7^{b}	21.4^{a-c}
	300	286^{a}	42.2^{a}	821^{a}	35.7^{a}	22.5^{a}
F		28.7**	4.25**	15.6**	24.5**	9.03**

(**):P≤0.01

Seed yield: In the unfertilized control group, the lowest seed yield was obtained at 197 kg da^{-1}, while the application of 20-20-0 chemical fertilizer (10 kg da^{-1}) increased the yield to 243 kg da^{-1}. Leonardite applications showed an increase in yield with higher doses, reaching 265 kg da^{-1} at 400 kg da^{-1}. Vermicompost applications increased seed yield at all doses, with the highest seed yield of 286 kg da^{-1} achieved at 300 kg da^{-1} (Table 6). These results indicate that organic fertilizers, especially leonardite and vermicompost, are effective at higher doses and have significant potential in increasing seed yield. Kaya et al. (2007) in their study on the effects of organic and commercial fertilizers on chickpea plants, found that the lowest seed yield was obtained from the unfertilized control plots (108.8 kg da^{-1}). In plots treated with both commercial and organic fertilizers, seed yields were similar, but higher yields were observed in plots treated with organic fertilizers. Amin & Moghadasi (2015), when investigating the effects of vermicompost and N fertilizers on chickpea plants, reported that the lowest yields were obtained from control plots, while high seed yields were obtained with both N and vermicompost applications, though the difference between them was insignificant. Additionally, the increase in seed yield with higher doses of vermicompost has been noted by several researchers (Bhattacharjya & Cahandra, 2013; Kumar et al., 2014; Pezeshkpour et al., 2014; Doğan, 2019).

100-seed weight: The 100-seed weight is associated with the size and health of plants and can be increased through fertilizer applications. The application of 20-20-0 fertilizer increased the 100-seed weight to 40.8 g, effectively enhancing seed size. Leonardite applications showed a dose-dependent effect: at 50 kg da^{-1}, the 100-seed weight was 38.9 g; at 200 kg da^{-1}, it increased to 40.4 g; and at 400 kg da^{-1}, it was 40.0 g. However, these effects were lower compared to the chemical fertilizer. Vermicompost fertilizer increased its effect with higher doses, reaching the highest weight of 42.2 g at 300 kg da^{-1}, making it the most effective fertilizer in increasing seed size (Table 6). Many researchers (Kumar et al., 2014; Doğan, 2019; Uçar, 2020) have reported significant effects of vermicompost application on 100-seed weight. Zeidan (2007) noted that as the amount of organic fertilizer increased, the 100-seed weight also increased. Mostofa & Akın (2017) and Gürsoy (2016) reported that leonardite applications increased the 100-seed weight.

Biological yield: Biological yield is an important growth indicator reflecting the total dry matter production of plants. The control group without fertilizer yielded the lowest biological yield at 733 kg da^{-1}, while the application of 20-20-0 fertilizer increased this value to 749 kg da^{-1}, demonstrating the growth-enhancing effect of chemical fertilizers. Leonardite applications showed an increase in yield with higher doses, reaching 783 kg da^{-1} biological yield at the 400 kg da^{-1} dose. Vermicompost applications achieved the highest biological yield of 821 kg da^{-1} at a dose of 300 kg da^{-1}, making it the most effective method for enhancing biological yield (Table 6). Amin & Moghadasi (2015), in their study on the effects of vermicompost and N fertilizers on biological yield in chickpea plants, found that the lowest average biological yield was obtained in the control plots. The highest yield was observed in the plots treated with vermicompost and N fertilizers, but the difference between them was not significant.

Harvest index: In the unfertilized control group, the harvest index was at its lowest level of 27.0%. The application of chemical fertilizer (20-20-0) increased this rate to 32.7%, demonstrating the yield-enhancing effect of fertilization. For leonardite applications, the harvest index increased with higher doses, reaching 33.7% at a dose of 400 kg da^{-1}. Vermicompost applications provided the highest harvest index of 35.7% at a dose of 300 kg da^{-1}, making it the most effective fertilizer for enhancing yield and quality (Table 6). Doğan (2019), highlighted that vermicompost applications increased the harvest index and contributed more positively compared to other fertilizer sources.

Protein content: Protein content is an important parameter reflecting the nutritional value of plants. In the unfertilized control group, the protein content was at its lowest level of 19.3%. The application of chemical fertilizer (20-20-0) increased this value to 22.0%, demonstrating the positive effect of fertilization on protein production. Leonardite applications showed a steady increase in protein content with increasing doses, reaching 22.0% at 400 kg da^{-1}. Vermicompost applications achieved the highest protein content of 22.5% at a dose of 300 kg da^{-1}, highlighting its potential to enhance the nutritional value of plants (Table 6). Doğan (2019) reported that in chickpea plants, the lowest protein content of 20.4% was obtained in control plots, whereas the application of vermicompost fertilizer increased protein content to 22.2%. Göksu (2012) in a study on peas using microbial, organic, and inorganic fertilizers, found that protein content ranged from 21.1% to 24.1%, with the lowest values observed in control plots and increases noted with fertilizer applications.

4. CONCLUSIONS AND RECOMMENDATIONS

In this thesis study, the effects of three different fertilizer types (20-20-0, leonardite, and vermicompost) on chickpea were examined. In the control treatments, all growth and yield parameters remained at the lowest levels. Although the chemical fertilizer increased plant height, pod length, number of primary branches, seed number, and protein content, the strongest effects were obtained from the organic fertilizers. High doses of leonardite (200-400 kg da^{-1}) led to significant increases in plant height and yield. Vermicompost, particularly at the 300 kg da^{-1} dose, resulted in the highest yield, seed number, and protein content. In conclusion, organic fertilizers not only improve chickpea yield but also contribute to soil health, offering an important and environmentally sustainable option for crop production.

However, the fact that the study is based on a single-year field trial limits the full assessment of climatic and environmental variability between years. Therefore, it is recommended that similar research be supported by multi-year trials lasting at least two years, and preferably longer, to ensure that the results obtained are more robust, reproducible, and generalizable.

ACKNOWLEDGEMENTS

This study was derived from the master’s thesis of the second author.

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CHAPTER 4

IMPACT OF CLIMATE CHANGE ON FIELD CROPS CULTIVATION

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DOI: https://www.doi.org/10.5281/zenodo.18093408

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Introduction

Climate change, caused by both natural and human activities, is considered one of the most serious environmental problems in the world (Stern, 2006). Evidence regarding changes in precipitation, temperature, and extreme weather events has been presented on a more systematic and scientific basis (IPCC, 2007; 2014). Climate change is expected to significantly impact global agricultural production, with effects varying across crop types and regions. Studies show that crop losses due to climate change are already being observed and are expected to intensify. The impacts of climate change on agricultural production are profound and multifaceted, including temperature changes, alterations in rainfall patterns, and an increase in the frequency of extreme weather events. The physiological responses of plants to increasing temperatures further complicate the situation. Yin et al. (2016) reported that some crops, such as maize and soybeans, may face yield reduction due to increased drought risk and heat stress. Variability in weather conditions, such as rainfall, will negatively impact crop yields. Studies show that for every degree Celsius increase in temperature, rainfall variability can increase by 4% to 5% (Thomas et al.,, 2019). Chen et al. (2009) reported that reduced rainfall, particularly during critical growing seasons in the North China Plain, significantly negatively impacted both wheat and maize harvests between 1961 and 2003. These findings illustrate how reduced rainfall increases moisture stress and ultimately leads to yield reductions. Studies highlighting that rising temperatures have a negative impact on agricultural yields and have significant consequences, particularly for staple crops such as wheat, maize, and rice, indicate that these changes could potentially disrupt global food security by threatening agricultural productivity and stability. Climate change, in addition to its direct impacts on yields, also threatens the diversity of food crops (Figures 1, 2).

Figure 1. Drought wheat field. Dry climate destroyed crops and harvest. Withered wheat on the field at the summer.
https://www.shutterstock.com/tr/image-photo/drought-wheat-field-dry-climate-destroyed-2107129712?trackingId=bf2735f9-efbb-4690-876b-18e05db71625

Figure 2. 1. Drought sunflower field. Dry climate destroyed crops and harvest. Withered sunflowers on the field at summer.
https://www.shutterstock.com/tr/image-photo/drougsunflower-field-dry-climate-destroyed-2057580887?trackingId=e6648e69-8dce-453e-bb32-638b880c50d1

Research shows that changes in climate conditions can alter the geographic distribution of suitable environments for various crops, thus reducing global crop diversity (Heikonen et al., 2025; Ren et al., 2023). This reduced diversity is concerning because it can lead to increased vulnerability of food systems to pests and diseases and decreased resilience to climate fluctuations. Agricultural adaptation strategies are crucial in overcoming these challenges posed by climate change. Innovations in crop management practices, such as optimizing planting dates, irrigation, and fertilization techniques, can mitigate some of the negative impacts of climate change on agricultural land (Heikonen et al., 2024; Tian et al., 2024; Zheng et al., 2022). Agricultural adaptation strategies are crucial in overcoming these challenges caused by climate change. Innovations in crop management practices, such as optimizing planting dates, irrigation, and fertilization techniques, can mitigate some of the negative impacts of climate change on agricultural land (Heikonen et al., 2024; Tian et al., 2024; Zheng et al., 2022).

Impact of Climate Change on Field Crop Production

Climate change poses a significant threat to global food security and agricultural productivity, particularly in field crop production. More specifically, the agricultural sector is considered to be more vulnerable to climate change (Hasan et al., 2016). Since climatic factors such as rainfall and temperature provide significant direct inputs to the crop sector, any changes and variability in these variables inevitably have a significant impact on crop yield (Barnwal & Kotani, 2010). Various studies have revealed the multifaceted impact of climate on crop yields, especially changes in temperature and precipitation patterns, increasing atmospheric carbon dioxide levels, and extreme weather events. It has been found that rice, wheat, and maize ,the three main field crops, respond differently to these factors, and their yields vary across different regions and environmental conditions. Increased temperatures are directly linked to reduced crop yields, primarily due to shorter growing seasons and increased heat stress during critical growth periods. Chen et al. (2009) reported that regions such as the North China Plain are facing adverse effects, with increasing temperatures and varying rainfall negatively impacting the yield potential of both wheat and maize. Zhao et al. (2017) reported that wheat production decreased by 11.6% for every degree Celsius increase in temperature, but this rate could vary depending on regional conditions and crop management strategies. The effects of excessive heat stress during critical stages of crop development have been quantitatively evaluated, and it has been reported that such stress can significantly reduce the yield of important crops such as maize, wheat, and soybeans (Deryng et al., 2014). Sufficient rainfall is essential for conserving soil moisture, a factor that limits crop production in many agricultural areas (Eze et al., 2021). Eze et al. (2021) tested the relationship between yield and precipitation characteristics by collecting yield and precipitation data for soybean, maize, and sorghum plants for a thirty-year period between 1990 and 2019. The data were analysed using statistical and climatic index analyses. They reported that sufficient rainfall is essential for conserving soil moisture, a factor that limits crop production in many agricultural areas (Eze et al., 2021).

