International Perspectives on Innovative Methods in Agriculture and Forestry Researches

Editor

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FOREWORD

When the new technologies and new-generation agricultural applications in the field of agriculture was examined, many topics and different applications is encountered . These technological developments aim to support the transition to sustainable systems, increase efficiency and productivity in production, reduce environmental pressures, and ensure food security. Among these technologies, precision agriculture, automation technologies in agriculture, drone applications, vertical farming varieties, soilless farming applications, artificial intelligence-supported product tracking, Internet of Things (IoT)-based irrigation systems, and autonomous agricultural machinery stand out. New generation agricultural applications are used in areas such as detecting diseases and pests in plants, providing the plant nutrients needed for crops, reducing the amount of plant protection products and fertilizers used, coordinating the water needs of plants and soil, monitoring product quality, and estimating production yield.

Additionally, with these technologies, processes such as seeding, irrigation, and fertilization can be carried out with robotic systems, minimizing human error. Automation systems used in agriculture can control all production in a closed area. Unmanned agricultural machines, which work with image processing systems and are moved by algorithm commands, can intervene only in the area where it is needed, such as weed control. With the precise and accurate application of automation technologies used in agricultural production for spraying and fertilizing, it is possible to increase production efficiency, reduce economic damage, and protect human and environmental health.

In conclusion, the new generation of agricultural technologies shaped by the Agriculture 4.0 approach represents an agricultural transformation that goes beyond increasing production efficiency and integrates environmental sustainability, resource efficiency, and rural development goals.

The book titled “**International Perspectives on Innovative Methods in Agriculture and Forestry Researches**” consists of six chapters that exemplify innovative approaches. The chapter titled “*Innovative Approaches to Energy Use in Agricultural Irrigation*” examines innovative approaches in agricultural irrigation; the chapter titled “*Biological Control of Macrophomina phaseolina: Microbial Agents and Mechanisms*” discusses microbial agents used in the biological control of the ***Macrophomina phaseolina*** fungus. The chapter titled “*Management of overwintering sites and integrated approaches for the brown marmorated stink bug-**Halyomorpha halys***” examines the management of overwintering sites and integrated approaches against the brown marmorated stink bug, which has increased significantly in our country in recent years.

The chapter titled “*Post-Wildfire Soil Measurement Methods*” examines post-fire soil measurements, while the section titled “*The Unseen Hazard: A Technical Analysis of Post-Wildfire Soil Evolution and its Impact on Geotechnical Stability*” analyzes the evolution of soil after a forest fire and its impact on geotechnical stability. Additionally, the chapter titled *“Digital Transformation in Irrigation: Efficiency and Sustainability in Water Management Through Smart Technologies”* explores the role of digitalization, smart technologies, and data-driven systems in enhancing irrigation efficiency and promoting sustainable water resource management.

We hope that these valuable and important sections will be useful to all our colleagues and anyone interested in the issues in terms of **Innovative Approaches in Agriculture and Forestry**.

Prof. Dr. Alaeddin BOBAT

Editor

CHAPTER I

INNOVATIVE APPROACHES TO ENERGY USE IN AGRICULTURAL IRRIGATION

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1. INTRODUCTION

Water and energy are two indispensable resources for sustaining life and carrying out economic activities. Over time, the secure, sustainable, and equitable distribution of these resources has become a major global challenge. Increasing population, urbanization, industrialization, and food demand have sharply intensified the need for both water and energy. This growing demand for water and energy affects all stages of the food production chain, turning it into a factor that threatens global food security. Today, more than 2.33 billion people worldwide experience varying degrees of food insecurity, and approximately 800 million people face the problem of undernourishment. With the global population continuing to rise, this trend is expected to intensify further in the coming years (FAO, 2024; Fitton et al., 2019).

At the global scale, the impacts of climate change on the water cycle directly threaten energy supply security and food production systems. Irregularities in precipitation patterns, prolonged droughts, and rising temperatures increase the dependence of agricultural production on water, leading to a growing demand for irrigation. This increase, in turn, entails higher energy consumption and renders the water-energy-food nexus more fragile.

Modern irrigation practices play a critical role in ensuring the sustainability of food production; however, they not only contribute to increased water consumption but also require high levels of energy input (Rosa et al., 2021). This process amplifies carbon emissions associated with energy use and accelerates environmental degradation (Daccache et al., 2014; Yang et al., 2023). The interdependence between water and energy creates a feedback loop in which water scarcity triggers greater energy consumption, consequently elevating greenhouse gas emissions and undermining the long-term sustainability of agricultural systems (Bhatti et al., 2024). Therefore, integrated approaches to agricultural energy management and water efficiency have become a strategic necessity for both the conservation of water resources and the reduction of the carbon footprint.

The agricultural sector is among the most intensive users of water resources globally. The deepening global warming crisis and the increasing climatic variability affecting agricultural production models in tropical regions are exerting growing pressure on food production systems (Muhammed et al., 2024). Agricultural production is a sector that is highly dependent on direct energy inputs. Processes such as soil tillage, fertilizer and pesticide production, harvesting, transportation, and particularly irrigation require substantial amounts of energy. Energy use in agriculture is not limited to direct electricity or fuel consumption; it also occurs indirectly, such as the production of agricultural inputs, especially the synthesis of nitrogenous fertilizers (Pawar and Pathak, 2018).

The efficiency of energy use in agricultural irrigation lies at the core of today's sustainable production policies and climate change mitigation strategies. Since the energy consumption of irrigation systems directly affects both production costs and carbon emissions, improving energy efficiency has become not only an economic necessity but also an environmental imperative. In this context, smart irrigation systems, renewable energy-based pumping technologies, and data-driven energy management approaches stand out as innovative solutions that enable the integrated management of water and energy resources. These technologies, which reduce energy demand while ensuring the efficient use of water, enhance both the economic sustainability and environmental resilience of agricultural production.

In this book chapter, the interdependence between water and energy and its impacts on agricultural production are examined, with particular emphasis on the critical role of energy use in irrigation systems from a sustainability perspective. The main objective of the study is to provide insights into innovative technologies aimed at improving energy efficiency in agricultural irrigation and to reveal their potential implications for the water-energy-food nexus. In this regard, various innovative applications have been compiled, from sensor-based systems to variable frequency drives, from renewable energy solutions to data-driven management approaches. As a review study, this chapter aims to present a holistic perspective that integrates current findings from the literature to guide the development of energy-efficient, low-carbon, and sustainable irrigation systems.

2. OVERVIEW OF ENERGY USE IN AGRICULTURAL IRRIGATION

The total amount of energy reported to be consumed worldwide was 428,771,368 TJ. The sector with the highest energy consumption was industry, with 30.1%, followed by transportation with 28.6% and residential with 19.6%. The agriculture and forestry sector accounts for approximately 2.2% of total energy consumption, a significant portion of which is due to irrigation activities (IEA, 2023). Especially in countries with intensive irrigation such as India, China, the USA, Mexico, and Turkey, a large portion of electricity consumption is used in agricultural pumping systems (Zhao et al., 2020; Mittal and Dhawan, 1989; Hendrickson and Bruguera, 2020; Juarez-Hernandez and Pardo, 2018; Topak et al., 2010). Data on energy consumption by sector in the world are presented in Table 1.

Table 1. 2023 World Energy Consumption Data by Sector (IEA, 2023)

World Energy Consumption Data for 2023		
Sector	Amount of Energy Consumed (TJ)	Percentage Value (%)
Industry	128 950 177	30,1
Transportation	122 904 119	28,6
Residential	84 171 150	19,6
Commercial and Public Services	34 520 014	8,1
Agriculture and Forestry	9 585 918	2,2
Other	6 691 395	1,6
Non-energy use	41 948 595	9,8
Total	428 771 368	100

Although the share of agricultural activities in the global energy balance appears relatively small compared to other sectors in quantitative terms, it holds a critical significance, particularly in relation to irrigation practices. This is because energy consumption in agriculture is not directly linked to production volume but is closely associated with the mode of water access and the type and efficiency of irrigation technology employed. Therefore, the energy demand of irrigation systems is a fundamental factor that determines not only the total consumption level but also the sustainability of agricultural production. When this aspect of energy use is considered alongside regional hydrological conditions, climatic variations, and the level of technological development, it becomes evident that the dynamics shaping energy demand in irrigation are inherently multidimensional.

Energy requirements for agricultural irrigation depend on numerous variables, including the water source, irrigation method, land topography, climatic conditions, and the distance of water transport. Especially in regions where groundwater resources are used, the pumping energy required to bring water to the surface accounts for a significant portion of total energy consumption (Siyal and Gerbens-Leenes, 2022). In contrast, surface irrigation systems generally have lower energy requirements but lower water use efficiency. The type of irrigation system, such as sprinkler, drip, or micro-irrigation, directly affects energy demand. Because pressurized systems (sprinkler and drip irrigation) require higher pumping pressure, their energy consumption is also higher than surface irrigation (Corcoles et al., 2010). Furthermore, these systems can offer advantages in terms of energy-water optimization in the long term because they increase water use efficiency.

Electricity, diesel fuel, and coal are the leading traditional energy sources for agricultural irrigation. While pumping systems in developed countries generally run on electricity, diesel engines are still widely used in developing regions. While such systems may be accessible in the short term, they are not sustainable in the long term due to their high operating costs and environmental impacts (Chel and Kaushik, 2011).

Energy consumption in agricultural irrigation is a multifaceted issue with technical, economic, and environmental dimensions. Accurately analyzing the factors that determine energy needs is crucial for developing sustainable energy strategies. Currently, irrigation activities in Turkey and globally still rely largely on diesel fuel and electricity. This creates both environmental and economic pressures, thus further increasing the importance of innovative approaches to energy efficiency and the transition to renewable energy.

3. INNOVATIVE TECHNOLOGIES FOR ENHANCING ENERGY EFFICIENCY IN IRRIGATION

Energy efficiency in agricultural irrigation holds strategic importance, not only for reducing energy costs but also for establishing a balance between water management, carbon emissions, and sustainable production. Traditional irrigation methods often lead to excessive water use and energy waste, whereas next-generation technologies enable the integrated management of these two vital resources. In recent years, modern irrigation technologies have emerged as innovative solutions that significantly enhance energy efficiency in irrigation. Some of these technologies are outlined below.

Sensor-based irrigation systems monitor the water requirements of crops in real time, preventing unnecessary irrigation and minimizing energy consumption. Data such as soil moisture, air temperature, evaporation rate, and solar radiation are collected through sensors, and irrigation decisions are made automatically based on these data. This approach ensures that only the required amount of water is used, thereby significantly reducing both pump operating time and overall energy use. Modern sensor-based irrigation systems have become revolutionary tools for achieving precision, efficiency, and sustainability in water management for crop production (Paul et al., 2024). Figure 1 shows the system setup of the wireless irrigation sensor network.

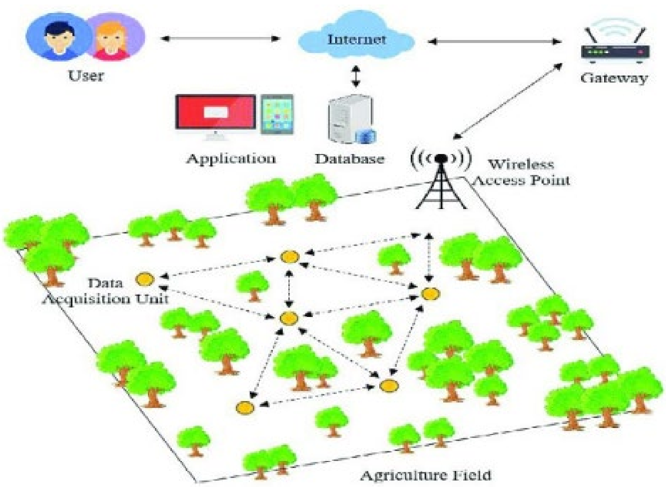

Figure 1. Wireless sensor network for automated irrigation (Li et al., 2020)

Internet of Things (IoT) based systems enable remote management of irrigation infrastructure, offering substantial potential for energy savings. These systems transmit field data to a centralized platform via wireless networks, allowing users to monitor and control irrigation processes through mobile devices. Through automatic on/off mechanisms and cloud-based data management, unnecessary pump operation is prevented and energy-use efficiency is optimized. Moreover, these systems allow for the dynamic management of different energy sources (such as solar panels) (Saraf and Gawali, 2017). López-Morales et al. (2021) found that energy costs for pumping account for 30–40% of total crop production expenses, and IoT-based systems can significantly reduce these costs.