Effects Of Temperature and Precipitation Variability

Studies show that temperature variability can negatively impact plant production through mechanisms such as increased sensitivity to thermal stress, disrupted phenological stages, and impairment of physiological processes essential for plant development. Significant yield reductions in wheat crops have been reported due to high temperature events, with losses ranging from 23% to 49% associated with high maximum temperatures above 34°C (Asseng et al., 2011; Asseng et al., 2018). This is a major concern for regions where wheat is a staple crop. Similarly, Riha et al. (1996) reported that increased intrayear temperature variability increases the risk of winter damage, particularly in crops such as winter wheat, and that temperature fluctuations can lead to increased stress and decreased resilience. Environmental considerations are also extremely important, especially in regions heavily reliant on rain-fed agriculture. Basit et al. (2024) reported that both temperature variability and decreasing rainfall negatively affect crop yields, a much more serious problem, especially in developing regions. It is emphasized that climate variability significantly hinders rain-fed subsistence farming, leading to complex effects on sorghum yield in the study areas (Tolosa et al., 2023). Rainfall, a critical environmental variable, also plays a significant role in crop yield. Studies show that rainfall variability and extreme rainfall can profoundly affect yield outcomes. For example, heavy rainfall occurring during critical growth stages can lead to flooding, increasing stress on crops and reducing yields (Sultan et al., 2013). On the other hand, insufficient rainfall during planting can delay germination processes and consequently affect crop development and yield potential (Lv et al., 2013). The relationship between rainfall patterns and crop responses to temperature changes contributes to overall variability in agricultural productivity (Asseng et al., 2011; (Gomaa et al., 2021). Islam et al. (2025) also analyzed the frequency and return times of extreme rainfall events at different thresholds during dry months to assess the risks that increased rainfall and water accumulation would create in the cultivation of rabi/non-rice crops and the potential of rabi crops. Consequently, they found that longer recurrence intervals between extreme events could delay the planting of winter crops and have negative effects, particularly during the maturity stages. Heavy rainfall negatively affects soil drainage, leading to reduced soil aeration, which adversely impacts crops such as maize and legumes (Eze et al., 2021; Bedane et al., 2022). Annual variability in frost-free seasonal characteristics highlights the significant impact of climate change on frost formation; recent studies show that many regions are experiencing changes that could further exacerbate the challenges faced by farmers (Chervenkov & Slavov, 2022). Frost events can cause serious crop damage, especially in wheat; exposure to freezing temperatures during critical growth stages can lead to yield reduction and even complete crop loss (Yue et al., 2016, Chen et al., 2023).

The Role of Soil Organic Carbon Influenced by Climate Change

Soil dynamics, particularly soil carbon stocks and nutrient status, are significantly affected by climate change; this is critical for maintaining crop growth and ecosystem services. As temperatures rise, there may be an increase in the decomposition rates of soil organic carbon (SOC), potentially exacerbating carbon losses from soils and contributing to greenhouse gas emissions (Davidson & Janssens, 2006; Crowther et al., 2016). There is a direct relationship between SOC and crop yield; high SOC levels increase soil fertility, contributing to improved crop yields and sustainable agricultural productivity (García-Palacios et al., 2018). The decrease in soil organic carbon due to climate variability, particularly rising temperatures and variable rainfall patterns, presents unique challenges in terms of crop yield and soil health, especially in regions heavily reliant on cereal production (Liu & Basso, 2020). Climate change is exacerbating both soil organic carbon loss and declines in grain yields, further highlighting the importance of adaptive management strategies (Liu & Basso, 2020) (Figure 3).

Figure 3. Climate change and drought affected the corn stalk.
https://www.shutterstock.com/tr/image-photo/drought-affected-corn-stalk-dry-field-2559538363?trackingId=c37ea057-0594-45d0-a564-f1a8da2e8f6b

Promising strategies include improved land management practices focusing on conservation tillage and organic fertilization, which could mitigate the anticipated decline in soil organic carbon (SOC) under ongoing climate change (Dasgupta & Mahanty, 2024). Soil organic carbon (SOC) levels are vital for maintaining soil health as they facilitate nutrient cycling, increase water-holding capacity, and improve soil structure (Georgiou et al., 2022). For example, the management of organic residues such as composting and mulching has been shown to improve SOC levels and overall plant yield and health by enriching the soil's nutrient status (Silva et al., 2022). Furthermore, studies have confirmed that SOC influences important physical soil properties such as aggregate formation, erosion resistance, and water-holding capacity, which are effective in providing the necessary conditions for plant growth (Shu et al., 2025; Xue et al., 2020) (Figure 4).

Figure 4. Dry crack earth at rice field
https://stock.adobe.com/tr/search?filters%5Bcontent_type%3Aphoto%5D=1&filters%

The presence of sufficient plant residues on the soil surface can promote SOC accumulation, which is critical under changing climate conditions, and improve soil physical properties (Srinivasarao et al., 2012). This management is particularly important because the interaction between plant residues, soil fertility, and carbon dynamics is complex; practices such as incorporating plant residues into the soil and rotational cropping are necessary to maximize SOC benefits (Bolinder et al., 2020).

Physiological Responses of Major Crops to Climatic Factors

The exchange of carbon between the soil and the atmosphere represents a significant control mechanism over atmospheric C concentrations and climate (Jobbágy et al.,2000, Bellamy et al., 2003, Mahecha et al.,2010). These processes are driven by plants, microbes, and animals living in the soil, and the activity of these organisms may accelerate due to human-induced global warming. High CO2 increases photosynthesis while inhibiting photorespiration, this is due to the increased carboxylation activity of the Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) enzyme (Dusenge et al.,2019). This type of response is significantly more pronounced in C3 plants (wheat and rice) than in C4 plants (maize, millet and sorghum) because CO2 is concentrated around Rubisco due to anatomical and biochemical changes in C4 species (Wang, et al.,2008). Stomatal conductivity decreases at high CO2 levels, thus increasing transpiration efficiency for both types of photosynthesis and minimizing water loss through the stomata (Wang, etal.,2015). Rising temperatures can cause stress in plants, affecting growth processes and consequently reducing yields. For cereals such as wheat, high temperatures have been associated with negatively impacting seedling development because they suppress germination and reduce planting density, a critical factor in maximizing yield potential (Ali et al., 2017, Lv et al., 2013). Specifically, temperatures above optimum thresholds can lead to increased respiration rates and stomatal closure, resulting in decreased photosynthetic efficiency during fertilization periods and nitrogen losses through evaporation (Mamann et al., 2019). This complex interaction shows that while moderate temperature increases may initially seem beneficial by allowing earlier planting in some areas, extreme heat can negatively impact yields, particularly in regions like sub-Saharan Africa where heat-induced drought is common (Farooq et al., 2025; Ali & Malik, 2021). Heat stress or extreme temperature events around the flowering and grain filling stages can cause significant yield loss due to reduced grain number due to pollen sterility, grain drop, reduced assimilation transport to grains, and accelerated leaf senescence (Rezaei et al., 2015). Various studies have reported the complex interplay of physiological, biochemical, and molecular mechanisms by which plants adapt to combined stress conditions. While some plant species exhibit adaptive traits that can increase their frost tolerance, these adaptations may become insufficient as climatic conditions change, leading to greater vulnerability to unexpected cold snaps during critical growing seasons (Xie et al., 2025). Furthermore, a meta-analysis by Yoldi-oldi-Achalandabaso et al. (2025) supports the variability in the responses of plants to climate-induced stresses and highlights that different species exhibit unique adaptation mechanisms depending on their genetic structures, which makes interspecies comparisons difficult.

Conclusion and Recommendations for Sustainable Agriculture

Innovative agricultural practices focused on increasing resilience to climate stressors, such as improved irrigation techniques, crop diversification, and the development of climate-resistant crop varieties, may provide ways to mitigate some of the negative impacts of climate change on crop production

(Wang et al., 2018; Asseng et al., 2018). Developing adaptive agricultural strategies is crucial in mitigating the effects of rainfall variability. Irawan and Komori (2024) advocate for dynamic agricultural calendars that better align crop planting and harvesting with changing rainfall patterns, particularly in rice cultivation in Indonesia, which is significantly affected by moisture availability. Similarly, Kumar et al. (2025) emphasized the importance of optimal planting times to minimize the risks associated with drought periods and to ensure that crops do not encounter moisture stress during their sensitive stages. This situation highlights the critical importance of effective soil and water management strategies in adapting to these pressures, as demonstrated in studies that quantitatively measure the impact of irregular rainfall on crop productivity in various ecological settings (Basche et al., 2016; Rahman et al., 2022). Taken together, the dual challenge of increasing temperatures and variable rainfall necessitates adaptive strategies to mitigate their effects on field crops. Researchers advocate for the development of plant varieties resistant to high temperatures and irregular rainfall through breeding (Wang et al., 2018; Schlenker and Roberts, 2009). Existing agricultural systems should incorporate climate-friendly practices, including modified crop rotations and irrigation strategies, to increase resilience to climate-induced disruptions. Liu et al. (2022) highlight the role of tillage practices in enhancing sustainability and productivity under changing climate conditions. Agricultural adaptation strategies are crucial in overcoming these challenges posed by climate change. Innovations in crop management practices, such as optimizing planting dates, irrigation, and fertilization techniques, can mitigate some of the negative impacts of climate change on agricultural land (Heikonen et al., 2024; Tian et al., 2024; Zheng et al., 2022). .However, adaptation capacity varies significantly across regions, with developing countries often facing increasing challenges due to limited resources and a lack of infrastructure to implement effective adaptation measures (Anderson et al., 2020). Historical crop production records can be used to improve, assess the impact of climate variability and hazards on crop yields, and make predictions for future crop yields under changing climate conditions (Irawan and Komori,2024). More specifically, understanding climate impacts through crop simulation models can provide insights into how best to mitigate negative consequences on yields (Annie et al., 2023). By predicting various climate scenarios and their potential impacts on crops, stakeholders such as farmers and policymakers can develop effective strategies aligned with real-time climate change and potentially stabilize agricultural outputs despite climatic challenges (Xiao et al., 2018).

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CHAPTER 5

CREATION OF IĞDIR GEOLOGICAL MAP WITH GEOGRAPHIC INFORMATION SYSTEMS (GIS) AND COMPARISON WITH LARGE SOIL GROUPS

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DOI: https://www.doi.org/10.5281/zenodo.18093464

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INTRODUCTION

Long-lasting and continuous changes such as ground movements in the lithosphere, the formation of mountains, volcanic activities, glaciers during and after the ice age, water movements, and the hydrological cycle have contributed to the earth becoming suitable for living things and to the formation of soil, which is an indispensable environment for living things (Demirören 2021). The continuity of geological events is also valid for soils. Soil formation is not an end, but a new beginning, and events are constantly continuing (Karaoğlu and Çelim 2018).

Earth formations are formed by internal forces such as orogenesis (mountain formation), eirogenesis (continent formation), earthquakes, volcanism, which are the source of magma and have a positive effect on the formation of the earth, and external effects that take energy from the sun and the moon and shape the earth into different shapes through erosion, transportation and deposition events. Different landforms are seen depending on the strength of the forces that create these internal and external effects. If the forces that affect the landforms of a region are known, it can be determined how these forces affect the landforms (Şaroğlu and Güner 1981).

In the Eastern Anatolia Region, which was formed in the Middle Miocene-Neotectonic period (Şengör et al. 1979), structural evolutions and volcanism were effective during a paleogeographic period close to peneplain or peneplain formation (Erinç 1953). These events and evolutions were effective in the geological change of the Eastern Anatolia Region. During the Neotectonic period, in other words, the period of change until today, events such as thrusts, folds, strike-slip (tear) faults and opening cracks have occurred in the geology of the Eastern Anatolia Region. As a result of these formations and events, the Eastern Anatolia Region was subjected to contraction in the North-South direction and extension in the East-West direction. As a result of contraction in the North-South direction, the continental crust thickened, and the region rose (Şengör et al. 1979).

There have also been changes in young volcanism in connection with the thickening and elevation of the earth's crust in the Eastern Anatolia Region. In general, volcanism spewed lava using the opening cracks as chimneys. Another feature seen in the region is the split valleys formed by North-South oriented streams and the meandering stream beds formed by East-West oriented streams.