The smart irrigation management system integrates cloud computing, IoT devices, and advanced algorithms to maximize water-use efficiency in agriculture. The system comprises three main components: IoT sensors, the ThingsBoard cloud platform for data processing, and a dashboard interface through which users can monitor and control operations (Figure 2). The sensors measure soil moisture, temperature, and environmental conditions, transmitting these data to the cloud. The algorithm operating in the cloud environment analyzes the incoming data to determine irrigation needs. When soil moisture falls below a predefined threshold, the system automatically activates the pump; if there is a risk of over-irrigation, it halts pumping.

Additionally, the system incorporates delay control and fault management mechanisms, enhancing its operational stability. Through this integrated approach, irrigation processes are automated, water and energy savings are achieved, environmental sustainability is strengthened, and producers are empowered to make more informed and data-driven decisions (Morchid et al., 2024).

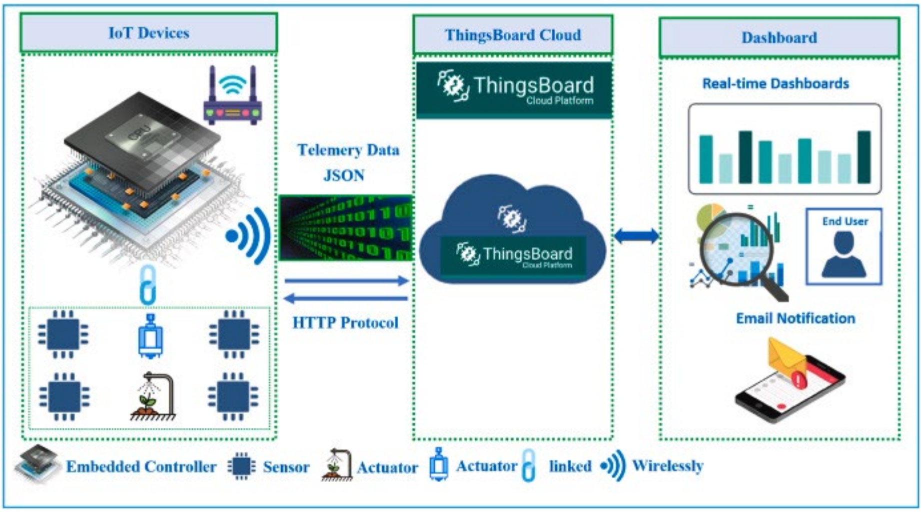

Figure 2. Proposed scheme for smart irrigation management system (Morchid et al., 2024)

Data-driven Decision Support Systems (DSS) integrate historical irrigation data, climate forecasts, and sensor measurements to optimize both the timing and amount of irrigation. Developed using artificial intelligence (AI) and machine learning algorithms, these systems analyze variables affecting energy consumption and enable the achievement of maximum efficiency with minimum energy input. Furthermore, data-driven management forms the foundation for sustainable agricultural planning (Rinaldi and He, 2014; Araújo et al., 2023). In Figure 3, a data-driven agricultural monitoring and analysis approach is illustrated, which integrates wireless sensor networks, remote sensing, AI, and decision support systems to maximize crop-water use efficiency .

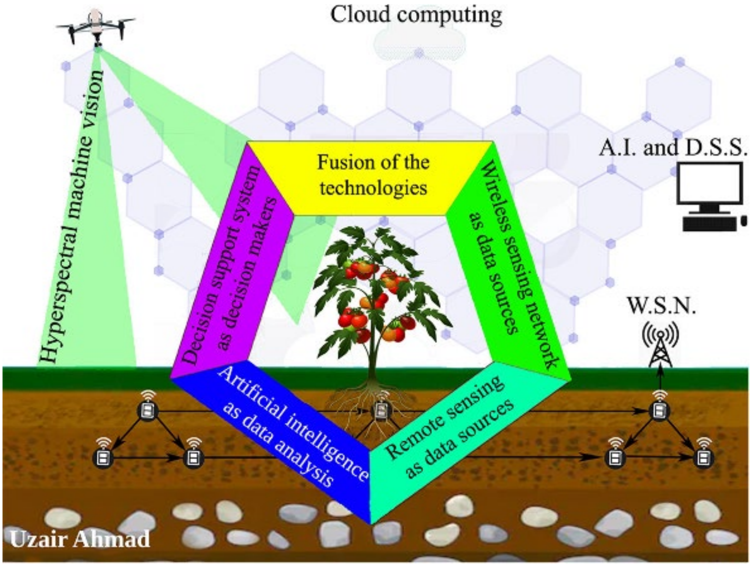

Figure 3. Integration of different technologies for monitoring surface and subsurface soil moisture (Ahmad and Sohel, 2025)

Technological advancements in pumps, motors, and pressure regulation represent some of the alternative approaches emerging for enhancing energy efficiency. These innovations reduce energy consumption in irrigation systems, thereby significantly lowering operating costs. Some of the prominent technologies in this area are outlined below.

In pumping systems, the highest energy consumption typically occurs due to motors operating at a constant speed. To address this issue, Variable Frequency Drives (VFDs) have been developed, which automatically adjust motor speed according to water flow and pressure requirements, preventing energy waste. This allows the system to reduce unnecessary energy use, extend equipment lifespan, and lower maintenance costs. Furthermore, the ability to remotely monitor and control VFDs enables flexible and sustainable energy management in irrigation operations (Buono da Silva Baptista et al., 2019; Marchi et al., 2012). An example of an irrigation system utilizing a variable frequency drive is shown in Figure 4.

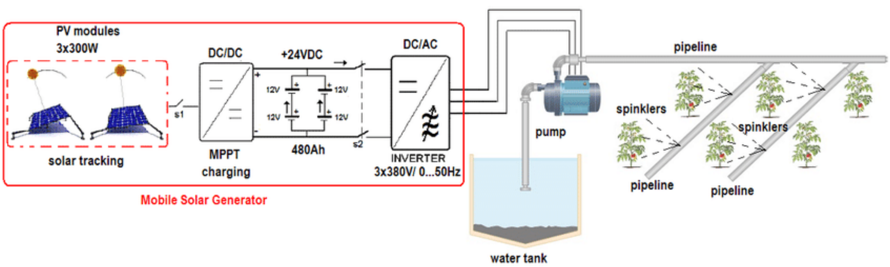

Figure 4. Irrigation system with centrifugal pump and variable frequency drive (VFD) (Despotović et al., 2017)

In irrigation systems, pressure-reducing valves or water flows in high-elevation areas often represent underutilized energy points. In modern systems, micro-turbines or pressure energy recovery devices can be installed at these points to reclaim energy. These systems are particularly used in gravity-fed conveyance lines to generate electricity, reducing pumping requirements and thereby improving net energy efficiency (Pérez-Sánchez et al., 2016; Rodríguez-Pérez et al., 2024).

Pressure control is a key factor in determining energy consumption. Systems operating at unnecessarily high pressure result in both water loss and energy waste. Modern smart pressure regulation systems dynamically adjust pressure based on sensor data, achieving an optimal balance between flow rate and energy use (Karadirek et al., 2016; Bawuah, 2025).

Innovative approaches in the design and operation of irrigation systems play a critical role in enhancing energy efficiency. Micro and drip irrigation systems, which deliver water directly to the plant root zone, are among the most efficient methods in terms of both water and energy use. These systems require relatively low pumping pressures and operate for shorter durations. Energy efficiency can be further improved through proper system design and precise pressure regulation (Bingöl et al., 2018). With the advancement of renewable energy technologies, solar-powered, pressure-less irrigation systems are becoming increasingly common. In these systems, water is pumped into storage tanks using photovoltaic (PV) panels, and irrigation occurs via gravity, eliminating electricity costs during pumping (Shinde and

Wandre, 2015; Kumar et al., 2020). These systems provide energy independence for farmers in rural areas with insufficient energy infrastructure, ensuring continuity of production. Additionally, by reducing carbon emissions and long-term operational costs, they offer a strategic solution for sustainable agricultural production.

Today, innovative technologies aimed at improving energy efficiency in agricultural irrigation are considered not only a technical advancement but also a strategic transformation shaping the future of sustainable agriculture. Sensor-based monitoring systems, variable frequency drives, and renewable energy-supported solutions reduce environmental burdens by enabling more efficient use of both water and energy resources. The widespread adoption of these technologies reduces producers' energy costs while strengthening the resilience of agricultural systems against the impacts of climate change. Therefore, these innovative applications focused on energy efficiency form the basis of future low-carbon, resource-efficient, and resilient agricultural models.

4. Conclusions and Recommendations

The interdependence between water and energy has become one of the most critical factors determining the sustainability of modern agricultural systems. The continuity of agricultural production is under increasing pressure due to rising water demand and energy costs. In particular, the energy required for the supply, conveyance, and distribution of water in irrigation activities constitutes a significant limiting factor for both economic sustainability and environmental impact. Therefore, adopting holistic and innovative approaches to enhance energy efficiency in agricultural irrigation has become a strategic necessity, not only to reduce production costs but also to facilitate climate change adaptation and carbon emission reduction.

Although global energy consumption data indicate that the agricultural sector accounts for a relatively small share of total energy use, this share plays a critical role in irrigation. Energy consumption in irrigation is closely linked not to production volume but to factors such as the source of water, conveyance distance, topography, climatic conditions, and the type of irrigation technology used. In this context, innovative technologies that optimize the water-energy nexus emerge as key enablers of sustainable production.

Technologies such as sensor-based systems, IoT-enabled automation solutions, data-driven decision support systems, and variable frequency drives developed in recent years provide significant energy savings in irrigation management. These systems optimize water use with real-time data, reducing pumping times and preventing unnecessary energy consumption, thus providing both economic and environmental benefits. Furthermore, solar-powered pumping systems and microturbine-based energy recovery mechanisms increase sustainable production capacity by providing energy independence in rural areas.

Based on these findings, the following recommendations can be developed:

1. Integrated Water - Energy Management; Agricultural irrigation policies should be based on the combined management of energy and water; planning approaches that target energy efficiency as well as the efficient use of water should be adopted.
2. Renewable Energy Applications: The widespread use of solar-powered pumping systems and pressure-free gravity irrigation solutions will both reduce energy costs and lower the carbon footprint.
3. Dissemination of Smart and Data-Driven Systems: Training, incentive and financial support mechanisms should be established for farmers for IoT-based sensor networks, decision support systems and automation infrastructures.
4. Pressure and Pumping Optimization: The use of **variable frequency** drives, intelligent pressure regulation systems and energy recovery technologies in irrigation systems will both increase system performance and reduce energy losses.

5. Local-Scale Energy Efficiency Analyses: The energy needs of irrigation systems should be analyzed in detail, taking into account the hydrological and topographic characteristics of each region; regional energy-water management strategies should be created based on this data.

Consequently, energy efficiency in agricultural irrigation should be considered not only a technical requirement but also a strategic objective central to sustainable development. The integration of smart technologies and renewable energy solutions enables rational management of water and energy resources, thus laying the foundation for a transition to an agricultural system that is both environmentally and economically resilient. This transformation will be a critical step in building future low-carbon, resource-efficient, and climate-adapted agricultural production models.