Under the influence of Neotectonic formations, East-West basin formations identified with synclines and ridges compatible with anticlines have emerged. Similar to these formations, basins have formed between the extensional cracks that emerged as a result of contraction in the North-South direction and the leaping strike-slip faults (Şaroğlu and Yılmaz 1986; Yılmaz et al. 1987).

Stream Power Index (SPI) is used to estimate erosion severity. Severe erosion is likely in lands with a high SPI. If the slope changes due to tectonic uplift, the SPI also changes. High index values indicate high slope and high tectonic activity (Avcı, 2016). River morphology carries important clues about tectonic activity and allows assessing the possible tectonic activity of a region. SPI is used to determine the Neotectonic activity of basins (Sarp, 2014). Streams are effective on the formation and development of landforms with erosion, transport and deposition (Utlu and Ekinci 2015). Hydrographic features are formed under the control of factors such as climate, soil, vegetation, geology, geomorphology, tectonic (Ekinci 2011). Water and wind erosion events caused by heavy rains, floods (snow and/or glacier melting and runoff) and strong winds are effective on landforms and formations, especially soil.

Geographic Information Systems (GIS) are everywhere in daily life; It is a computer program developed to store and analyze different types of data in a database based on the real coordinates plane and to present the results visually (Demirci 2008; Fitzpatrick and Maguire 2000). Nowadays, different and rapid studies are carried out in many fields with GIS.

Soil Information Systems, which are described as creating maps of soil properties, storing and analyzing them in a digital environment (Harmon and Anderson 2003; Lillesand and Kiefer 2000), entered the life of soil scientists and were put into practice. With the development of GIS; important developments have been achieved in many agricultural disciplines such as distribution maps of soil characteristics, plant nutrient element levels, detection of crop patterns, erosion risk maps, and yield estimations (Mercan and Arpağ 2020; Yaşar et al. 2020; Karaca et al. 2019; Başayiğit and Uçar 2019). GIS studies in Iğdır were carried out on soil properties (Karaoğlu and Erdel 2022a, b), changes in land cover/use (Karaoğlu and Erdel 2022c), and the soil surface of Aralık wind erosion area (Karaoğlu and Erdel 2023).

In this study, 1/25000 scale topographic map of the General Directorate of Mapping (GDM); General Directorate of Land Reform (GDLR) 1/25000 scale digital soil data; General Directorate of Mineral Research and Exploration (GDMRE) 1/500000 scale Turkey geological map Kars (Erentöz, 1974) and Van sheets (Altınlı, 1964) and ArcGIS Pro 3.0.1 software were used and new geology, hydrography, basin and stream power index (SPI) distribution maps of Iğdır province were created.

MATERIAL AND METHODS

Material:

Iğdır province, which borders Nakhichevan, Iran and Armenia, is located in the easternmost part of Turkey, in the Erzurum-Kars section of the Eastern Anatolia Region, between 39°-41° North latitudes and 43°-45° East longitudes and has a surface area of 3674.42 km^2. The central, eastern and northern parts of Iğdır are plain lands. These lands are flat and slightly sloped (0-2°) and spread over an area of 109647 ha (29.8%). The total area of medium slope lands (2-6°) was determined as 88371.3 ha (24.05%). The slopes of the lands located at the foothills of the mountainous areas in the west and south of Iğdır are high (>12°) and cover an area of 90167.8 ha (24.54%) (Karaoğlu and Erdel 2022a; GDRS 1998). The climate of Iğdır, which has an Eastern Anatolian type of continental climate, is determined in different climate classifications as semi-arid, arid and very arid. According to long-term data (1991-2020), the average annual temperature is 12.8 °C and total precipitation is 265.8 mm (TSMS 2023).

Maps of GDRS (1/25000 Kars province land assets), GDLR (1/25000 digital soil data), GDMRE (1/500000 Türkiye geological map), GDM (1/25000 topographic) and ArcGIS Pro 3.0.1 software were used to create geology, hydrography, basin and SPI distribution maps.

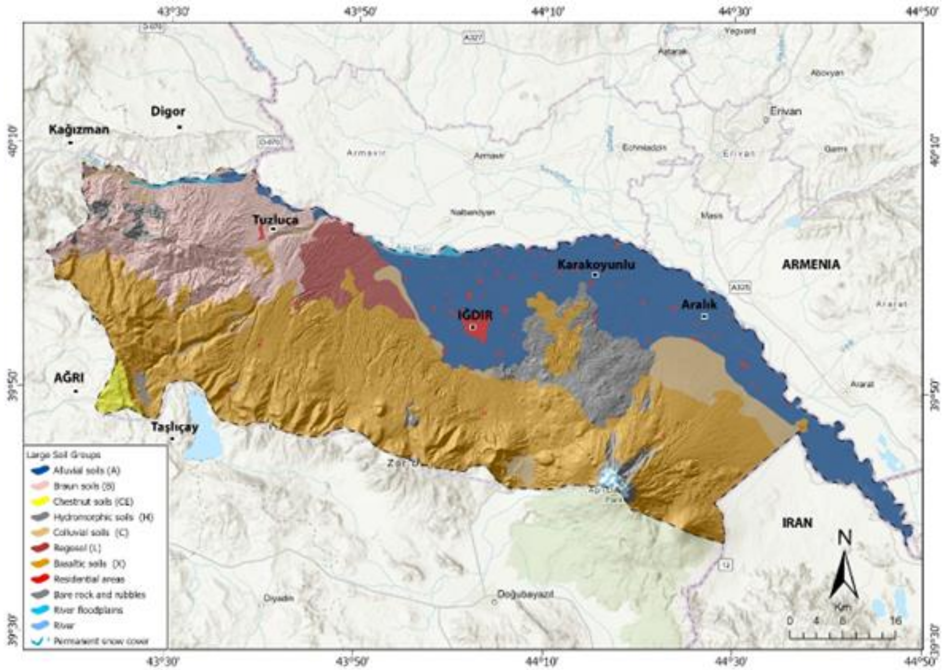

Figure 1. Large soil groups map of Iğdır province

The Iğdır large soil groups map prepared by Karaoğlu and Erdel (2022a) was given in Figure 1. In the south and east-west direction Basaltic (X 173330 ha and 47.2%); in the southwest Chestnut (CE 2680 ha and 0.7%) and Hydromorphic (H 670 ha and 0.2%) soils are located. There are Colluvial (C) soils (18730 ha and 5.1%) between Alluvial (A) soils covering the Iğdır plain (76260 ha and 20.8%) and Basaltic soils. In the west of Iğdır, Regosol (L 11460 ha and 3.1%); in Tuzluca district and its west, Brown (B 50130 ha and 13.6%) soils are seen. Basaltic rocks in the south of Karakoyunlu district and at the foot of Mount Ararat; Clastic and Carbonate rocks and Ophiolitic Melange in the west of Tuzluca district were defined as Bare Rocks and Rubbles (26742 ha and 7.3%).

Method:

A digital elevation model (DEM) was created digitizing GDM 1/25.000 medium-scale topography maps and using ArcGIS Pro, one of the GIS software. DEM data provides a three-dimensional (3D) representation of the surface topography of the study area in a better image. To ensure that the created maps provide good visual and topographical results, hillshade data was used with 65% transparency.

Sections related to Iğdır (according to current provincial borders) from the Kars and Van sheets of the Turkey geological map (1/500.000) prepared by GDMRE have been digitized. Numerical data were transferred to the GIS environment and a database of all features present on the maps was created as an attribute table. The geological map of Iğdır province was created using the attribute table and the numerical soil data of the GDLR (1/25.000). Area calculations regarding the Iğdır geological map were made with ArcGIS Pro 3.0.1 software.

To create the drainage network or hydrographic map of the study area, the digital elevation model (SYM) of the basin and the geological sheets of Kars and Van (1/500000) were used in the Universal Transverse Mercator (UTM) European Datum 1950. 35 Zone Coordinate system with a resolution of 10 m obtained from numerical data. ArcGIS Pro Spatial Analyst module was used to create the drainage network from DEM data.

First, anomalies such as troughs and peaks were eliminated, and necessary corrections were made to the data. To create the river network, the eight-way (D8) model, first proposed by Jenson and Domingue (1988), was used. Additionally, a flow accumulation process was conducted on the DEM using a threshold value of 750 to define and depict the river network. Hydrographic map was created with DEM and data. A basin map was produced by determining 6 bifurcation sequences and 13 river sub-basins belonging to the river directories on the hydrographic map.

There are a number of indices developed with the help of geomorphometric analyses, which help to relatively detect the erosion, transport and deposition processes occurring on river basins. The equation regarding the Stream Power Index (SPI) used in the study, which is one of the indices used to determine the transport and accumulation processes proportionally depending on the erosive power in river basins, is given below.

$$SPI = As \tan\beta \tag{1}$$

Where, As is the specific catchment area (m^2/m) and β is the slope gradient in degrees. SPI, corresponding to the stream network and slope status, expresses the erosive force of the mainstream and its tributaries in the stream network (Moore et al. 1991) and is calculated using map algebra with any GIS software. High values obtained indicate high erosion potential and risk; values of 0 and below generally describe accumulation areas (Moore et al. 1991; Kakembo et al. 2009). SPI values describe the maximum and minimum stream power index at 10 m resolution.

RESULTS AND DISCUSSION

Geological map of Iğdır province:

The geological map of Iğdır province prepared according to today's provincial borders is given in Figure 2, and the formations related to geological times, places where they are seen, calculated area and ratio values are given in Table 1.

Table 1. Events of geological times in Iğdır province

Geological times and formations		**Locations**	**Area**	**Ratio**
			ha	**%**
4	Andesite	Mountainous areas and	44011	11.98
	Undifferentiated Quaternary	NW of Tuzluca, Iğdır plain	91787	24.98
	Alluvial Fans, Slope Debris	N of Tuzluca, slopes in the S and SE	31045	8.45
3-4	Basalt	Mountainous areas and slopes	118905	32.36
	Continental Clastic Rocks	E and SE of Tuzluca, slopes in the S	20809	5.66
3	Pyroclastic Rocks	E of Iğdır, Mountainous areas in the S	19220	5.23
	Continental Clastic Rocks	W of Tuzluca	1062	0.29
	Clastic and Carbonate Rocks	Surrounding of Tuzluca	19341	5.26
2	Granitoid	NW of Tuzluca	117	0.03
	Ophiolitic Melange	Tuzluca batısı ve güneybatısı	20790	5.66
	Pelajik kireçtaşı	W and SW of Tuzluca	219	0.06
	Undifferentiated basic ve ultrabasic rocks	NW border of Tuzluca	24	0.01
1	Carbonate Rocks and Clastic Rocks	SE of Aralık, NW of Dilucu	112	0.03
Total			367442	100

According to the geological map and spatial distribution of Iğdır, formations were determined for 4th time Andesites (44011 ha, 11.98%), Undifferentiated Quaternary (91899 ha, 24.98%), Alluvial Fans and Slope Debris (31045 ha, 8.45%); for 3-4th time Basalts (118905 ha, 32.36%), Continental Clastic Rocks (20809 ha, 5.66%); for 3rd time Pyroclastic Rocks (19220 ha, 5.23%), Continental Clastic Rocks (1062 ha, 0.29%), Clastic and Carbonate Rocks (19341 ha, 5.26%); for 2nd time Granitoid (117 ha, 0.03%), Ophiolitic Melange (20790 ha, 5.66), Pelagic Limestone (219 ha, 0.06%), Undifferentiated Basic and Ultrabasic rocks (24 ha, 0.01); and for 1st time Carbonate and Clastic Rocks (112 ha, 0.03%).

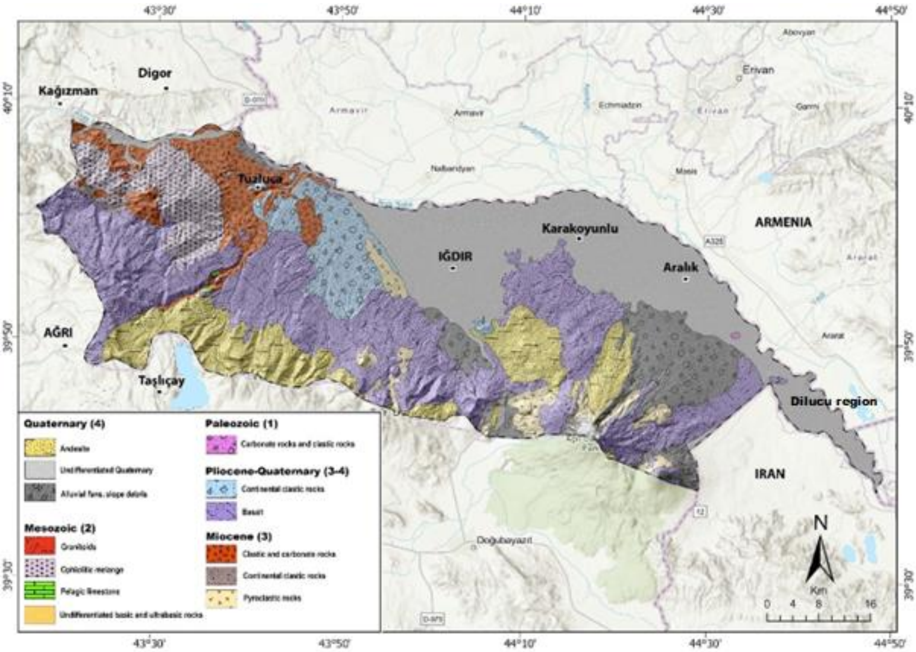

Figure 2. Geological map of Iğdır province

The general characteristics of the large soil groups of Iğdır province (GDRS 1998; Anonymous 2023) and the geological formations on which they are located were presented together in Table 2.

When examining soil properties, the geology of the region should also be known. Because the geological structure of a certain region is an effective factor in shaping the parent soil materials in that region (Everest and Özcan 2018). As a common view, Andesite is formed from the decomposition of

Basaltic magma at depth (Seyhan 1971) and both are hard and durable in structure. Basalt (3-4th Time) and Andesites (4th Time) cover the south of Iğdır province in the east-west direction and are overlain by Basaltic (X), Chestnut (CE) and Hydromorphic (H) soils. When basic igneous rocks decompose, they cause clay-rich soils to form. Basaltic, Chestnut soils and Hydromorphic soil properties confirm this explanation. These large soil groups located in high and rugged geography are soils formed on site and have the characteristics of the geological formation and parent material on which they are located.

Sedimentary rocks are the most common rock type on earth. They cover approximately 75% of the Earth's surface (Wilkinson et al. 2008) and approximately 8 percent of the Earth's crust (Buchner and Grapes 2011). The most important feature of sedimentary rocks is that they show a layered structure. Differences in colour, texture, composition and hardness of the layers in question help distinguish them from each other (Dirlik 2023). Alluvial cones and slope debris on the sloping lands in the south of Iğdır and the district of Aralık and Colluvial (C) soils on the Undifferentiated Quaternary sedimentary rocks in the west of Iğdır were formed on young and transported parent material. The properties of colluvial (K) soils show a strong similarity with the geological structure and parent material on which they are located.

Table 2. Characteristics of large soil groups-geological formations

Soil properties	**Large soil groups**						
	Basaltic (X)	**Chestnut CE)**	**Hydromorphic (H)**	**Colluvial (C)**	**Regosol (L)**	**Braun (B)**	**Alluvial (A)**
Colour	Grey-black	Dark	Dark	Light	Light	Dark	Dark
Texture	Heavy clayey	Much clayey	Fine	Coarse	Coarse	Fine	Fine-Coarse
Profile	Undeveloped	ABC	Under water	AC	AC	ABC	Young A
Depth	30-50 cm	30-50 cm	30-50 cm	30-50 cm	50-90 cm	<20, 30-50 cm	>90 cm
pH	7-8.5	7-8.5	5	7-8.5	7-8.5	7-9	7-8.5
Lime	0	15-30	0	0	0	30-55	30-55
Organic M.	0-1	3-4	>4	0-1	3-4	2-3	>4
Fertility	Lower	Good	Under water	Lower	Lower	Good	Good
Problem	Stony	Slopy	Airless	Coarse stone	Weak Form.	Slopy	Weak layer
Slope	>12°	6-15°	0°	>15°	>15°	2-6° and >12°	0-2°
Drainage	Bad	Good	Bad	Bad	Bad	Good	Poor-Good
Bottom layer	Basic	Gypsum layer	Under water	Young	Stoneless	Lime-Gypsum	Ground water
Main M.	Igneous	Igneous	Igneous	Sedimentary	Sedimentary	Sedimentary	Transported
Ordo	Azonal	Zonal	İntrazonal	Azonal	Azonal	Zonal	Azonal
Geology	A, B	A, B	A, B	AF, SD	CaCR, CCR	OM, CaCR	UQ, CRaCR

M: Matter; A: Andesite; B: Basalt; AF: Alluvial Fan; SD: Slope Debris; CaCR: Clastic and Carbonate Rocks; CCR: Continental Clastic Rocks; OM: Ophiolitic Melange; UQ: Undifferentiated Quaternary; CRaCR: Carbonate Rocks and Clastic Rocks.

Around the Tuzluca district, from the Miocene period Clastic and Carbonate Rocks, the Clastic ones were brought to the environment where they were deposited, foreign (allochthonous); Carbonates, on the other hand, are autochthonous formations because they were formed in the environment in which they were deposited. Although sudden events stop carbonate deposition, they cannot stop the deposition of clastics (Derman 2004). Continental Clastic Rocks of the Pliocene-Quaternary period can accumulate in different environments such as desert, delta, lake, glacier, stream and shelf. There is no obvious similarity between the Regosol (L) soils formed on the Clastic and Carbonate Rocks of the Miocene and Pliocene periods and the Continental Clastic Rocks, on the other hand, sand-sized grains resulting from volcanic eruptions accumulate on Colluvial (C) soils accumulated at the foothills of volcanic mountains and Regosol (L) soils are formed. There are significant similarities between colluvial (C) and Regosol (L) soil properties, except for organic matter content.

In the Anatolian plate, Neotethys remains are represented from top to bottom by ophiolites, ophiolite base metamorphisms and ophiolitic melanges (Robertson 2002). Neotethys consists of two oceanic facies, southern and northern (Şengör and Yılmaz 1981). Ophiolites formed on the subduction zone, which is important in the Neotethyan evolution process of Turkey (Dilek and Thy 2009), show a series of events compatible with each other during the formation and settlement periods (Rızaoğlu et al. 2019). No description could be made between the Ophiolite Melange in the west of Tuzluca, which is connected to the Kağızman ophiolite, which is one of the northern ophiolites, and the Brown soils on the surface. It is thought that there is a relationship between Clastic and Carbonate Rocks and Brown soils with a calcification basis and lime accumulation layers.

Since the alluvial soils on the Unseparated Quaternary sediments located in the Iğdır plain and the northwestern Aras River were formed as a result of transportation, their similarity with the Unseparated Quaternary is the accumulation (sedimentary) phenomenon.

Hydrographic map of Iğdır province:

According to the hydrography, basin and SPI distribution maps prepared with the help of GIS for Iğdır province (Figure 3), the rivers of Iğdır province flow in the south-north direction, depending on the elevation, and consist of seasonal (flood) surface flows. Many of the rivers drain their waters into the Aras River and form the sub-basins of the Aras River. The flow rate of the rivers is not regular, and they mostly have dry stream beds. However, in the spring months (March-May), flow rates in riverbeds increase due to heavy rains, snow and glacier melting. These waters, which suddenly and rapidly flow to the surface within the borders of Iğdır province, cause flood events to occur due to the direct increase in the flow rate of the rivers (Utlu and Ghasemlounia 2021).

Morphological and lithological characters are primarily effective in the formation and development of a natural drainage network. In other words, the drainage structure formed in a region is a reflection of factors such as basin form, lithological structure, soil properties, slope status and climate characteristics in the region (Al Saud 2009). When we pay attention to the drainage of Iğdır province, it is seen that the most common drainage type is the dendritic drainage network. There are many side branches on the 5 main drainage trunks from west to east. The main trunks are generally parallel or semi-parallel to each other. This is related to the fact that the mountainous area and foothills in the south of Iğdır have high slopes (12-64°) (Karaoğlu and Erdel 2022a). If the slope slopes are dominant in one direction in large areas, as is the case from south to north in Iğdır province, a parallel drainage type occurs (Görüm 2018). Furthermore, in areas fragmented by parallel and semi-parallel faults, consecant streams following newly emerged fault scarps (Erinç and Bilgin 1956) or subsecant (steep or diagonal) valleys that conform to previous fault lines at the time of rejuvenation are also suitable areas for the emergence of this drainage type (Görüm 2018).

6 sequences emerged as stream bifurcations, and depending on these values, there is a high water erosion potential and risk in the current period of surface flow. It is seen that there are 13 river sub-basins within the borders of Iğdır province, and these basins, except W13, generally correspond to small-scale basins, and there is a large water collection basin in Mount Ararat and its surroundings. The increased amount of surface flow, especially from steep slopes, as a result of heavy rains and snow-glacier melting, increases the risk and potential of erosion with the high slope and high abrasion power in narrow and deep channels.

Understanding the sediment transport load and the potential of accumulation and transport activities on drainage channels in river basins is of great and critical importance, especially in terms of sustainable geography and basin management (Bizzi and Lerner 2015). SPI values for Iğdır province decrease from 14.6 to -13.8 in the south-north direction from the 5137 m peak to the 788 m depression plain. High values were calculated in the mountainous areas to the west and south of Iğdır. This is because increased gully erosion due to insufficient vegetation. These values show that the potential and risk of downslope surface flow and water erosion are high in the spring months. In other words, the transportation of tuff material in Aralık wind erosion area, which is the second largest one in Türkiye and located in the northeast of the depression plain, is carried out by water erosion.