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CHAPTER II

BIOLOGICAL CONTROL OF *MACROPHOMINA PHASEOLINA*: MICROBIAL AGENTS AND THEIR MECHANISMS

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1. INTRODUCTION

Macrophomina phaseolina (Tassi) Goid. is recognized as the sporulating form of *Rhizoctonia bataticola* (Taub.) Butler, and it belongs to the fungal family Botryosphaeriaceae (Lodha & Mawar, 2020). This fungus is a globally distributed soilborne ascomycete that plays a significant role in the development of charcoal rot disease. It acts as an opportunistic and facultative pathogen, often targeting plants under environmental or physiological stress (Tesso et al., 2005; Crous et al., 2006; Khaledi & Taheri, 2016; Al-Askar et al., 2025). Until recently, *M. phaseolina* was believed to be the sole species classified under the *Macrophomina* genus. However, advances in multilocus phylogenetic analysis have led to the reclassification of this group into four distinct species: *M. pseudophaseolina*, *M. euphorbiicola*, *M. vaccinii*, and *M. tecta* (Sarr et al., 2014; Machado et al., 2019; Zhao et al., 2019; Poudel et al., 2021).

This pathogen has a notably broad host range, capable of infecting more than 500 plant species from over 100 different families. Among its major hosts are economically important crops such as soybean (*Glycine max*), maize (*Zea mays*), sorghum (*Sorghum bicolor*), common bean (*Phaseolus vulgaris*), cotton (*Gossypium hirsutum*), sesame (*Sesamum indicum*), sunflower (*Helianthus annuus*), melon (*Cucumis melo*), tobacco (*Nicotiana tabacum*), and safflower (*Carthamus tinctorius*) (Duduk et al., 2023). While this extensive host range suggests a non-specific interaction, the fungus's level of physiological specialization remains unclear. Interestingly, isolates from various parts of the same plant have demonstrated noticeable differences in traits such as morphology, virulence, and physiological responses (Khan, 2012).

The conidia of *M. phaseolina* are characterized as hyaline, aseptate, elliptical, and thin-walled. Under favorable conditions, the fungus germinates through sclerotia, developing hyphae that can breach plant root tissues by mechanical force or through the enzymatic breakdown of the cell wall. As root tissue integrity deteriorates, symptoms like chlorosis and leaf wilting begin to appear. At later stages, microsclerotia accumulate at infection sites, ultimately causing decay and plant death (Islam et al., 2012; Sridharan et al., 2021).

Functioning as a seedborne pathogen, *M. phaseolina* is able to colonize both seed coats and cotyledons. Upon germination, the microsclerotia attached to the seed surface facilitate early root infection, leading to charcoal rot symptoms (Kunwar et al., 1986; De Mooy & Burke, 1990). In young seedlings, the disease typically appears as irregular black spots on the foliage, gradually advancing through the hypocotyl and stem and eventually resulting in damping-off or death. Mature plants often exhibit vascular blockage and wilting, with visible signs of black or gray microsclerotia (You et al., 2011).

In natural field environments, infection commonly begins when microsclerotia or fungal conidia from infected residues are transferred to host plants via rain splashes. Initially, the hyphae occupy intercellular spaces, slowly moving toward the vascular cylinder. The disease often begins in a biotrophic manner without visible symptoms, but external factors like stress, plant senescence, or changing environmental conditions can trigger a necrotrophic shift. During this phase, wilting and branch tip dieback are frequently observed. These outcomes are typically caused by vascular tissue blockage, phytotoxin-induced necrosis, enzymatic tissue degradation, and mechanical pressure on cell structures (Twizeyimana et al., 2012).

The microsclerotia of the fungus allow it to persist in dry soil, seeds, and plant residues for up to 15 years. In contrast, its survival is significantly reduced under moist soil conditions lasting only about 7–8 weeks in sclerotial form and just a few days in its mycelial state (Meyer et al., 1974; Sinclair, 1982). The fungus thrives best at temperatures between 30-35°C, although some strains can continue growing even at 40°C. Under hot and arid soil conditions (particularly when soil moisture drops below 60%) the pathogen can cause substantial yield losses in crops like sorghum and soybean. These effects are especially concerning given current climate change trends, which continue to exacerbate soil stress conditions in many agricultural regions (PalaniArul et al., 2025). In extreme pre-emergence infections, complete yield loss has been documented (Duduk et al., 2023; Sassenrath et al., 2025; Al-Askar et al., 2025).

A major contributor to the aggressive nature of *M. phaseolina* is its complex enzymatic arsenal. The pathogen is capable of synthesizing a diverse array of hydrolytic enzymes, which are effective in breaking down key plant cell wall components such as cellulose, hemicellulose, lignin, pectin, and cutin. Studies have shown that its cellulase activity significantly surpasses that of other fungi like *Aspergillus niger* Tiegh. and *Trichoderma reesei* Simmons, which highlights its pathogenic potential. Additionally, the fungus harbors over 20 genes encoding laccases enzymes believed to play critical roles in lignin degradation, melanin biosynthesis in infection structures (appressoria), and overall virulence (Ramos et al., 2016).

The primary objective of this review is to comprehensively evaluate current microbial agents and their mechanisms of action in the biological control of *Macrophomina phaseolina*, a pathogen responsible for significant economic losses in agricultural production. In this context, the biocontrol potential of various fungal and bacterial antagonistic microorganisms (particularly species of *Trichoderma* and *Bacillus*) has been examined with respect to pathogen suppression, promotion of plant growth, and induction of systemic resistance in host plants. Considering the limitations and environmental impacts of chemical fungicides, this study aims to contribute to the development of sustainable and ecologically sound disease management strategies.

2. MANAGEMENT OF *MACROPHOMINA PHASEOLINA*

Effective management of plant diseases such as *M. phaseolina* involves several integrated strategies, including host resistance, crop rotation, cultural modifications, biological control, and chemical fungicides. Among these, growing resistant cultivars is generally considered the most reliable approach. However, the significant genetic and pathogenic diversity observed among *M. phaseolina* isolates has limited the success of breeding resistant commercial varieties (Mondal & Hyakumachi, 1998).

Due to its extensive host range and high variability, the efficacy of chemical fungicides against this pathogen is often inconsistent. Moreover, the long-term use of these chemicals can lead to detrimental effects on soil microbial communities, and pose health risks to both humans and animals (Mondal & Hyakumachi, 1998; Gupta et al., 2002; Javaid et al., 2017). This has led to an increased focus on alternative, eco-friendly management methods that offer more sustainable disease control.

Managing charcoal rot also requires efforts to reduce drought-induced stress in plants. Approaches such as conservation tillage, optimized plant spacing, selection of drought-tolerant varieties, and maintaining adequate soil fertility can significantly mitigate disease impact. In areas with high infection pressure, rotating with non-host crops for 1-2 seasons, ensuring balanced nutrient inputs, intercropping, and using mulch can also help lower disease incidence (Mondal & Hyakumachi, 1998; Das et al., 2015).

Recently, biological control has gained traction as a viable solution for managing soilborne pathogens like *M. phaseolina*. Employing antagonistic microbes offers an environmentally safe and residue-free method for disease suppression. Particularly in cases where host resistance or fungicides fall short, biocontrol presents a sustainable and effective alternative (Das et al., 2015).

2.1. Antagonists Targeting *Macrophomina phaseolina*

Fungal pathogens are responsible for approximately one-third of global crop yield losses, presenting serious ecological and economic concerns (Fisher et al., 2012). *M. phaseolina* is especially notorious due to its strong virulence and its ability to thrive under environmental stress conditions (Masi et al., 2021). Its microsclerotia allow prolonged survival in soil, while its phytotoxin production significantly complicates management efforts (Naseri et al., 2018).

Although chemical fungicides remain widely used, increasing resistance and environmental safety issues have spurred interest in biological alternatives (Aravind& Brahmbhatt, 2018; Iqbal & Mukhtar, 2020). Fungal genera like *Trichoderma*, *Gliocladium*, and *Chaetomium*, along with bacterial genera such as *Bacillus*, *Pseudomonas*, *Burkholderia*, *Serratia*, and *Streptomyces*, have shown promise as biocontrol agents against *M. phaseolina*. These organisms suppress pathogen activity and simultaneously enhance the plant's own defense mechanisms, providing a holistic and eco-friendly disease management approach (Vinale et al., 2009; Kaur et al., 2022).

2.2.Fungal Biological Control Agents

2.2.1.Trichoderma spp.

The *Trichoderma* genus includes filamentous fungi commonly found in soil environments and well-known for their antagonistic potential against various phytopathogens. These fungi can directly parasitize pathogens such as *M. phaseolina* and suppress them by producing antifungal secondary metabolites (Kapadiya et al., 2024). Utilizing such microorganisms is increasingly viewed as a sustainable and environmentally safe method for managing soilborne diseases (Sohaliya et al., 2019).

Species like *T. asperellum* Samuels, Lieckfeldt & Nirenberg, *T. atroviride* P. Karst., *T. gamsii* Samuels & Druzhinina, *T. harzianum* Rifai, *T. virens* J.H. Miller, Giddens & A.A. Foster, and *T. koningii* Oudem. demonstrate strong biocontrol efficacy against a broad range of plant pathogens including *Rhizoctonia*, *Fusarium*, *Pythium*, *Phytophthora*, *Aspergillus*, and *Macrophomina* (Moosa et al., 2017; Javaid et al., 2018; Sharma & Prasad, 2018; Ingale & Patale, 2019). Their spores are environmentally stable, making them suitable for both field applications and commercial formulations (El-Mougy & Abdel-Kader, 2018).

Trichoderma species are efficient colonizers of the rhizosphere, and they often promote plant growth through biostimulation. Their success as biocontrol agents depends on traits such as persistence, shelf life, and colonization efficiency (Kamal et al., 2018; Rini et al., 2018). Their antagonistic effects largely stem from bioactive compound synthesis (Khan et al., 2019). For example, *T. pseudokoningii* Rifai has been reported to degrade *M. phaseolina* DNA, while *T. harzianum* inhibits pathogen growth through VOC production and mycoparasitism (Jadhav et al., 2018; Khalili et al., 2016).

The introduction of *Trichoderma* strains into the rhizosphere improves microbial community balance and primes plant defense systems such as Induced Systemic Resistance (ISR) and Hypersensitive Response (HR). Dual culture assays confirm that this antagonism involves multiple actions-coiling around pathogen hyphae, secretion of antifungal metabolites (harzianic acid, peptaibols, gliotoxin), volatile organic compound (VOC) emission, and upregulation of host defense genes (Vinale et al., 2009; Moran-Diez et al., 2021; Panchalingam et al., 2022; Dutta et al., 2023).

Under both lab and greenhouse conditions, *Trichoderma* isolates such as *T. harzianum*, *T. viride* Pers., and *T. asperellum* have been shown to inhibit *M. phaseolina* mycelial growth by up to 100%, reduce microsclerotia formation by over 70%, and enhance crop productivity (Vinale et al., 2008; Sarzi et al., 2024; Bayrak et al., 2021). Isolates like *T. viride* AMUTVR 61 and *T. harzianum* AMUTHZ 72 achieved 94–95% control of charcoal rot in lentils (Ahmad & Khan, 2024).

These fungi can also synthesize plant growth-promoting hormones such as IAA and gibberellins, which indirectly enhance plant tolerance. In one study, application of *T. harzianum* Tr28 increased root length by 177% and biomass by 77% (Bayrak et al., 2021). In combination with carbendazim, species like *T. viride* and *T. polysporum* have further improved control of root rot (Vyas, 1994; Kumari et al., 2012).

An endophytic isolate, *T. longibrachiatum* Rifai EF5, produced volatiles like bisabolol and diethyl trisulfide, effectively inhibiting *M. phaseolina* while activating systemic defenses (Sridharan et al., 2021). Seed treatments with *T. harzianum* have similarly enhanced peroxidase and phenolic activity (Khaledi & Taheri, 2016). Organic substrates such as peanut shells and coconut coir have improved the performance of *Trichoderma* strains, with added biochar further enhancing disease suppression (Araujo et al., 2019).