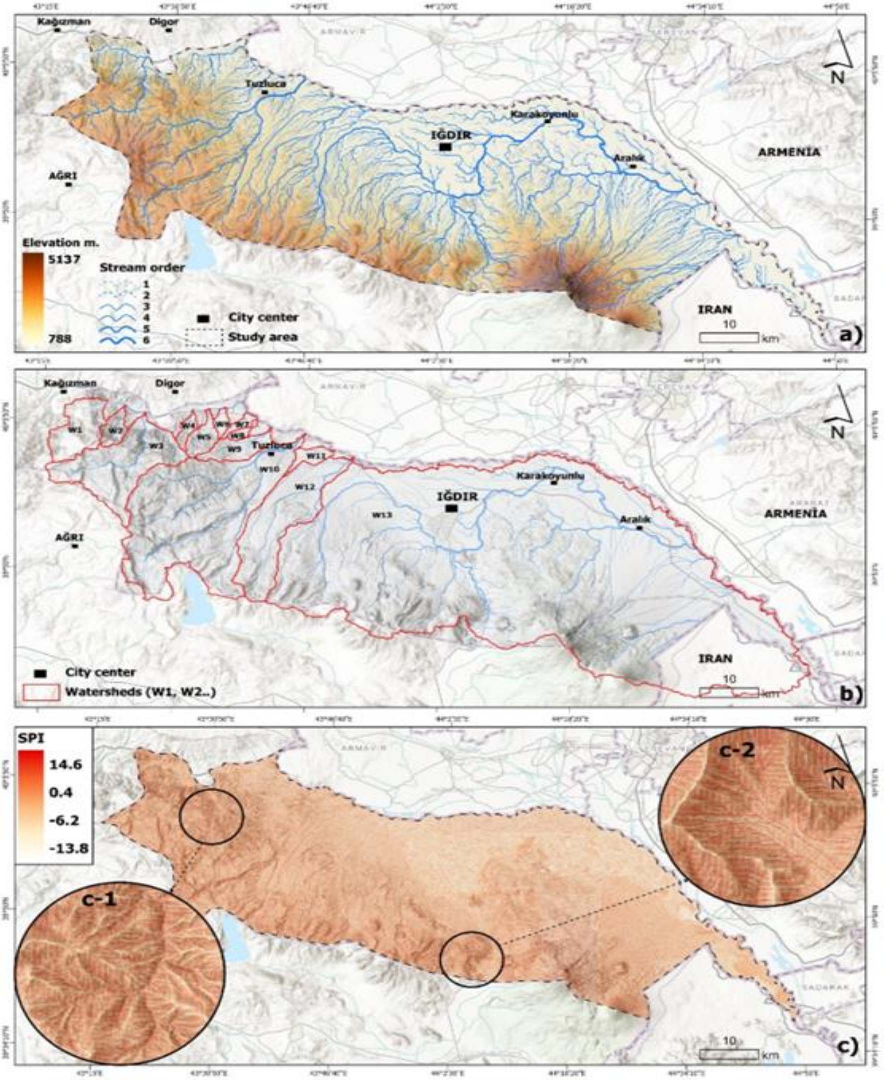

Figure 3. Iğdır province hydrography, sub-basin and SPI distribution map

CONCLUSION

1. The rapid or slow cooling and hardening of magma, the formation of lithosphere, the beginning of geological formations and soil formation, which are the results of each other, are a continuous and dynamic process. The last, rarest, non-increasing and most valuable product of this process is soil.
2. Today, changes continue both underground and above ground as a result of earthquakes, volcanic activities and floods. The soil, which is the most fertile part of the earth, is not static and is in constant change and metamorphosis under the influence of climate, vegetation and humans.
3. Having knowledge about the geological structure of a region will contribute to the healthy and economical conduct of many studies on the ground. It is more suitable for construction on areas consisting of hard rocks. However, since these areas generally have a certain slope and the ground is hard, the cost of construction is high.
4. Flat and almost flat sloped (0-2°) soils are generally deep and are ideal soils for agriculture and especially mechanized agriculture. Since this type of soil is easy to use in all kinds of ways, studies on urbanization are also carried out and important agricultural areas are lost.
5. Obtaining geological and hydrographic maps using GIS methods is of interest to soil scientists as well as geological and mapping engineers. The similarities observed between geological formations and the large soil groups on them can make important contributions to explaining the special situations of the regions.
6. Since the soils in mountainous areas are generally shallow and have a high slope, they are particularly resistant to water erosion and are inevitably carried downhill by heavy rains. This situation negatively affects the soil structure in the plains where the slope and flow end.
7. The most important difference of the Iğdır geological map prepared in this study from previous studies is that the area covered by the determined geological structures and their ratios are calculated.
8. The geological map and the previously prepared map of large soil groups show great similarities in terms of distribution. Significant

structural similarities have been identified between geological structures and the large soil groups on them.

9. Creating a hydrographic map for a region; It is necessary to determine the basin, sub-basin and bifurcation indices. Basin and sub-basin information contributes to the determination of surface flow periods and water erosion risk.
10. SPI values revealed that the erosion, transport and deposition processes of water erosion were strong. Hydrography and topography are formations that affect and are affected by each other. The hydrography of Iğdır province is in the form of seasonal flows in the south-north direction, depending on the topography and climate.
11. The source of wind erosion material, especially tuff, in the Iğdır-Aralık region, which is the second largest wind erosion area in Turkey, is water erosion that occurs in the spring period (March-May).

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CHAPTER 6

THE HAZELNUT MICROBIOME: INTERACTIONS WITH WEEDS, BACTERIAL COMMUNITIES, AND MICROBIAL CONTROL STRATEGIES

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DOI: https://www.doi.org/10.5281/zenodo.18093659

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1. INTRODUCTION

Hazelnut (*Corylus avellana* L.) is a globally important nut crop cultivated extensively across temperate regions, with Türkiye, Italy, and the United States as leading producers (FAO, 2023). The crop's economic value lies in its use for confectionery, oil, and nutraceutical industries. Beyond its commercial importance, hazelnut plays a vital ecological role in agroforestry systems by contributing to biodiversity and soil stability. However, its sustainable production faces multiple biotic and abiotic challenges, including soil degradation, pathogen infection, and competition from weeds (Severino et al., 2022).

In recent years, increasing attention has been devoted to understanding the plant microbiome, the community of bacteria, fungi, archaea, and viruses that inhabit the rhizosphere, phyllosphere, and endosphere of plants (Berg et al., 2020). These microbial communities are not merely passive inhabitants; they actively influence plant nutrition, growth regulation, stress tolerance, and defence mechanisms. In perennial crops such as hazelnut, where long-term soil–plant interactions are critical, the structure and functionality of the microbiome can directly determine productivity and resilience (Compant et al., 2019).

The hazelnut microbiome is a complex and dynamic consortium that mediates plant health through multiple pathways, including nitrogen fixation, phosphorus solubilization, phytohormone production, and antagonism against pathogens. Recent advances in high-throughput sequencing and omics technologies have enabled detailed characterisation of these microbial consortia, revealing both taxonomic and functional diversity across different tissues and ecological conditions (Gómez et al., 2021). Yet, compared to annual crops, studies on hazelnut-associated microbial communities remain relatively limited, especially regarding their interactions with weeds and bacterial populations in orchard ecosystems.

Weeds represent one of the major management challenges in hazelnut orchards. They compete with the main crop for nutrients, water, and light, and can serve as alternate hosts for plant pathogens or insect vectors (Bàrberi et al., 2018). Beyond direct competition, weeds can indirectly affect the microbiome composition by altering soil physicochemical properties and root exudate profiles. Conversely, certain weed species may harbour beneficial microbial taxa that can promote soil health or suppress pathogenic populations. Understanding these tripartite interactions — hazelnut, weeds, and microbiome — is therefore essential for designing ecologically sound management strategies.

Bacteria constitute one of the most influential microbial groups within this system. Beneficial rhizobacteria, such as *Pseudomonas*, *Bacillus*, and *Rhizobium* species, can enhance plant growth and confer biocontrol effects against pathogens through the production of antibiotics, secretion of siderophores, and induction of systemic resistance (Mitter et al., 2019). However, the same environment also supports potentially harmful bacteria, including *Xanthomonas arboricola pv. corylina*, which causes bacterial blight in hazelnut (Scortichini et al., 2020). Balancing these interactions through targeted microbiome management represents a promising frontier in sustainable orchard production.

This chapter examines the intricate relationship between the hazelnut microbiome, weed communities, and bacterial populations. It integrates current findings on microbial diversity, weed-associated microbiota, and microbial-based weed or disease control strategies. The overall aim is to provide a comprehensive synthesis of how microbiome understanding can be harnessed to improve hazelnut health and productivity while minimising chemical inputs. By combining insights from microbiology, plant ecology, and biotechnology, this chapter seeks to highlight microbiome-informed approaches as a cornerstone of next-generation hazelnut orchard management.

2. THE HAZELNUT RHIZOSPHERE MICROBIOME

2.1 Overview of the Rhizosphere Environment

The rhizosphere is the narrow zone of soil directly influenced by plant roots and their exudates. It serves as the primary interface between the plant and the soil microbiome (Philippot et al., 2013). Root exudates—comprising sugars, amino acids, organic acids, and secondary metabolites—act as chemical cues that attract, select, and sustain specific microbial populations. In perennial woody species such as hazelnut (*Corylus avellana* L.), the rhizosphere environment is particularly complex due to long-term root systems, seasonal variation in exudation patterns, and interactions with both beneficial and pathogenic microorganisms (Compant et al., 2019).

The rhizosphere microbiome plays a crucial role in key ecological functions, including nutrient cycling, decomposition of organic matter, and suppression of soilborne diseases. This microbial assemblage typically consists of bacteria, fungi, actinomycetes, and archaea, each playing distinct roles in soil–plant interactions. In hazelnut orchards, the rhizosphere hosts a remarkably diverse microbial community whose structure and function are influenced by factors such as soil type, orchard age, agricultural practices, and weed pressure (Berg et al., 2020; Gómez et al., 2021).

2.2 Composition and Diversity of the Hazelnut Rhizosphere Microbiome

Recent metagenomic studies have revealed that the dominant bacterial phyla in the hazelnut rhizosphere include *Proteobacteria*, *Actinobacteria*, *Bacteroidetes*, *Firmicutes*, and *Acidobacteria* (Lopes et al., 2020). Within these groups, genera such as *Pseudomonas*, *Bacillus*, *Rhizobium*, *Burkholderia*, and *Streptomyces* are frequently reported as core members. These taxa are associated with plant growth–promoting traits, such as nitrogen fixation, phosphate solubilization, siderophore production, and the synthesis of phytohormones like indole-3-acetic acid (IAA) (Mitter et al., 2019).

Fungal communities in the hazelnut rhizosphere are dominated by members of *Ascomycota* and *Basidiomycota*, with frequent detection of *Trichoderma*, *Penicillium*, and *Mortierella* species (Severino et al., 2022). Many of these fungi exhibit antagonistic properties against phytopathogens, contributing to natural disease suppression. Additionally, mycorrhizal associations, particularly ectomycorrhizae, play a significant role in hazelnut nutrient uptake and stress tolerance, facilitating the acquisition of phosphorus and nitrogen while improving soil structure.

Environmental and management factors significantly influence the composition of the microbiome. Organic amendments, such as compost or biochar, tend to increase bacterial diversity and enhance populations of beneficial microorganisms, whereas intensive chemical fertilisation can reduce microbial richness and disrupt ecological balance (Zhou et al., 2021). Moreover, weed management practices, whether mechanical, chemical, or mulching-based, can indirectly alter the rhizosphere microbiota by modifying soil temperature, moisture, and carbon inputs.

2.3 Functional Roles of Rhizosphere Microbes

The functional potential of the hazelnut rhizosphere microbiome extends far beyond its role in providing nutrients. Beneficial bacteria and fungi can modulate root architecture, enhance tolerance to abiotic stress, and inhibit pathogen growth through competitive exclusion or antimicrobial compound production (Barea et al., 2005). For example, *Bacillus subtilis* and *Pseudomonas fluorescens* strains isolated from hazelnut rhizospheres have been shown to suppress *Xanthomonas arboricola pv. corylina*, the causal agent of hazelnut bacterial blight (Scortichini et al., 2020).

Nitrogen fixation by diazotrophic bacteria, such as Azospirillum and Rhizobium species, contributes to soil fertility in low-input systems, while phosphate-solubilising bacteria enhance nutrient availability from insoluble mineral sources (Vessey, 2003). Additionally, certain actinobacteria produce siderophores that chelate iron, making it more accessible to plants while limiting the growth of pathogenic microbes.

Metabolomic analyses suggest that root exudates from hazelnut contain phenolic compounds, fatty acids, and sugars that selectively enrich for beneficial microbial taxa (Gómez et al., 2021). These chemical signals are crucial in establishing mutualistic relationships and maintaining rhizosphere homeostasis. The resulting microbiome is not static but dynamically shifts in response to environmental conditions, plant developmental stage, and management interventions.