2.3. Other Antagonistic Fungi

2.3.1.Aspergillus spp.

Fungi in the *Aspergillus* genus (particularly *Aspergillus fumigatus* Fresen., *Aspergillus flavipes* (Bainier & Sartory) Thom & Church, and *Aspergillus versicolor* (Vuill.) Tirab.) exhibit antifungal activity against *M. phaseolina* through the secretion of bioactive compounds and modulation of plant cell structures (Khan & Javaid, 2022a). Metabolites such as cyclosporin A, asperfuranone, terrein, and kojic acid contribute significantly to this effect (Wu et al., 2019; Chigozie et al., 2022; Ding et al., 2019). Additionally, siderophore production by *Aspergillus niger* limits pathogen development by sequestering iron (Francis et al., 2010). Internal Transcribed Spacer (ITS) and β-tubulin–based molecular studies have demonstrated 37–53% inhibition of *M. phaseolina* growth (Khan & Javaid, 2021), with *A. versicolor* degrading pathogen DNA within 48 hours (Khan & Javaid, 2022b).

2.3.2. Penicillium spp.

Penicillium species are also effective, thanks to their extensive secondary metabolite arsenal (Cherkupally et al., 2016). *Penicillium italicum* Wehmer, *Penicillium expansum* Link, and

Penicillium citrinum Thom have demonstrated up to 57% inhibition of *M. phaseolina* growth *in vitro* (Khan & Javaid, 2022c). Their metabolites disrupt pathogen metabolism and cause hyphal lysis (Damasceno et al., 2019; Javaid et al., 2020). Under greenhouse conditions, *P. citrinum* achieved up to 75% disease control (Boughalleb-M'Hamdi et al., 2018).

2.3.3. ***Chaetomium* spp.**

Chaetomium globosum Kunze is a promising saprophytic antagonist. Dual culture tests revealed 63-67% inhibition of *M. phaseolina* isolates (Kumar et al., 2020; Lewaa & Zakaria, 2023; Varsha et al., 2025). It produces antifungal compounds like chaetoglobosin and chaetomugilin that disrupt cell wall integrity and reduce metabolic activity (Park et al., 2005; Zhang et al., 2012; Chen et al., 2016).

2.4. **Alternative Fungal Agents**

Beyond traditional antagonists, yeasts and mycorrhizal fungi have shown potential in integrated biocontrol systems. *Brettanomyces naardenensis* Kufferath & van Laer, when used alongside arbuscular mycorrhizal fungi (AMF), suppressed *M. phaseolina* in sunflower by up to 90% while boosting antioxidant enzyme activity (Nafady et al., 2019). AMF such as *Rhizophagus intraradices* (N.C. Schenck & G.S. Smith) C. Walker & A. Schüßler have been shown to improve biomass, nutrient uptake, and disease tolerance in soybean (Spagnoletti et al., 2020).

Transcriptome studies indicate that AMF primes plant immune responses and reduces stress signals (Marquez et al., 2018). Other studies confirm AMF's ability to limit pathogen colonization and restore plant vigor after infection (Doley et al., 2014; Oyewole et al., 2017). Therefore, AMF and yeasts may complement biocontrol strategies (Dar & Reshi, 2017).

In summary, both classical and alternative fungal biocontrol agents (including *Trichoderma*, *Aspergillus*, *Penicillium*, *Chaetomium*, and AMF) provide multifaceted benefits. They suppress *M. phaseolina* through direct antagonism and stimulate plant immune responses, offering eco-friendly and long-term solutions to manage charcoal rot (Thakur et al., 2022).

2.5. Bacterial Biological Agents

2.5.1. *Bacillus* Species

Rhizospheric beneficial bacteria contribute to plant growth not only by facilitating nutrient acquisition and stimulating development but also by limiting pathogen activity and supporting overall plant health. Their biocontrol capacity relies on mechanisms including the release of antibiotics, lytic enzymes, hydrogen cyanide, siderophores, and volatile compounds, as well as engaging in competition and mycoparasitism (Loganathan et al., 2010).

Among these, *Bacillus* species (Gram-positive spore-forming bacteria prevalent in soil environments) are highly valued due to their durability under environmental stress, which supports their application in biocontrol strategies (Maughan & Van der Auwera, 2011). They exhibit both direct antagonistic action and indirect induction of systemic resistance (ISR) against pathogens such as *M. phaseolina* (Cawoy et al., 2011).

Their antifungal activities are associated with the secretion of cyclic lipopeptides (iturin, fengycin, surfactin), hydrolytic enzymes (e.g., chitinases, β-1,3-glucanases, proteases), siderophores, and plant hormone analogs. These metabolites collectively hinder the germination of microsclerotia, disturb hyphal growth, and compromise the pathogen's structural integrity, while also reducing its competitive advantage in the rhizosphere (Sabaté et al., 2019).

Additionally, many *Bacillus* strains display plant growth-promoting (PGPR) capabilities through the synthesis of indole-3-acetic acid (IAA), phosphate solubilization, and siderophore production. For example, *B. pumilus* Meyer & Gottheil was shown to enhance root formation and yield via elevated IAA synthesis and phosphate mobilization (Swarnakar & Chakraborty, 2025), while other isolates demonstrated similar benefits by promoting nutrient availability and biomass accumulation (Güler, 2025).

The mechanisms by which *Bacillus* operates can be grouped into three levels:

1. **Direct antagonism:** Destruction of fungal cell walls via antimicrobial lipopeptides and enzymes (Ding et al., 2025).
2. **ISR induction:** Enhancement of plant immune responses by activating peroxidase (PO), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) enzymes (Ajuna et al., 2024).
3. **Ecological niche competition**: Rapid rhizosphere colonization that limits pathogen access to nutrients and space (Parra-Cota et al., 2024).

This multifaceted strategy makes *Bacillus* a promising candidate as both a biocontrol agent and a biofertilizer in sustainable agriculture (Villarreal-Delgado et al., 2018).

Multiple studies confirm the strong antagonistic properties of *Bacillus* strains against *M. phaseolina*. For instance, *Bacillus sp.* P12 suppressed the growth of six fungal isolates by 55–70% and enhanced soil enzymatic activities by up to 31% (Sabaté et al., 2019). Application of *B. cereus* Frankland & Frankland to peanut crops reduced root rot incidence and encouraged plant growth (Kumar et al., 2019).

Desert-derived *B. amyloliquefaciens* Fukumoto strains BsA3MX and BsC11MX achieved 66.8% inhibition *in vitro*, blocked microsclerotia germination, and caused hyphal deformation. These strains also displayed PGPR features, such as siderophore and IAA production, along with phosphate and zinc solubilization. In greenhouse tests, BsA3MX significantly reduced root lesions and improved both root and leaf biomass (Rangel-Montoya et al., 2022). Likewise, *B. subtilis* (Ehrenberg) Cohn enzymes like chitinase and β-1,3-glucanase were effective in compromising fungal structure (Shafi et al., 2017).

In a screening of 71 bacterial isolates from Çumra, Konya (Turkey), *B. cereus* DP145.1 (100%), *B. pumilus* DP25 (91%), and *B. subtilis* DP143.6 (86%) were the most potent antagonists, also demonstrating phosphate solubilization, siderophore secretion, and IAA production indicating a dual role in both disease suppression and plant stimulation (Koçak & Salman, 2023).

Co-inoculation strategies have also shown promise. For example, *Pantoea agglomerans* (Beijerinck) Gavini et al., *Bacillus* sp. BIN, and *Trichoderma harzianum* Rifai suppressed soybean root rot by 73.8%, 63.3%, and 55.3%, respectively. *Bacillus* sp. alone inhibited microsclerotia formation by 87.6% (Safaie et al., 2025). A similar synergy was observed when *Trichoderma viride*, *Pseudomonas fluorescens* Flügge, and *B. subtilis* were applied to mung bean plants. The Pf1 + Tv1 combination notably suppressed fungal growth, reduced disease incidence, and enhanced the activity of defense-related enzymes, ultimately leading to improved yield (Thilagavathi et al., 2007).

Recent isolates also show remarkable promise. Bojórquez-Armenta et al. (2021) identified four *Bacillus* species (BA97, BN17, BN20, BR20) from the bean rhizosphere capable of inhibiting *M. phaseolina* by up to 85%. The BN20 strain notably produced IAA (1.98-3.87 µg/ml), solubilized phosphate, and emitted antifungal volatiles.

Furthermore, *B. velezensis* (Rossi) Priest et al. KSAM1 exhibited the strongest inhibitory activity (38.6%) among 17 *Bacillus* strains (Al-Askar et al., 2025). Other strains such as *B. subtilis* BGS-10 and *B.velezensis* BGS-21 effectively mitigated root rot in *Gloriosa superba* L. by 61%, stimulated ISR-related enzyme activity, and produced various beneficial enzymes including amylase and cellulase. Greenhouse experiments using talc-based formulations lowered disease incidence to 27.78% (Dhanabalan et al., 2024).

Altogether, these studies underline the broad-spectrum biocontrol potential of *Bacillus* species against *M. phaseolina*. With their robust antifungal activity and PGPR capabilities, strains like *B. subtilis*, *B. amyloliquefaciens*, *B. cereus*, and *B. velezensis* are ideal candidates for developing eco-friendly microbial inoculants. Moreover, synergistic use with genera like *Pantoea*, *Trichoderma*, or *Pseudomonas* could lead to highly effective biopreparations that reduce reliance on chemical fungicides (Miljaković et al., 2020).

2.5.2. *Pseudomonas* Species

Species from the *Pseudomonas* genus (particularly *Pseudomonas fluorescens* Flügge, *Pseudomonas putida* Trevisan, and *Pseudomonas aeruginosa* (Schroeter) Migula) are well-documented rhizospheric bacteria known for their strong antagonistic properties against a wide range of soilborne phytopathogens, including *M. phaseolina*. Their success as biocontrol agents lies in their exceptional metabolic versatility, rapid root-colonization ability, and adaptability to diverse environmental conditions (Höfte, 2021; Rajkumar et al., 2017).

These bacteria exert biocontrol through a multi-pronged strategy. They produce antifungal compounds such as 2,4-diacetylphloroglucinol (DAPG), pyrrolnitrin, and pyoluteorin; release iron-chelating siderophores like pyoverdin; emit hydrogen cyanide (HCN) and volatile organic compounds (VOCs); and activate the plant's induced systemic resistance (ISR), which enhances the expression of defense-related genes in the host (Dave et al., 2021).

Numerous studies have verified the real-world effectiveness of these mechanisms. For example, when *P. fluorescens* was applied alongside soil solarization, a significant reduction in damping-off disease was observed (Elmore et al., 1997). Additionally, *Pseudomonas thivervalensis* Kaiser & Gasson and *Pseudomonas aeruginosa* (Schroeter) Migula isolates demonstrated up to 98% suppression of *M. phaseolina* mycelial growth under *in vitro* conditions (Güler Güney, 2018; Saravanakumar et al., 2007). In the case of *Vigna mungo*, the Pfkkm7 isolate achieved 88.5% inhibition in dual culture assays and lowered disease severity by 75.5% in greenhouse settings (Pothiraj et al., 2018).

Under saline conditions, *P. aeruginosa* (Schroeter) Migula PF23 maintained its antagonistic effectiveness through the production of exopolysaccharides (EPS) and salicylic acid-mediated signaling, resulting in reduced disease incidence and improved growth in sunflower (Tewari & Arora, 2017). At the biochemical level, *P. fluorescens* strain 9 produced potent antifungal metabolites, including phenazine and mesaconic acid derivatives. Notably, phenazine-1-carboxylic acid (PCA) has emerged as a strong candidate for biopesticide development (Castaldi et al., 2021).

Beyond antifungal metabolite production, *Pseudomonas* spp. also play a crucial role in enhancing plant immune responses. For instance, fluorescent *Pseudomonas* strains CTPF31 and CTPF36, isolated from the rhizosphere of safflower, significantly reduced disease severity in greenhouse conditions while boosting the activity of defense enzymes such as POX, PAL, β-1,3-glucanase, and chitinase (Govindappa et al., 2011). In cotton, a combination of *P. aeruginosa* and neem cake raised endogenous levels of salicylic acid (6.9-8.6 mg/mL) and polyphenols, decreasing disease incidence from 75% to 37.5% and enhancing antioxidant activity (Rahman et al., 2016).

In maize trials, *P. syringae* van Hall alone achieved 55% disease control, which rose to 90% when integrated with NPK fertilization, alongside notable improvements in plant growth and biochemical parameters (Ahmed & Shoaib, 2024). Similarly, in strawberry, co-inoculation with *P. aeruginosa* AC17, *Bacillus velezensis* FC37, and *Brevibacterium frigoritolerans* Hvs8 led to marked reductions in charcoal rot severity and crown colonization (Camacho et al., 2023).

Additional evidence comes from endophytic *P. aeruginosa* isolates collected in Karachi. Fourteen of these strains showed strong antifungal activity *in vitro* and, under greenhouse conditions, decreased disease symptoms while enhancing chlorophyll, carbohydrate, and protein content in plants thereby reinforcing plant immunity (Shaheen et al., 2025).

Collectively, these findings affirm that *Pseudomonas* species are potent, eco-compatible biocontrol agents against *M. phaseolina*. They operate through both direct modes (such as producing antibiotics, siderophores, and VOCs) and indirect pathways involving plant defense induction. Their adaptability, broad-spectrum activity, and synergy with other beneficial microbes make them a key component in integrated disease management systems (Höfte, 2021; Rajkumar et al., 2017; Dave et al., 2021; Elmore et al., 1997; Güler Güney, 2018; Saravanakumar et al., 2007; Pothiraj et al., 2018; Tewari & Arora, 2017; Castaldi et al., 2021; Govindappa et al., 2011; Rahman et al., 2016; Ahmed & Shoaib, 2024; Camacho et al., 2023; Shaheen et al., 2025).

2.5.3. Other Bacterial Antagonists

A number of non-traditional bacterial genera (namely *Stenotrophomonas maltophilia* (Hugh) Palleroni & Bradbury, members of the *Burkholderia cepacia* (Burkholder) Yabuuchi et al. complex, *Serratia marcescens* Bizio, and various *Streptomyces* species) have emerged as promising biocontrol candidates against *M. phaseolina*. These organisms are known for producing diverse antifungal secondary metabolites, many of which belong to the polyketide and macrolide classes. Notably, isolates of *S. maltophilia* suppressed *M. phaseolina* growth by causing visible hyphal deformations, likely triggered by volatile organic compounds (VOCs) (Güler Güney, 2018).

2.5.3.1.*Burkholderia* Species

The genus *Burkholderia* is distinguished by its dual function: suppressing fungal pathogens and enhancing plant development. These bacteria produce compounds such as indole-3-acetic acid (IAA), siderophores, and ACC deaminase, all of which contribute to plant health. Strains of *B. contaminans* Vandamme et al. have demonstrated strong antagonism against *M. phaseolina* and other pathogens, largely attributed to the production of bioactive substances like pyrrolnitrin, catechol, and ergotaman (Mannaa et al., 2018; Zaman et al., 2021).

Genomic analyses suggest that *B. cepacia* (Burkholder) Yabuuchi et al. complex members hold considerable promise for biocontrol applications, although thorough biosafety evaluations are critical due to potential clinical risks. These bacteria inhibit soilborne pathogens through siderophore secretion and antifungal compound biosynthesis (Al-Dhabaan & Bakhali, 2017). Proteomic investigations further confirm that *B. contaminans* not only suppresses *M. phaseolina* but also influences fungal virulence factors and stress-related proteins (Zaman et al., 2020). The antifungal effects of *B. cepacia* are similarly linked to molecules such as pyrrolnitrin and cepacin (Francis et al., 2010; Jung et al., 2018).

In vitro comparisons have shown *B. cepacia* to be more effective in inhibiting *M. phaseolina* (43.5%) than both *Serratia* *plymuthica* (Lehmann & Neumann) Breed, Murray & Hitchens and *Bacillus subtilis*, which exhibited less than 10% inhibition (Cruz-Martín et al., 2014). Despite their biocontrol potential, caution is advised due to the pathogenic nature of some strains.

2.5.3.2. *Stenotrophomonas* Species

Stenotrophomonas species, which are Gram-negative and environmentally resilient, are recognized for both pathogen suppression and plant growth promotion (Kumar et al., 2023; Sharma et al., 2024). In particular, strain AG3 inhibited *M. phaseolina* by 52.2%, producing lytic enzymes and polyamines like putrescine and spermidine. Electron microscopy confirmed extensive structural damage to fungal hyphae (Santos et al., 2021). Among 38 isolates obtained from Urla, İzmir (Türkiye), *Stenotrophomonas*, *Bacillus cereus*, and *B. amyloliquefaciens* showed the highest levels of antagonism (55-74% inhibition) (Salman et al., 2021), indicating a strong link between enzyme activity and pathogen suppression (Güler Güney, 2018).

2.5.3.3. *Serratia* Species

Serratia spp., known for their metabolic diversity and resilience, exhibit antifungal properties through secondary metabolites whose biosynthesis can be enhanced at lower temperatures and specific carbon sources (Ortiz & Sansinenea, 2023; Mai, 2018). Species such as *S. marcescens* Bizio, *S. plymuthica* (Lehmann & Neumann) Breed, Murray & Hitchens, and *S. rubidaea* (Stapp)

Ewing et al. produce antifungal agents including pyrrolnitrin, zeamin I–II, oocidin A, and prodigiosin (Liu et al., 2007; Masschelein et al., 2013; Matilla et al., 2015). These compounds have shown promising activity against *M. phaseolina* in recent studies (Hellberg et al., 2015; Li et al., 2023; Pereira et al., 2023; Helmy & Abu-Hussien, 2024; Rashad et al., 2025).

The combination of *Serratia proteamaculans* (Paine & Stansfield) Grimont et al. isolates 136 and 137 with *Burkholderia gladioli* (Severini) Yabuuchi et al. MB39 demonstrated synergistic effects, reducing disease indices in greenhouse trials to as low as 10% and 0%, respectively, while also enhancing seed germination through increased IAA and siderophore activity (Sarli et al., 2022).

2.5.3.4. *Streptomyces* Species

Streptomyces spp., a dominant group within actinomycetes, are extensively studied for their antimicrobial capabilities. Their biocontrol efficiency against *M. phaseolina* stems from the production of antibiotics, lytic enzymes, and ISR-stimulating compounds such as HCN, siderophores, and defense-related enzymes (Gopalakrishnan et al., 2021).

Strains like *S. violaceoruber* Waksman & Curtis and *S. hirsutus* Waksman & Henrici significantly inhibited *M. phaseolina* in sesame, reducing disease incidence by over 50% while improving plant nutritional status and outperforming chemical controls like Topsin-M (Amin & Abd-Elbaky, 2024). *Streptomyces* sp. KP109810 suppressed both *Rhizoctonia solani* J.G. Kühn and *M. phaseolina* with inhibition rates of 84.6% and 78.7%, respectively, with VOCs contributing an additional 66.3% inhibition (El-Mageed et al., 2020).

In other greenhouse studies, *S. puniceus* (Waksman) Pridham et al. RHPR9 achieved 76% inhibition and activated host defense systems (Ravinder et al., 2022). *S. albus* Rossi Doria, *S. griseus* (Krainsky) Waksman & Henrici, and *S. cavourensis* (Falcao de Morais) Witt & Stackebrandt strains provided 63–74% suppression while enhancing antioxidant enzyme activity (Gopalakrishnan et al., 2021). *S. bacillaris* (Waksman) Waksman & Henrici 23, in combination with *Trichoderma longibrachiatum* 1, demonstrated high efficacy against both *M. phaseolina* and *Phytophthora sojae* Kaufmann & Gerdemann (Mirzaei et al., 2023). Among tested strains, *S. clavuligerus* GRS-8 showed the highest antagonism (76.5%) and reduced root rot incidence by 73%, aided by IAA, siderophore, and hydrolytic enzyme production (PalaniArul et al., 2025). Furthermore, *Streptomyces* strains CBQ-EA-2 and CBQ-B-8 surpassed commercial fungicides such as Celest® Top 312 FS in reducing disease and boosting plant growth in field trials (Díaz-Díaz et al., 2023).

3. CONCLUSION AND FUTURE PERSPECTIVES

Soilborne phytopathogens continue to pose a major threat to global crop production, leading to significant yield losses and undermining the sustainability of agricultural systems. The detrimental environmental impacts of chemical fungicides (especially their disruption of soil microbial communities) have led to an increasing emphasis on biological control strategies as more ecologically sound alternatives. Among these, rhizospheric microbes play a pivotal role due to their dual function in both enhancing plant growth and suppressing pathogenic organisms (Pandey & Yarzábal, 2019).

This review highlighted the key fungal and bacterial antagonists with demonstrated efficacy against *M. phaseolina*. Fungal biocontrol agents such as *Trichoderma*, *Aspergillus*, *Penicillium*, and *Chaetomium* function via multiple modes, including mycoparasitism, antibiosis, volatile organic compound (VOC) production, and triggering of induced systemic resistance (ISR). In parallel, bacterial genera like *Bacillus* and *Pseudomonas* provide disease suppression through both direct antifungal mechanisms (including the secretion of lipopeptides (iturin, fengycin, surfactin), DAPG, pyoluteorin, siderophores, and hydrolytic enzymes) and indirect activation of host plant defense pathways (Sabaté et al., 2019; Ajuna et al., 2024).

Moreover, additional bacterial genera such as *Burkholderia*, *Stenotrophomonas*, *Serratia*, and *Streptomyces* also exhibit notable antagonistic potential against *M. phaseolina*. These microbes suppress fungal growth through bioactive metabolites like pyrrolnitrin, catechol, cepacin, zeamin, and prodigiosin, while simultaneously promoting plant vigor via the biosynthesis of IAA, siderophores, and ACC deaminase (Zaman et al., 2021; Sarli et al., 2022; Gopalakrishnan et al., 2021). Many of these microbes also bolster plant immunity by enhancing the activity of defense-related enzymes such as POX, PPO, and PAL.

Recent investigations have brought attention to extremophilic bacteria from Antarctic and sub-Antarctic ecosystems as promising sources of novel biocontrol agents. These organisms, having evolved under harsh environmental pressures such as extreme salinity, drought, and low temperatures, may demonstrate greater stability and efficacy under stress-prone agricultural conditions (Acuña-Rodríguez et al., 2019; Danilovich et al., 2018). Noteworthy examples include *Stenotrophomonas proteamaculans* 136-137 and *Burkholderia gladioli* MB39, which exhibit strong antimicrobial activity and offer potential for application in stress-affected cropping systems (Sánchez et al., 2009; Sarli et al., 2021).

However, the effectiveness of biological control is not solely dependent on microbial selection; formulation technology also plays a vital role. The choice of carrier materials, shelf-life optimization, and thermal stability are critical parameters that determine field-level success. In this regard, microbial consortia (comprising complementary strains) are being increasingly recognized for their enhanced performance and broader pathogen suppression capabilities compared to single-strain formulations (Miljaković et al., 2020).

Looking ahead, the development of integrated biocontrol platforms that combine multiple microbial strains with complementary antifungal mechanisms and stress tolerance traits holds great promise for managing persistent soilborne pathogens like *M. phaseolina*. In-depth exploration of microbial biodiversity, especially from underexplored extreme environments, may lead to the discovery of novel bioactive metabolites and genetic traits for use in next-generation biofungicides and biofertilizers (Pandey & Yarzábal, 2019; Kunakom & Eustáquio, 2019).