2.4 Rhizosphere–Weed–Microbiome Interactions

In hazelnut orchards, weeds influence the rhizosphere microbiome through both direct and indirect mechanisms. Their root systems exude diverse metabolites that shape microbial community structure and competition patterns. Some weed species may serve as reservoirs of beneficial microbes that can later colonise hazelnut roots, while others may harbour deleterious pathogens or allelopathic microbes (Bàrberi et al., 2018). For instance, *Amaranthus retroflexus* and *Convolvulus arvensis*, common weeds in hazelnut orchards, have been shown to alter soil bacterial diversity and functional gene abundance in surrounding rhizospheres (Lopes et al., 2020).

Integrated weed management strategies that preserve soil microbial diversity—such as cover cropping, organic mulching, or reduced herbicide use—tend to foster a more stable and beneficial rhizosphere microbiome. Such practices enhance microbial-mediated nutrient cycling and contribute to the sustainable health of orchards. The balance between weeds, soil microbes, and hazelnut roots represents an ecological equilibrium that, if properly managed, can promote resilience against both biotic and abiotic stressors.

In summary, the hazelnut rhizosphere microbiome plays a vital role in the orchard ecosystem, serving as both a mediator of plant health and a determinant of soil fertility. Its composition reflects complex interactions among plant genotype, soil characteristics, management practices, and weed dynamics. Advances in metagenomic and metabolomic tools continue to deepen our understanding of these relationships, opening avenues for microbiome engineering and bioinoculant development. Strengthening beneficial microbial consortia through ecological management could lead to more sustainable and productive hazelnut systems in the future.

3. ENDOPHYTIC AND EPIPHYTIC MICROBIAL COMMUNITIES

3.1 Introduction to Plant-Associated Microbiota

Plants are colonised by a diverse set of microorganisms that inhabit both external and internal tissues. These microbial communities are typically classified into epiphytes (living on plant surfaces such as leaves, stems, and roots) and endophytes (living within plant tissues without causing disease) (Hardoim et al., 2015). In hazelnut, both groups play vital roles in plant development, disease resistance, and environmental adaptability.

While the rhizosphere microbiome governs nutrient availability and root health, endophytic and epiphytic microbes form a protective and functional interface above and below ground, mediating plant-environment interactions. These communities can directly influence hazelnut productivity by enhancing nutrient assimilation, modulating defence responses, and contributing to biological control of pathogens and pests (Compant et al., 2019).

3.2 Epiphytic Microbial Communities in Hazelnut

The phyllosphere (leaf surface) and carposphere (fruit surface) of hazelnut represent unique habitats with fluctuating environmental conditions—high UV exposure, desiccation, and nutrient scarcity. Despite these stresses, a diverse microbiota colonises these surfaces, dominated by bacteria from the phyla *Proteobacteria*, *Firmicutes*, and *Bacteroidetes* (Müller et al., 2021).

Typical bacterial genera include *Pseudomonas*, *Methylobacterium*, *Sphingomonas*, *Bacillus*, and *Micrococcus*, many of which exhibit traits beneficial to the host plant. For instance, *Pseudomonas* spp. produce siderophores and antimicrobial metabolites that suppress foliar pathogens such as *Botrytis cinerea* and *Monilinia fructigena* (Liu et al., 2020). *Methylobacterium* and *Sphingomonas* species are known to utilise methanol emitted from stomata, forming mutualistic associations that improve plant vigour and stress tolerance (Vorholt, 2012).

Fungal epiphytes are also abundant, with genera such as *Cladosporium*, *Aureobasidium*, and *Alternaria* frequently detected on hazelnut leaves and fruits (Gómez et al., 2021). Some of these fungi act as saprophytes or mild commensals, while others can switch to pathogenic lifestyles under stress conditions. Epiphytic yeasts like *Cryptococcus* and *Rhodotorula* contribute to the degradation of leaf exudates and may suppress harmful fungal spores through niche competition and antifungal compound production (Urbez-Torres et al., 2018).

Management practices and environmental factors strongly affect the composition of epiphytic microbiota. For example, organic orchards tend to support higher microbial diversity on leaves and fruits compared to conventional systems, where the use of pesticides may reduce community complexity (Lopes et al., 2020). Seasonal variation also plays a role, with microbial abundance typically peaking during the early summer when leaf surface moisture and nutrient exudation are optimal.

3.3 Endophytic Microbial Communities

Endophytes inhabit the internal tissues of plants—including roots, stems, leaves, and nuts—without causing apparent harm. They can exist intercellularly or within vascular tissues, establishing stable associations through vertical transmission (via seeds) or horizontal transmission (from soil or insects) (Hardoim et al., 2015).

In hazelnut, both bacterial and fungal endophytes contribute significantly to plant health and resilience. Bacterial endophytes commonly isolated from hazelnut include *Bacillus*, *Pseudomonas*, *Enterobacter*, *Paenibacillus*, and

Burkholderia species (Scortichini et al., 2020). Many of these produce lytic enzymes (such as chitinases and glucanases), siderophores, and phytohormones that promote plant growth and suppress pathogens. *Bacillus subtilis* strains, for instance, have demonstrated antagonistic activity against *Xanthomonas arboricola pv. corylina*, one of the most destructive hazelnut bacterial pathogens (Severino et al., 2022).

Fungal endophytes, particularly species of *Trichoderma*, *Penicillium*, and *Epicoccum*, are associated with enhanced plant resistance and stress adaptation. *Trichoderma harzianum* isolates from hazelnut roots have been shown to stimulate root growth and reduce disease incidence under field conditions (Marra et al., 2021). These fungi can induce systemic resistance (ISR) through jasmonic acid and ethylene signalling pathways, improving hazelnut's ability to withstand pathogen invasion and abiotic stresses.

Endophytic communities also play a role in secondary metabolite production, influencing the flavour, aroma, and nutritional quality of hazelnuts. Metabolomic profiling indicates that certain endophytes can modulate the biosynthesis of phenolic compounds, flavonoids, and fatty acids—key determinants of nut quality and antioxidant capacity (Severino et al., 2022).

3.4 Functional Interactions and Ecological Roles

Endophytic and epiphytic microorganisms engage in multiple ecological functions:

A. **Plant growth promotion – Endophytic bacteria synthesise** auxins, gibberellins, and cytokinins, directly influencing plant growth and development.

B. **Stress tolerance enhancement – Some endophytes produce** ACC deaminase, which reduces ethylene levels under stress, thereby promoting improved root growth.

C. **Biocontrol of pathogens – Both epiphytic and endophytic microbes** inhibit pathogens through competition, antibiosis, and induced resistance.

D. **Nutrient mobilisation – Endophytic fungi and bacteria** enhance the uptake of phosphorus, iron, and micronutrients from soil.

E. **Environmental detoxification – Microbes degrade harmful compounds**, including pesticide residues and phenolic toxins, contributing to soil remediation (Barea et al., 2005).

The balance between beneficial and potentially pathogenic endophytes is influenced by plant genotype, environmental stress, and agricultural practices. For example, excessive pesticide use can disrupt microbial equilibrium, potentially allowing opportunistic pathogens to colonise internal tissues. Conversely, sustainable practices such as biofertilizer application or organic amendments foster beneficial endophyte colonisation (Zhou et al., 2021).

3.5 Endophyte–Weed–Hazelnut Interactions

Weeds in hazelnut orchards can act as microbial reservoirs, hosting diverse endophytic bacteria and fungi capable of transferring to nearby hazelnut plants. Some of these microbes may confer benefits, such as improved stress tolerance or disease suppression, while others could introduce competition or pathogenic risk (Bàrberi et al., 2018).

Studies in other perennial systems show that endophytes from weed roots, such as *Pseudomonas putida* and *Bacillus amyloliquefaciens*, can colonise crop roots and stimulate plant growth (Gao et al., 2020). Exploring such cross-species microbial exchanges in hazelnut orchards may reveal novel bioinoculant candidates for sustainable management.

In summary, endophytic and epiphytic microbial communities constitute integral components of the hazelnut holobiont. Their collective functions—ranging from growth promotion and disease suppression to metabolite enhancement—underscore their ecological and agricultural importance. Understanding these complex microbial networks opens opportunities to develop bioinoculant-based management strategies that complement or replace chemical inputs in hazelnut cultivation.

Future research integrating multi-omics approaches and ecological modelling will be essential to unravel the functional interconnections among hazelnut, its microbial partners, and associated weeds.

4. WEED–MICROBIOME INTERACTIONS IN HAZELNUT ORCHARDS

4.1. Ecological Role of Weeds in Orchard Ecosystems

Weeds are often perceived solely as competitors for nutrients, water, and light. However, in the context of hazelnut (*Corylus avellana* L.) orchards, weeds can also exert subtle ecological influences through their interactions with soil microbial communities. Weeds modify the soil environment via root exudation, organic matter deposition, and rhizosphere microbial recruitment (Storkey & Neve, 2018). These belowground interactions can affect not only the composition and diversity of the weed-associated microbiota but also the overall microbiome structure of adjacent hazelnut plants.

In hazelnut orchards, the persistence of certain perennial weeds such as *Convolvulus arvensis*, *Cirsium arvense*, *Elymus repens*, and *Taraxacum officinale* often indicates the presence of stable microbial consortia adapted to low-disturbance, nutrient-limited environments (Molinari et al., 2020). While conventional management aims to eliminate these species, emerging evidence suggests that moderate weed cover can maintain soil microbial activity, protect against erosion, and enhance beneficial mycorrhizal networks (Hartwig & Ammon, 2002). Therefore, weeds play a dual ecological role, as competitors and as microbial facilitators, depending on the intensity and timing of management interventions.

4.2. Weed Rhizosphere as a Reservoir of Microbial Diversity

The rhizosphere of weeds represents a microbial hotspot where diverse bacterial and fungal populations coexist, many of which possess plant growth-promoting or biocontrol properties. These include *Pseudomonas fluorescens*, *Bacillus subtilis*, *Azospirillum brasilense*, and *Rhizobium leguminosarum*, among others (Kaur et al., 2021). Such taxa are known for producing phytohormones (auxins, gibberellins), solubilising phosphorus, fixing nitrogen, and synthesising siderophores that limit pathogen proliferation.

In hazelnut orchards, weeds can serve as microbial reservoirs, maintaining populations of beneficial bacteria during periods of fallow or stress when hazelnut roots are less active. When weed management is performed gradually or selectively (rather than through complete herbicidal removal), these microbial communities can recolonise hazelnut roots, thereby enhancing resilience and productivity. For example, *Trifolium repens* and *Medicago lupulina*, both common in Mediterranean orchards, host rhizobia that may indirectly improve hazelnut nitrogen dynamics through microbial spillover effects (Ferreira et al., 2022).

4.3. Allelopathic Weeds and Microbiome Shifts

Particular weed species exert allelopathic effects that disrupt hazelnut growth either directly through phytotoxic compounds or indirectly by altering soil microbial networks. For instance, *Avena fatua* and *Sorghum halepense* release phenolic acids and benzoxazinoids that suppress root elongation and microbial symbioses (Macías et al., 2019). These compounds can selectively inhibit beneficial bacterial taxa, such as *Bradyrhizobium* and *Bacillus*, resulting in reduced nitrogen fixation and weakened plant defence responses.

Conversely, some weeds produce exudates that stimulate beneficial microbes. *Plantago lanceolata*, for example, secretes mucilage that enhances microbial polysaccharide production, improving soil aggregation and water retention. Understanding these species-specific effects is critical for designing microbiome-informed weed management practices that minimise harm while preserving microbial ecosystem services.

4.4. Weed Management and Microbiome Engineering

Traditional weed control in hazelnut orchards relies heavily on chemical herbicides such as glyphosate, glufosinate, and oxyfluorfen. However, repeated herbicide application can disrupt soil microbiota, decrease microbial biomass, and select for resistant microbial strains with altered metabolic capacities (Nguyen et al., 2018). Furthermore, herbicide residues can interfere with microbial enzymatic pathways, impairing nitrogen cycling and organic matter decomposition.