In conclusion, rhizospheric and extremophilic microorganisms (owing to their combined roles in disease suppression, plant growth promotion, and stress mitigation) are poised to become the cornerstone of future sustainable agricultural biotechnology. Advancements in bioformulation technologies using key genera such as *Bacillus*, *Pseudomonas*, *Trichoderma*, *Burkholderia*, and *Streptomyces* are expected to pave the way for eco-friendly, cost-effective, and durable solutions against devastating pathogens like *M. phaseolina*, particularly in the context of a changing climate and increasing soil degradation.

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CHAPTER III

OVERWINTERING SITES MANAGEMENT AND INTEGRATED APPROACHES FOR BROWN MARMORATED STINK BUG-*HALYOMORPHA HALYS* Carl Stål (HEMIPTERA: PENTATOMIDAE)

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1. INTRODUCTION

The brown marmorated stink bug [*Halyomorpha halys* Carl Stål (Hemiptera: Pentatomidae)] has become a significant agricultural pest in Turkey over the past three years, causing economic losses in numerous crops, particularly hazelnuts. Its polyphagous feeding behavior and rapid dispersal capacity necessitate comprehensive and integrated approaches in pest management.

The species has spread to numerous countries, especially the United States and several European nations, and extensive research has been conducted regarding its management. Despite intensive efforts, it is difficult to conclude that current mechanical, biotechnical, and chemical control methods provide satisfactory or sufficient results (Özdemir & Tuncer, 2021a, 2021b).

The overwintering behavior of the brown marmorated stink bug in enclosed spaces makes conventional agricultural control methods difficult to apply effectively. Based on literature review and field observations conducted in Turkey, biocidal treatment techniques for overwintering sites, mechanical and cultural measures, and chemical control methods were examined. Indoor residual spraying (IRS) provides up to 90 days of persistent effect, making it one of the most effective methods for population suppression. Mechanical and cultural measures serve as complementary strategies that enhance the efficacy of chemical treatments.

An integrated approach that combines residual biocidal treatments with mechanical measures is strongly recommended, as these complementary strategies collectively enhance the suppression of overwintering populations, increase treatment persistence, and reduce the likelihood of reinfestation in early spring. To further improve management efficiency and ensure reproducibility across different regions and infestation levels, future studies should prioritize the quantitative assessment of treatment efficacy, long-term monitoring of population dynamics, and the development of standardized, evidence-based protocols that can guide practitioners and policymakers in implementing consistent and scientifically grounded control programs.

This study aims to emphasize the importance of biocidal treatments conducted in enclosed areas during the overwintering period, to outline the fundamental principles that should be followed during the control process, and to provide a scientifically grounded framework for chemical and mechanical methods applicable in overwintering site management. In this respect, the study serves as both a practical and academic guide for practitioners, field technicians, and researchers.

2. BROWN MARMORATED STINK BUG (*HALYOMORPHA HALYS*)

Over the past two decades, the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), an invasive and highly polyphagous pest that has rapidly spread worldwide and throughout Türkiye, has become a serious threat to numerous cultivated plants with more than 300 recorded host species (Rice et al., 2014; Hamilton et al., 2018). This rapid global expansion has been closely associated with its strong dispersal capability, high reproductive potential, and ability to exploit diverse ecological niches, characteristics that have driven similar invasion patterns in Europe and North America (Lee et al., 2013; Leskey & Nielsen, 2018).

The species was first detected in Türkiye in 2017 (Ministry of Agriculture and Forestry, 2017). Initial reports originated from the provinces of İstanbul and Artvin, and subsequent survey studies conducted in the following years confirmed its widespread presence across the Eastern Black Sea, Western Black Sea, and Marmara regions. As of 2025, under the national management program implemented by the Ministry of Agriculture and Forestry (2024), the pest has been recorded in 46 provinces and 212 districts, and regular monitoring and control activities continue in affected regions

Damage assessments conducted particularly in hazelnut orchards indicate that in samples with heavy brown marmorated stink bug infestation, kernel yield ranged between 25.40% and 32.76%, while moldy kernels were recorded at 20.00%, rotten kernels at 16.67%, and "lemon-shaped" kernels at 10.00%. In addition, even under short-term storage in ordinary warehouse conditions, hazelnuts severely damaged by the pest showed an increased tendency toward oxidation (Karakaya et al., 2024; Kan et al., 2024). Comparable post-harvest quality losses resulting from *H. halys* feeding damage have also been documented in apples, peaches, and berries across Europe and the United States (Leskey et al., 2012), underscoring the species' substantial economic impact across diverse cropping systems.

2.1. Biology and Behavior

Adults are 12-17 mm in length and exhibit a marbled pattern in shades of brown. Light-colored bands on the antenna segments are among the distinguishing features of the species (Figure 1).

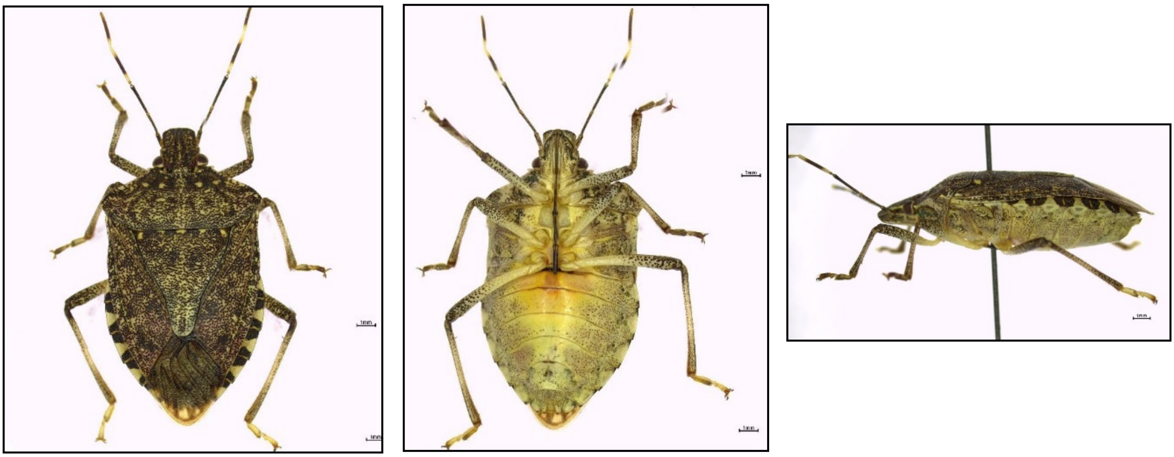

Figure 1. Dorsal(a) ventral(b) and lateral(c) views of the insect specimen (original photos by authors)

The eggs of the brown marmorated stink bug are smooth-surfaced and have a matte appearance. They are laid in clusters of 20–30 eggs. Newly hatched nymphs are brightly colored, exhibiting black and reddish-orange tones, and they spend their first instar aggregated on or around the egg mass (Hoebeke & Carter, 2003).

Under favorable conditions, they can produce 250-400 eggs per season. Nymphs emerging from eggs pass through five developmental stages before reaching adulthood. Depending on climatic conditions, the species typically produces 1-2 generations per year; in warmer regions, this number may reach up to three.

One of the most distinctive characteristics of this species is its tendency to seek enclosed and sheltered structures during autumn in preparation for overwintering. The aggregation tendency of *H. halys* becomes more pronounced in early autumn, coinciding with the period when individuals respond strongly to aggregation pheromones, leading to increased clustering in sheltered areas (Altanlar & Tuncer, 2023). When temperatures begin to decline, adults first exhibit dense aggregation behavior on exterior building walls (Figure 2).

Figure 2. Aggregation of adult *Halyomorpha halys* on exterior building walls prior to entering overwintering sites (orginal photos by authors)

They then move into narrow spaces such as houses, warehouses, attics, abandoned structures, wood piles (Figure 3), and gaps between bricks, where they overwinter in large aggregations

Figure 3. Wood piles and *Halyomorpha halys* adults exhibiting overwintering behavior among these piles (original photos by authors)

2.2.Necessity of Overwintering Site Management

Unlike other members of the Pentatomidae family, the brown marmorated stink bug (*Halyomorpha halys*) spends the winter not in open areas but in enclosed and sheltered spaces. This behavior enables the pest to survive low temperatures and maintain a high survival rate.

Studies have shown that during autumn, these insects enter houses, warehouses, attics, behind furniture, and wood piles, preferring narrow gaps (4.5-5.5 mm) for overwintering. It has been reported that they commonly aggregate in areas such as wall corners, gaps between wooden boards (Figure 4), and furniture behind (Cira et al., 2016; Chambers et al., 2020a; Chambers et al., 2020b; Leskey et al., 2012).

While other Pentatomidae species typically overwinter outdoors under vegetation or in soil, *H. halys* prefers man-made structures. This characteristic enhances its invasion capacity and amplifies its agricultural impact. (Leskey et al., 2012; USDA Forest Service, 2018a).

Figure 4. Halyomorpha halys adults sheltering inside buildings, in gaps between wooden boards, and in corner crevices (original photos by authors)

Enclosed spaces reduce temperature fluctuations, improving survival rates. Consequently, the pest migrates en masse to agricultural areas in spring, leading to rapid population growth (Chambers, 2018; Ciancio, 2018).

In Georgia, Halyomorpha halys (BMSB) has caused significant damage to hazelnut production; according to a report by StopBMSB, estimated losses in 2016 exceeded US $60 million (StopBMSB, 2020). In Italy, Halyomorpha halys (BMSB) has become a major pest of fruit orchards; estimated losses in fruit production in 2019 have been reported to exceed € 350 million (Maistrello et al., 2020). Despite intensive insecticide treatments in agricultural areas, the lack of overwintering site management led to uncontrolled population growth in both countries

Therefore, overwintering site management is a critical component of integrated pest management. Biocidal treatments applied in enclosed spaces remain among the most effective methods for controlling the brown marmorated stink bug.

3. OVERWINTERING-SITES TREATMENTS

Overwintering-site treatments should be addressed under three categories: cultural, mechanical-physical, and chemical control. Cultural control focuses on preventing pest entry into indoor spaces through structural improvements such as sealing cracks, installing door sweeps, repairing damaged screens, and improving insulation, which significantly reduce overwintering pressure. Mechanical control involves collection and cleaning practices, including vacuuming and manual removal of pests that have already entered, followed by proper disposal to prevent reinfestation (USDA Forest Service, 2018b). Chemical control should only involve biocidal products registered for indoor use;

plant protection products must never be applied indoors due to safety concerns.

Biocidal treatments in overwintering sites should be carried out between September and April when pest aggregation in enclosed spaces is highest. Autumn is the most critical period, as adults migrate from agricultural areas into shelters, responding strongly to environmental cues and aggregation pheromones (Chambers et al., 2020a; Altanlar & Tuncer, 2023).

Timely management interventions during this critical period effectively disrupt overwintering behavior and significantly reduce pest populations before spring emergence. This is particularly important, as overwintering success directly determines the intensity of early-season infestations and the extent of subsequent crop damage, thereby influencing overall yield losses and economic outcomes. Previous studies have highlighted the ecological and economic significance of overwintering dynamics. For instance, Cira (2017) reported that *Halyomorpha halys* aggregates in sheltered human-made structures during winter, and that physiological cold tolerance varies by season, sex, and acclimation location, influencing overwintering survival. Collectively, these findings underscore the need for timely and targeted interventions to mitigate early-season pest outbreaks and minimize crop damage.

These practices are integral to an integrated pest management (IPM) framework, combining preventive, physical, and chemical strategies to achieve sustainable pest management while minimizing environmental impact. Below are the methods that can be implemented within this framework.

3.1. Cultural, Mechanical and Physical Control in Overwintering Sites

These methods support chemical treatments by helping reduce population density:

- Removal of plant debris: Collect and dispose of organic materials that may serve as shelter for the pest around the houses.
- Cleaning overwintering sites: Regular inspection and cleaning of areas such as behind furniture, attics, and wood piles.
- Sealing entry points: Seal gaps around doors and windows with silicone or gaskets. These measures alone are insufficient but significantly enhance the effectiveness of biocidal treatments.