Recent research supports microbiome-based weed management, an approach that integrates ecological and microbial principles. Strategies include:

- **Cover cropping and mulching:** Using cover crops such as vetch or clover can suppress weeds while enhancing beneficial bacterial populations (e.g., *Bacillus*, *Paenibacillus*, *Rhizobium*).
- **Bioherbicides:** Leveraging microbial metabolites (from *Pseudomonas* or *Streptomyces*) that selectively inhibit weed germination without harming crops.

- **Biostimulants:** Applying microbial consortia to improve hazelnut competitiveness and reduce weed establishment.
- **Soil microbiome restoration:** Introducing beneficial microbial inoculants following herbicide use to reestablish functional microbial networks.

These eco-compatible practices reduce chemical inputs and foster a balanced microbiome that supports both weed suppression and hazelnut vigour. The long-term goal is to transition from eradication-oriented weed control toward ecological coexistence that harnesses the beneficial aspects of the weed–microbiome interface.

5. BACTERIAL PATHOGENS AND BIOCONTROL IN HAZELNUT ORCHARDS

5.1. Overview of Bacterial Diseases Affecting Hazelnut

Bacterial pathogens represent a significant threat to hazelnut (*Corylus avellana* L.) production worldwide. Among them, *Xanthomonas arboricola* pv. *corylina* (Xac) is the most destructive, causing bacterial blight — a disease characterised by bud necrosis, shoot dieback, and canker formation (Scortichini et al., 2020). This pathogen thrives in humid, cool conditions, typically infecting young shoots and leaves through natural openings or wounds. Once established, it colonises xylem vessels, disrupting water transport and inducing systemic wilt symptoms.

In addition to *X. arboricola*, other bacterial taxa such as *Pseudomonas syringae*, *Erwinia amylovora*, and *Agrobacterium tumefaciens* have been sporadically reported in hazelnut orchards, particularly under stress conditions or after pruning injuries (Cardinale et al., 2022). These opportunistic bacteria can aggravate disease complexes, leading to yield losses and increased susceptibility to secondary infections.

5.2. Pathogen Ecology and Environmental Factors

The epidemiology of bacterial diseases in hazelnut is tightly linked to climatic and edaphic factors. Prolonged leaf wetness, high humidity, and moderate temperatures (18–24 °C) favour *X. arboricola* multiplication and dispersal (Pothier et al., 2011). The bacterium overwinters in dormant buds, fallen debris, and soil residues, forming a persistent inoculum reservoir. Spring rainfall and pruning operations further facilitate pathogen dissemination through splash and mechanical contact.

The composition of the soil microbiome plays a crucial role in modulating disease severity. Microbially diverse soils generally exhibit “disease suppressiveness”, where antagonistic microorganisms compete for niches and nutrients, produce antibiotics, or induce systemic resistance in plants (Berendsen et al., 2012). Conversely, orchard soils with reduced microbial diversity — often a consequence of herbicide or copper overuse — tend to show higher pathogen incidence. Understanding the microbial ecology of hazelnut rhizospheres is thus crucial for sustainable management of bacterial diseases.

5.3. Beneficial Bacteria and Antagonistic Interactions

Several bacterial genera have demonstrated strong antagonistic effects against *X. arboricola* and other pathogens of hazelnuts. Chief among them are Bacillus, Pseudomonas, and Streptomyces species, known for their ability to produce secondary metabolites such as lipopeptides, siderophores, and antibiotics (Compant et al., 2019).

- *Bacillus subtilis* and *B. amyloliquefaciens* produce iturin, fengycin, and surfactin, which inhibit pathogen cell membrane integrity.
- *Pseudomonas fluorescens* secretes 2,4-diacetylphloroglucinol (DAPG) and pyoluteorin, compounds that suppress bacterial and fungal pathogens while promoting plant systemic resistance.
- *Streptomyces* spp. Contribute to the production of volatile organic compounds (VOCs) that inhibit *Xanthomonas* colonisation in planta.

Such antagonistic bacteria not only suppress disease agents but also enhance hazelnut root growth, nutrient uptake, and stress tolerance. Field inoculations in Mediterranean orchards have shown that *Bacillus velezensis* strains can reduce blight incidence by over 60% compared to untreated controls (Scortichini & Marchesi, 2021).

5.4. Biological Control Mechanisms

The modes of action of bacterial biocontrol agents (BCAs) can be broadly classified into four mechanisms:

1. **Competition for Resources and Niches:** Beneficial bacteria colonise root surfaces and outcompete pathogens for carbon sources and attachment sites, thereby reducing pathogen establishment.

2. **Antibiosis and Lytic Enzyme Production:** Many BCAs produce antibiotics (e.g., DAPG, phenazines) and enzymes (chitinases, glucanases) that degrade pathogen cell walls or inhibit biofilm formation.
3. **Induced Systemic Resistance (ISR):** Certain rhizobacteria trigger host immune pathways via jasmonic acid and ethylene signalling, priming hazelnut defence responses without direct pathogen attack.
4. **Quorum Sensing Interference:** Some antagonists disrupt the quorum-sensing systems of pathogens, preventing the coordinated expression of virulence genes essential for infection.

The integration of these mechanisms contributes to a multi-layered defence in hazelnut plants, resulting in more stable and durable disease resistance.

5.5. Microbial Consortia and Bioformulation Development

Recent advances in microbiome research have shifted focus from single-strain inoculants to microbial consortia, where complementary bacterial taxa are co-formulated to enhance efficacy and stability. For hazelnut, consortia combining *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Trichoderma harzianum* have shown synergistic effects in suppressing *X. arboricola* infections and improving root vigour under field conditions (Benítez et al., 2022).

Bioformulation technologies now aim to enhance bacterial survival and shelf life through encapsulation in alginate beads, biochar carriers, or polymeric films. Such formulations maintain microbial viability and facilitate gradual release into the rhizosphere, ensuring long-term colonisation. Combining these formulations with prebiotics (e.g., humic acids, chitosan) can further promote beneficial bacterial proliferation.

5.6. Integrating Biocontrol with Orchard Management

For maximum effectiveness, biocontrol strategies should be integrated into a holistic orchard management framework that includes:

- Minimising copper and synthetic chemical use to prevent disruption of beneficial microbiota.
- Encouraging weed species that harbour antagonistic bacteria.

- Implementing pruning and sanitation measures to limit pathogen entry points.
- Incorporating organic amendments (e.g., compost, manure) that enhance microbial diversity and nutrient cycling.

Ultimately, the goal is to establish a resilient orchard microbiome where beneficial bacteria dominate ecological niches, suppress pathogens, and sustain long-term hazelnut productivity.

6. Microbiome-Based Weed Suppression Strategies in Hazelnut Orchards

6.1. Transitioning from Chemical to Biological Weed Control

Conventional hazelnut orchard management has long depended on synthetic herbicides such as glyphosate, glufosinate, and oxyfluorfen for weed suppression. While effective, these chemicals present multiple drawbacks, including soil microbiome disruption, reduced microbial biodiversity, accumulation of toxic residues, and negative impacts on pollinators and non-target organisms (Nguyen et al., 2018). Moreover, prolonged herbicide dependence can lead to the evolution of herbicide-resistant weed biotypes, complicating long-term management.

In contrast, microbiome-based weed control leverages naturally occurring microbial processes and metabolites to suppress weed germination, growth, or competitiveness. This approach emphasises ecological compatibility, aiming not to eradicate weeds entirely but to maintain a balanced orchard ecosystem where beneficial microbes and plants coexist harmoniously. Such strategies can reduce chemical reliance while enhancing soil fertility, water retention, and disease resistance in hazelnut orchards (Kaur et al., 2021).

6.2. Mechanisms of Microbial Weed Suppression

Microorganisms can interfere with weed establishment through several key mechanisms:

A. **Allelochemical Production:** Certain rhizobacteria and actinomycetes produce allelochemicals that inhibit seed germination or root elongation of weeds. For example, *Pseudomonas fluorescens* synthesises phenolic compounds and hydrogen cyanide (HCN) that suppress weed species such as *Amaranthus retroflexus* and *Chenopodium album* (Inderjit & Weston, 2003).

B. **Resource Competition:** Beneficial microbes compete with weed-associated microbes for nutrients and root colonisation sites, limiting the establishment of weed-favourable microbiota.

C. **Enzymatic Degradation of Weed Exudates:** Some bacteria degrade allelopathic compounds released by invasive weeds, reducing their competitive advantage over hazelnut roots.

D. **Soil Microbiome Reprogramming:** By inoculating soils with tailored microbial consortia, it is possible to shift microbial networks toward communities that suppress weed-promoting microbes or pathogens.

Collectively, these microbial functions can be integrated into holistic weed management strategies aligned with sustainable hazelnut production.

6.3. Bacterial Bioherbicides and Their Potential

Bioherbicides are microbial formulations, either living cells or their metabolites, that selectively suppress weeds. They have emerged as a promising alternative for orchard systems where mechanical control is limited and chemical regulation is increasingly restricted.

Prominent bacterial genera with bioherbicidal activity include:

- *Pseudomonas* spp. – produce toxins and secondary metabolites that inhibit seed germination of *Echinochloa crus-galli* and *Setaria viridis*.
- *Xanthomonas campestris* – certain nonpathogenic strains release lytic enzymes and organic acids that disrupt weed cuticles.
- *Bacillus* spp. – generate volatile compounds such as acetoin and 2,3-butanediol that interfere with weed hormonal signalling (Duke et al., 2020).
- *Streptomyces* spp. – known for producing phenazine-type antibiotics and herbicidal metabolites like thaxtomin A.

When applied to hazelnut orchards, these microbial agents can reduce weed cover without disturbing beneficial plant–microbe associations, unlike nonselective herbicides. Moreover, many bioherbicides enhance soil organic matter and microbial enzyme activity, supporting overall orchard health.

6.4. Allelopathic and Rhizosphere-Active Bacteria

Microbiome-based weed management also exploits allelopathic bacteria, which are microorganisms that release phytotoxic compounds that naturally inhibit competing plants. Rhizobacteria isolated from hazelnut orchard soils—particularly *Pseudomonas putida*, *Bacillus cereus*, and *Burkholderia gladioli*—have been reported to produce compounds such as indole derivatives, phenolics, and organic acids that selectively inhibit the elongation of weed roots (Ferreira et al., 2022).

These bacteria often act synergistically with plant roots, modulating the release of hazelnut root exudates and enhancing selective allelopathic interactions. Some strains even induce hazelnut-mediated allelopathy, amplifying the plant's own ability to suppress weeds via root exudation of flavonoids and terpenoids.

6.5. Engineering Soil Microbiomes for Weed Suppression

With advances in metagenomics, transcriptomics, and synthetic biology, it is now feasible to engineer soil microbial consortia with targeted weed-suppressive traits. These engineered communities can be designed to:

- Maintain a high abundance of beneficial taxa (*Bacillus*, *Paenibacillus*, *Pseudomonas*).
- Support decomposition of weed seedbanks through enzymatic activity.
- Promote beneficial fungal–bacterial interactions that outcompete weed-associated microbiota.

Techniques such as microbiome transplantation—the transfer of entire beneficial soil microbial communities from suppressive to infested soils—are also being explored in hazelnut systems. Early field studies indicate that such interventions can reduce weed emergence by up to 40% while improving hazelnut growth parameters (Ruzzi et al., 2023).

6.6. Integration with Sustainable Orchard Practices

To maximise the benefits of microbiome-based weed suppression, these approaches must be integrated with other sustainable practices, including:

- **Cover cropping and mulching:** suppresses weed germination while feeding beneficial microbes with root exudates.

- **Reduced tillage systems:** preserve soil microbial structure and organic matter content.
- **Organic amendments (such as compost and manure)** promote microbial proliferation and nutrient cycling.
- **Biodiversity corridors maintain microbial and plant diversity, which stabilis**es orchard ecosystems.

Together, these strategies contribute to a self-regulating orchard microbiome, minimising weed competition and maintaining ecological balance without reliance on chemical herbicides.

7. INTEGRATING MULTI-OMICS APPROACHES TO STUDY HAZELNUT–MICROBIOME–WEED INTERACTIONS

7.1. The Rationale for Multi-Omics Integration

The complexity of interactions among hazelnut plants, their microbiomes, and surrounding weed communities cannot be fully understood through classical microbiological methods alone. Traditional culture-dependent techniques capture only a small fraction—typically less than 5%—of the total microbial diversity present in soil or plant tissues (Vartoukian et al., 2010). Multi-omics approaches—comprising metagenomics, metatranscriptomics, metaproteomics, and metabolomics—enable comprehensive insights into the structure, function, and dynamics of microbial communities under various ecological and management conditions.

By integrating these omics layers, researchers can identify the microbial taxa present, determine which genes are actively expressed, and characterize metabolites mediating plant–microbe–weed interactions. Such a holistic understanding provides the foundation for developing targeted microbiome manipulation strategies that enhance hazelnut health, nutrient use efficiency, and weed suppression potential (Bulgarelli et al., 2013).

7.2. Metagenomics: Profiling Microbial Community Structure

Metagenomics involves sequencing all genetic material present in an environmental sample, allowing the identification of microbial taxa and their functional genes without the need for cultivation. In hazelnut orchards, metagenomic studies can reveal how soil management, weed diversity, and seasonal changes shape the microbial community composition (Ruzzi et al., 2023).

Applications include:

- Characterising core microbiomes in hazelnut roots and rhizospheres.
- Detecting weed-associated microbes that either promote or inhibit hazelnut growth.
- Assessing impacts of herbicides or organic amendments on microbial diversity and functional potential.

Shotgun sequencing technologies (e.g., Illumina NovaSeq, Oxford Nanopore) now permit deep metagenomic coverage, enabling the reconstruction of metagenome-assembled genomes (MAGs) and the identification of novel genes related to nitrogen fixation, phosphorus solubilization, and allelochemical degradation.

7.3. Metatranscriptomics: Decoding Active Microbial Functions

While metagenomics reveals genetic potential, metatranscriptomics identifies which genes are actively expressed under specific environmental conditions. This approach provides dynamic insights into microbial responses to biotic and abiotic factors, such as weed interference, nutrient fluctuations, or pathogen attack (Yuan et al., 2021).

In hazelnut systems, metatranscriptomic profiling can identify:

- Genes linked to stress resilience (e.g., heat shock proteins, catalases).
- Expression of allelopathic biosynthetic pathways triggered by weed root exudates.
- Microbial signalling molecules involved in rhizosphere communication.

Such analyses allow researchers to pinpoint keystone taxa—microbes whose functional activity disproportionately influences orchard health and weed suppression.

7.4. Metabolomics: Chemical Dialogue Between Hazelnut, Microbes, and Weeds

Metabolomics investigates the small molecules (<1500 Da) produced by plants and microbes that mediate their interactions. In hazelnut–weed systems, metabolomic studies can uncover root exudates, microbial secondary metabolites, and allelochemicals shaping rhizosphere ecology (Chaparro et al., 2012).

Key applications include:

- Profiling hazelnut root exudates in the presence and absence of specific weed species.
- Identifying microbial metabolites with herbicidal or plant growth-promoting activity.
- Linking metabolite production to metagenomic and transcriptomic data to build integrated pathway maps.

Mass spectrometry (LC–MS/MS, GC–MS) and nuclear magnetic resonance (NMR) spectroscopy are the primary analytical platforms used for these studies.

7.5. Metaproteomics: Functional Validation of Microbial Processes

Metaproteomics complements other omic layers by directly analysing the proteins produced by microbial communities. It enables the quantification of enzymes involved in nutrient cycling, defence, and allelochemical degradation. In hazelnut orchard soils, metaproteomics can reveal the expression of phosphatases, dehydrogenases, and peroxidases linked to beneficial microbial activity (Bastida et al., 2019).

Integrating metaproteomics with metagenomics allows for functional annotation of microbial genes and the validation of active biochemical pathways influencing weed suppression and plant performance.

7.6. Bioinformatics and Systems Biology Integration

The massive datasets generated from multi-omics analyses require advanced bioinformatics pipelines and systems biology frameworks to extract biologically meaningful insights. Key computational tools include:

- QIIME2, Kraken2, and MetaPhlAn3 for taxonomic profiling.

- KEGG, MetaCyc, and EggNOG databases for functional annotation.
- Cytoscape and CoNet for microbial network visualisation.
- Machine learning models (e.g., random forests, neural networks) to predict microbial functions associated with hazelnut health or weed suppression (Langille et al., 2013).

Through multi-omics data integration, it becomes possible to construct holistic interaction maps illustrating how specific microbial taxa and metabolites influence hazelnut performance under diverse weed management systems. Such predictive frameworks lay the groundwork for precision microbiome engineering—the deliberate design of beneficial microbial communities tailored to hazelnut orchard conditions.

7.7. Challenges and Future Directions

Despite technological advances, multi-omics research in perennial orchard systems faces several challenges:

- Difficulty in distinguishing plant, microbial, and weed-derived molecules in mixed samples.
- High cost and data complexity requiring multidisciplinary expertise.
- Limited reference genomes for orchard-associated microbes.
- Need for long-term field validation of omics-derived hypotheses.

Future research should emphasise longitudinal sampling, cross-seasonal analyses, and integration with environmental metadata (e.g., soil type, microclimate, management history). The ultimate goal is to translate omics knowledge into actionable tools—bioindicators, predictive models, and microbiome-based products—that support sustainable hazelnut and weed management.

8. PRACTICAL APPLICATIONS AND FUTURE PROSPECTS FOR MICROBIOME-BASED HAZELNUT AND WEED MANAGEMENT

8.1. Translating Microbiome Knowledge into Agricultural Practice

The integration of microbiome science into hazelnut orchard management offers an unprecedented opportunity to improve productivity, sustainability, and ecological balance. However, to transform omics-based discoveries into actionable outcomes, it is necessary to bridge the gap between laboratory insights and field-scale implementation (Sessitsch & Mitter, 2021).

Practical translation requires:

- Validated microbial inoculants specifically adapted to hazelnut rhizospheres.
- Microbiome-friendly management practices, such as reduced tillage, organic amendments, and diversified cover crops.
- Monitoring frameworks using microbial indicators of soil health and weed pressure.

Such strategies should align with local environmental regulations and support the ecological integrity of surrounding habitats, particularly in the sensitive Mediterranean and Black Sea regions, where hazelnut cultivation is predominant.

8.2. Microbial Inoculants and Bioformulations

Microbial inoculants, including beneficial bacteria such as *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azospirillum brasilense*, have shown strong potential for enhancing nutrient uptake, suppressing soil-borne pathogens, and indirectly reducing weed competitiveness (Compant et al., 2019).

Recent developments in consortia-based bioformulations—combinations of complementary microbial strains—have demonstrated greater effectiveness than single-strain inoculants. These consortia can perform multiple functions simultaneously, such as:

- Promoting root growth through phytohormone (IAA, gibberellin) production.
- Solubilising phosphorus and mobilising micronutrients.
- Producing allelochemical analogues that suppress weed germination.
- Inducing systemic resistance (ISR) in hazelnut roots against bacterial and fungal pathogens.

Field trials are crucial for validating the persistence and performance of these inoculants under real orchard conditions, where environmental variability significantly affects microbial colonisation dynamics.

8.3. Weed–Microbiome–Hazelnut Triad: A Holistic Management Concept

Traditionally, weed control in hazelnut systems has relied heavily on the use of herbicides or mechanical removal. However, such practices can disrupt beneficial microbial networks, alter soil chemistry, and promote the development of herbicide-resistant weed populations (Chauhan & Johnson, 2011).

The weed–microbiome–hazelnut triad framework fosters an ecological balance in which each component supports system-level sustainability. In this model:

- Microbial communities are managed as allies, not merely as background biota.
- Weeds are considered reservoirs of both beneficial and harmful microbes.
- Hazelnut root exudates serve as chemical mediators that shape microbial assembly.

By optimising this triad, growers can design microbiome-informed weed management programs that reduce dependence on chemicals and enhance ecosystem resilience.

8.4. Next-Generation Tools for Precision Microbiome Management

Emerging digital and biotechnological innovations are accelerating the practical application of microbiome research:

A. High-Throughput Sequencing and AI-Based Prediction Models

a. Artificial intelligence (AI) and machine learning (ML) algorithms analyse complex omics datasets to identify microbial signatures linked to hazelnut productivity or weed suppression (Tripathi et al., 2022).

b. Predictive modelling supports targeted inoculant design and adaptive management decisions.

B. CRISPR-Based Microbiome Engineering

a. Genome-editing tools like CRISPR-Cas9 are being explored to enhance beneficial traits in soil bacteria (e.g., nitrogen fixation efficiency, allelopathic compound production).

   b. Ethical and biosafety frameworks must accompany such innovations to ensure ecological safety and sustainability.

C. Biosensors and Environmental Monitoring Systems

   a. Portable biosensors detecting microbial biomarkers (enzymes, volatile organic compounds) provide real-time monitoring of orchard soil health.
   b. Integration with Internet of Things (IoT) platforms allows remote tracking of microbial dynamics and environmental parameters.

D. Decision Support Systems (DSS) for Growers

   a. DSS tools that incorporate microbiome and weed data help optimise irrigation, nutrient management, and biological control measures, ensuring site-specific sustainability.

8.5. Policy And Socioeconomic Perspectives

Successful implementation of microbiome-based approaches depends not only on scientific innovation but also on policy frameworks, farmer education, and market incentives (FAO, 2022).

- Governments should support research and development of biological alternatives to herbicides through grants and certification programs.
- Extension services must train growers in microbiome-friendly practices.
- International collaboration is essential to harmonise standards for microbial inoculants and environmental biosafety.

Microbiome technologies should also be made economically accessible to small-scale farmers, who form the backbone of hazelnut production in regions like Turkey, Italy, and Georgia.

8.6. Future Research Directions

Several research gaps remain in the field of hazelnut microbiome and weed management:

A. **Long-Term Multi-Omics Monitoring:** Seasonal and interannual variation of rhizosphere microbiomes under different management regimes.

B. **Microbial Ecology of Weed Species:** Identification of weed species harboring beneficial microbes that could be harnessed for biological control.
C. **Network Modelling of Microbial Interactions:** Elucidation of keystone taxa mediating competition between hazelnut roots and weeds.
D. **Microbiome-Based Biocontrol Agents**: Exploration of rhizobacteria producing natural herbicidal metabolites as eco-friendly alternatives to synthetic herbicides.
E. **Integration with Climate-Smart Agriculture:** Understanding how temperature, moisture, and CO_2 fluctuations reshape hazelnut–microbiome–weed relationships.

9. CONCLUSIONS

The convergence of microbiome research, weed ecology, and precision agriculture marks a transformative era for hazelnut production systems. Harnessing the power of beneficial microbes can:

- Enhance nutrient cycling and soil fertility,
- Reduce reliance on chemical herbicides,
- Improve hazelnut resistance to stress,
- Foster sustainable and climate-resilient orchard ecosystems.

Ultimately, the microbiome-centred paradigm reframes hazelnut cultivation as a living network of biological interactions rather than a monocultural system. By embracing microbial allies and understanding their relationships with weeds, growers and researchers can co-create a future where productivity, biodiversity, and sustainability coexist harmoniously.

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