3.2. Chemical Control

Chemical treatments for overwintering sites should be applied when the pest is about to enter enclosed spaces and during the period it remains indoors (typically September-April in Turkiye).

These treatments aim to prevent the pest from leaving overwintering sites and migrating to agricultural areas, thereby suppressing population growth.

The following methods are recommended in accordance with WHO and Turkish Ministry of Health guidelines.

3.2.1. Residual Surface Treatments

All treatments must be performed using biocidal products licensed by the Ministry of Health. Residual surface treatment is the most effective method in overwintering site management because the insecticides used provide long-lasting activity. Depending on the product, residual efficacy can last up to 90 days, helping maintain population control.

Figure 5. Halyomorpha halys adults attempting to enter warm indoor areas through window and door edges (original photos by authors)

The areas to be treated are those where the pest enters enclosed spaces and prefers to overwinter. Starting from the building's exterior perimeter and prioritizing these zones for treatment will largely control the pest before it enters indoors. Inside the structure, key target areas include door and window frames (Figure 5), attics, eaves, behind cabinets and sofas, shoe racks, gaps between furniture and walls, wood piles, and storage rooms. In addition, unfinished buildings with brick gaps, abandoned structures, and unused materials (Figure 6) in warehouses are locations where the pest is commonly found. Therefore, residual treatments must be applied in these areas without exception.

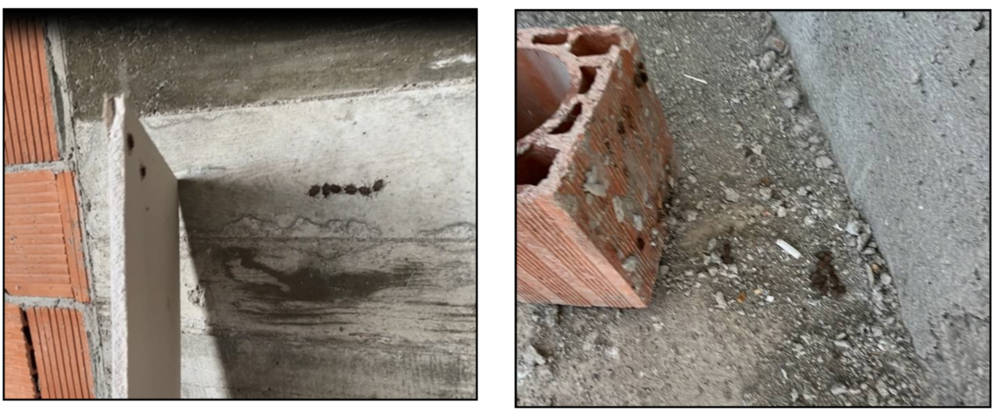

Figure 6. *Halyomorpha halys* adults sheltering among discarded materials and between bricks (original photos by authors)

3.2.1.1. Pre-Treatment Requirements

- All spraying equipment to be used must be thoroughly inspected and properly calibrated prior to treatment.
- Before treatment, the area should be inspected to identify locations where the pest hides, nests, moves, and rests.
- Prior to application, it is recommended to remove dust and dirt from the surfaces, as applying the treatment on clean surfaces enhances pesticide efficacy.
- For treatments in enclosed spaces, ventilation systems (such as air conditioners or fans) should be turned off, and doors and windows must be closed.
- The operator conducting the application (i.e., the individual responsible for performing the treatment) must always use appropriate personal protective equipment (PPE). (gloves, mask, and safety goggles).
- The area must be vacated by humans and animals during treatment.
- Food items must not be left exposed in the treatment area. If present, they should be sealed in plastic packaging or stored in closed cabinets.
- Even if packaged, treatments must not be applied directly to food items or to clothing and materials that encounter the human body.

3.2.1.2. Treatment Procedure

Once the pre-treatment requirements are done, the treatment device should be filled halfway with water, then the required amount (which is on the product label) of product is added. Close the lid and shake thoroughly, then add the remaining water and shake again to ensure proper mixing.

During spraying, the nozzle should be positioned 40–45 cm from the surface. The ideal spraying pressure is between 35–55 psi, with an optimum of 45 psi. Correct dosage and pressure settings are critical for treatment effectiveness. On average, a one-minute spray should deliver approximately 750 ml of solution. This ensures uniform coverage and promotes contact with the target pest (WHO, 2022b).

A good surface coating must be achieved, and the active ingredient should be applied at the dose specified on the product label. For example, treatments with Deltamethrin 5% SC formulations require 0.03 g a.i/m^2 as effective dose (Figure 7)

Figure 7. Dead *Halyomorpha halys* adults following application with a biocidal product formulated as Deltamethrin 5% SC (original photos by authors)

The area should remain closed for at least 30 minutes after the treatment, followed by ventilation for at least 60 minutes. Kitchen surfaces and utensils exposed during treatment must be washed thoroughly with soapy water before use.

After pesticide application, the spraying equipment tank must be immediately cleaned. Any remaining solution in the tank should be emptied (preferably onto the treated area, if permitted) and the tank rinsed three to four times with clean water; a single rinse is insufficient. The tank, hoses, filters, nozzles, pumps, and all other components must be thoroughly cleaned. Additionally, any personal protective equipment used during spraying (gloves, masks, etc.) should not be reused if disposable. All cleaning operations should be carried out in an area equipped with appropriate wastewater treatment, and the resulting rinse water must never be discharged into ponds, rivers, or other natural water sources. After washing, the tank should be completely drained and left open to dry. All components of the equipment should be inspected, worn or damaged parts replaced, and the equipment prepared for the next application.

3.2.2. Thermal Fogging Treatments

According to WHO guidelines, thermal fogging should only be used in emergency situations or when rapid suppression of high pest populations is required, as it provides only short-term effects (WHO, 2022a).

Field observations in the Eastern Black Sea region indicate that thermal fogging treatments applied in overwintering sites (particularly in attics, storage lofts, and narrow spaces between wood piles) can help achieve immediate population reduction. However, this effect is temporary, and thermal fogging does not provide residual activity.

It should also be noted that no product is currently registered for this method in Turkey; therefore, thermal fogging should be considered only as a supplementary measure and must never replace residual surface treatments.

4. CONCLUSION AND RECOMMENDATIONS

The overwintering period represents one of the most critical stages in the management of the brown marmorated stink bug, offering a strategic opportunity for intervention based on the pest's biology and behavioral characteristics. The aggregation and inactivity of the pest in enclosed spaces during winter significantly increase the effectiveness of biocidal treatments applied at this time, directly influencing the intensity of spring migration into agricultural areas.

Therefore, an integrated approach combining mechanical measures with residual chemical treatments is essential. Mechanical control during the overwintering periods, such as sealing entry points, improving indoor sanitation, and organizing high-risk areas like wood piles and storage sites-reduces the pest's sheltering capacity. Although these methods alone are insufficient, they play a complementary role in enhancing the success of chemical treatments.

Residual surface treatments maintain long-term efficacy in enclosed spaces, killing overwintering adults through contact. Correct dosage, optimal spraying pressure, and uniform distribution on target surfaces are key factors determining the success of this method.

Although comprehensive scientific studies on this subject remain limited, field observations and international experiences consistently show that field observations and international experiences indicate that regions without overwintering site management exhibit significantly higher spring populations. Similar dynamics have been observed in Turkey, where intensified biocidal overwintering-site treatments resulted in a marked reduction in pest migration to agricultural areas during spring.

Increasing awareness, providing training for farmers on treatment practices, and ensuring abandoned structures are treated by local authorities will further improve control effectiveness.

In conclusion, the overwintering period is a critical control point in managing the brown marmorated stink bug. Residual treatments in enclosed spaces, supported by mechanical measures, suppress population growth before spring and reduce agricultural damage. The information presented in this study offers a scientifically grounded framework for practitioners and technical personnel, while future research should focus on developing regional risk maps, quantitatively assessing treatment efficacy, and establishing standardized protocols.

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CHAPTER IV

POST-WILDFIRE SOIL MEASUREMENT METHODS

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1. INTRODUCTION

Fire intensity and duration determine the extent of soil heating, which alters organic matter, pore structure, hydrophobic layers, nutrient availability, and microbial activity. These transformations shape post-fire runoff, sediment dynamics, and vegetation regrowth. Because soil responses shift from immediate to long-term timescales, effective monitoring requires both rapid evaluations (such as ash leaching and water repellency tests) and extended observations (such as infiltration recovery and erosion measurements). This chapter presents a practical toolkit of sampling strategies, protocols, and examples that can be applied across scales from individual plots to entire catchments.

Post-wildfire soil monitoring relies on a combination of field sampling, laboratory analysis, and remote sensing approaches. Field sampling includes soil core extraction for bulk density and porosity, aggregate stability testing, and hydrophobicity assessments using methods such as the Water Drop Penetration Time (WDPT) and Molarity of Ethanol Droplet (MED) tests (Jones et al., 2020). Laboratory analyses assess organic matter, nutrient dynamics, pyrogenic carbon, and particle size distribution. Recent studies emphasize integrating field data with geospatial tools for more comprehensive assessments (Martínez et al., 2022).

In the last years, researches have advanced our understanding of how soils recover after wildfire. Studies show that soil respiration and carbon cycling undergo long-term changes, with altered microbial activity persisting for decades after severe burns (Johnson et al., 2023). Similarly, hydrophobicity can persist for multiple seasons, affecting infiltration and runoff dynamics (Garcia & Torres, 2021). Modeling approaches such as the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) have been widely used to predict erosion under post-fire conditions (Chen et al., 2022). Case studies demonstrate that rehabilitation structures like log erosion barriers and silt fences are effective but need to be combined with vegetation restoration for long-term resilience (Nguyen et al., 2024).

Understanding post-fire soil dynamics has direct policy implications. Effective soil monitoring informs hazard mitigation strategies, such as erosion control measures and slope stabilization in vulnerable landscapes (Peterson et al., 2021). Public health concerns have also emerged, particularly regarding heavy metal mobilization in urban soils affected by wildfires (Ramirez et al., 2022). Policymakers are increasingly adopting integrated fire and soil management strategies that combine rapid assessments with long-term monitoring. These policies are supported by advances in technology and the availability of open-access satellite imagery.

Future monitoring programs should adopt a multi-scale approach that integrates rapid assessments (e.g., hydrophobicity tests, ash leaching studies) with long-term data collection (e.g., soil organic matter recovery, microbial activity). Remote sensing tools should be combined with field measurements to prioritize restoration areas. Best practices include: (1) developing standardized soil monitoring protocols, (2) integrating modeling with empirical data, and (3) promoting cross-disciplinary collaboration among soil scientists, hydrologists, and ecologists (Hernandez et al., 2023).

Below are mostly used field and laboratory methodologies derived from research practices.

2. FIELD SAMPLING TECHNIQUES

Field methods provide rapid, on-site characterization of the fire's effect on the soil, often focusing on Burn Severity and Hydrological Changes.

2.1. Soil Core Sampling

Soil core sampling in post-wildfire environments is a critical research and safety procedure used to collect undisturbed, cylindrical soil samples for laboratory analysis. This process helps scientists and property owners understand the physical, chemical, and biological changes that occur in soil after a wildfire. The primary goals of collecting soil cores after a fire are to assess Heavy metals and organic pollutants and to evaluate soil properties such as soil water repellency, hydraulic conductivity/infiltration rate, and soil bulk density and aggregation. Depths of soil often include 0–10 cm, 10–20 cm, and 20–30 cm layers (Figure 1).

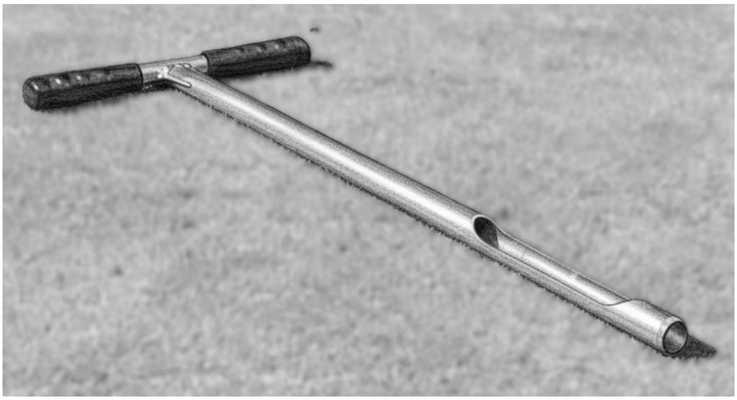

Figure 1. Soil Sampling Auger

Aggregate Stability Tests:

The Aggregate Stability Test evaluates how well soil aggregates—clusters of sand, silt, and clay particles held together—can withstand breaking apart when exposed to disruptive forces such as water (rainfall or irrigation) or mechanical disturbance from tillage. It is an essential measure of soil health, as the stability of these aggregates plays a key role in maintaining many critical soil functions. High aggregate stability is critical for maintaining a productive and healthy soil system. Stable aggregates are less likely to break apart when exposed to raindrop impact or wind, reducing both water and wind erosion. Stable aggregates contribute to a well-structured pore system in the soil. Larger pores between aggregates promote fast water infiltration and allow air to move freely to plant roots and soil organisms. Smaller pores within aggregates help retain moisture. A well-aggregated soil provides natural pathways that make it easier for roots to penetrate and expand. Aggregate stability is strongly associated with soil organic matter and biological activity—key drivers of nutrient availability and turnover. When aggregates are unstable, they break down into fine particles that can clog surface pores. As the soil dries, this forms a hard crust that limits water infiltration and makes it difficult for seedlings to emerge.

Aggregate stability tests often involve a process that simulates a disruptive event, most commonly exposing a soil sample to water. There are various methods, but they generally fall into two categories:

1. Wet Sieving: A soil sample is placed on a sieve and immersed in water, often with a mechanical up-and-down motion. The amount of soil that remains on the sieve after a certain period indicates the stability of the aggregates.

2. Slake Test: This is a fast, simple visual test, often used for on-farm demonstrations.

The wet sieving method is the most widely used quantitative technique for determining soil aggregate stability, as it provides a numerical stability index. In this procedure, air-dried aggregates within a selected size fraction (e.g., 1–2 mm or 2–5 mm) are placed on a nested series of sieves with progressively smaller mesh sizes. The sieve stack is submerged in water and oscillated vertically at a controlled frequency for a defined duration (typically 3–10 minutes). Upon wetting, aggregates may disintegrate due to slaking processes such as entrapped air expansion and clay swelling, causing unstable particles to pass through the sieves (Figure 2). The soil retained on each sieve is then oven-dried and weighed. Aggregate stability is subsequently quantified using indices such as the Mean Weight Diameter (MWD) of the retained fractions or the Percentage of Water-Stable Aggregates (%WSA). Higher values of MWD or %WSA represent greater aggregate stability.

Figure 2. Test sieves for testing soils

Slake Test is a simpler, more qualitative test where a dry soil clod is simply placed in water. The observer watches how quickly and completely the clod disintegrates, with rapid disintegration indicating poor aggregate stability (Figure 3). The results of these tests can help farmers and land managers evaluate the health of their soil and make informed decisions about practices like tillage and cover cropping to improve soil structure over time.

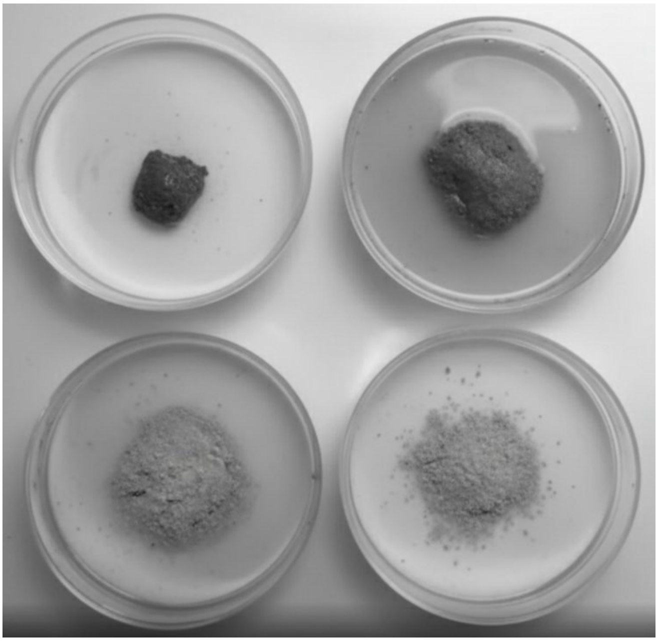

Figure 3. Slake Test

Hydrophobicity assessment involves evaluating the degree, persistence, and spatial variation of water repellency created by the heat-induced volatilization and redistribution of organic compounds. Hydrophobicity is typically measured using standardized field or laboratory tests. Most used tests are; Water Drop Penetration Time, and Molarity of Ethanol Droplet tests.

Water Drop Penetration Time (WDPT): Apply water droplets to soil surfaces to determine hydrophobicity persistence. WDPT measures the time it takes for a water drop to be completely absorbed by the soil after it hits the ground.

Molarity of Ethanol Droplet (MED) Test: Identify the minimum ethanol concentration required for droplet penetration, quantifying hydrophobic strength. The test uses a series of ethanol solutions with different concentrations. A single droplet of a solution is placed on a soil sample. Ethanol is used because it lowers the surface tension of water. The point at which a droplet just starts to soak into the soil within a 5-second window is recorded. The molarity of that specific ethanol solution is called the MED value. This test is often used to study soils after wildfires, where the intense heat can create organic coatings that make the soil water-repellent. Understanding soil hydrophobicity (wettability) is crucial in hydrology and soil science as it helps predict and explain phenomena like surface runoff, water infiltration, and soil erosion.

3. LABORATORY ANALYSIS

Key laboratory methods for analyzing the physical and chemical properties of soil and sediment includes focusing on organic matter, nutrients, pyrogenic carbon, texture, and metal mobility.

3.1. Organic Matter and Nutrients

The Walkley–Black method is a widely used chemical procedure to measure soil organic carbon (SOC). it’s a wet oxidation method that provides an estimate of soil organic carbon, important for soil fertility, carbon cycling, and land management studies. Soil is treated with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4), which oxidize the organic carbon. The remaining dichromate (not consumed in oxidation) is then titrated with ferrous sulfate ($FeSO_4$) to determine how much was used. From this, the organic carbon content of the soil is calculated.

The Kjeldahl digestion method is a classic technique used to measure total nitrogen (TN) in soils, plants, and other materials. The sample is digested with concentrated sulfuric acid (H_2SO_4), often with a catalyst (like selenium, copper, or mercury), which converts organic nitrogen into ammonium (NH_4^+). After digestion, the solution is made alkaline, releasing ammonia gas (NH_3). The ammonia is then distilled and captured in a trapping solution, and its amount is measured by titration. Kjeldahl digestion converts all nitrogen in a sample into a measurable form (ammonium/ammonia), allowing calculation of total nitrogen content, which is important for soil fertility and nutrient studies.
Colorimetric/Flame Photometric Methods quantify total phosphorus (TP) and potassium (TK).

-Pyrogenic Carbon (PyC) analysis is the study and measurement of carbon that is produced when organic matter (like vegetation or litter) burns incompletely during fires. This material is often called black carbon, charcoal, or biochar. PyC is more resistant to decomposition than regular organic matter, so it can persist in soils and sediments for centuries.

Analysis methods include:
Chemical oxidation (e.g., with dichromate or nitric acid) to isolate resistant carbon.
Thermal/thermogravimetric analysis to detect carbon that withstands high temperatures.
Spectroscopic methods (e.g., NMR, Raman, or FTIR) to study molecular structure.
Benzene polycarboxylic acids (BPCA) method for precise quantification.
PyC analysis measures how much fire-derived, stable carbon is present in soil or sediment, helping scientists understand fire history, carbon cycling, and long-term soil fertility.

- Particle Size Distribution: Determine texture changes using sieve and hydrometer methods (for sand/silt/clay) or laser diffraction. Report the full gradation curve and textural class. Avoid ash contamination by removing loose ash before sampling or treating it as a separate layer for analysis.

To determine soil texture (sand, silt, clay proportions), scientists use:

Sieve method → separates coarse fractions (sand) by particle size.
Hydrometer method → measures suspension density over time to calculate finer fractions (silt and clay).
Laser diffraction → uses light scattering to estimate the full particle-size distribution quickly.

The results are plotted as a gradation curve, and soil is assigned a textural class (e.g., sandy loam, silty clay) using standard classification charts. Because wildfire ash can alter results, loose ash should be removed before sampling or analyzed separately as its own layer, so that soil texture reflects the actual mineral soil beneath.

- Laser diffraction (e.g., MasterSizer 2000) to classify clay, silt, and sand content. Laser diffraction is a rapid particle size analysis method used to classify soil into clay, silt, and sand fractions. For this following steps are applied.

A soil sample is dispersed in water (sometimes with dispersing agents).

A laser beam passes through the suspension, and particles scatter light at different angles.

Large particles (sand) → scatter light at small angles.
Medium particles (silt) → scatter at intermediate angles.
Very small particles (clay) → scatter at wide angles.
The instrument converts this scattering pattern into a particle size distribution curve.

From this, the proportions of sand, silt, and clay are calculated, and the soil can be assigned a textural class (e.g., loam, sandy clay).

In short: laser diffraction measures how soil particles scatter light to quickly determine their size distribution and classify texture.

3.2. Metal Mobility Testing

Metal mobility testing is a laboratory procedure used to evaluate how easily metals (like Pb, Zn, Cu, Cd, etc.) can move or leach out from soils, sediments, or ash under environmental conditions. It helps determine whether metals are tightly bound to soil particles or mobile and potentially hazardous.

3.3. Common approaches include

Leaching tests (e.g., Toxicity Characteristic Leaching Procedure, TCLP) → simulate rainwater infiltration.
Sequential extraction → separates metals into fractions (exchangeable, bound to carbonates, oxides, organic matter, residual).

Results indicate the environmental risk of metal contamination, such as groundwater pollution or bioavailability to plants.
In short: metal mobility testing shows how likely metals are to move from soil/sediment into water or living organisms.

4. REMOTE SENSING & GEOSPATIAL MODELING

- Fire Severity Mapping:
- Use differenced Normalized Burn Ratio (dNBR) or Relative dNBR (RdNBR) from satellite imagery (e.g., Landsat, Sentinel-2) to classify burn severity.

4.1. Erosion Risk Prediction

- Combine rainfall-runoff models (e.g., SCS-CN method) with soil erodibility factors (e.g., RUSLE) in GIS frameworks.
- Monitor vegetation recovery via Normalized Difference Vegetation Index (NDVI) to infer ground cover impact on erosion.

4.2. Drone-Based Multispectral Imaging

- Deploy drones for high-resolution canopy-under soil surveys, bypassing vegetation interference in spectral indices.

5. HYDROLOGICAL IMPACT ASSESSMENT

- Runoff and Sediment Yield Monitoring:
- Install plots or sensors to measure post-fire runoff rates and sediment transport during rain events.

- Soil Water Repellency Studies:
- Correlate hydrophobic layer depth/strength with soil temperature profiles during fires (lab simulations or field measurements).

6. LONG-TERM MONITORING STRATEGIES

6.1. Pre- and Post-Fire Comparisons

- Pair pre-fire baseline data with post-fire samples (e.g., forest floor depth, mineral soil C/N ratios) to quantify losses.

6.2. Time-Series Sampling

- Track recovery over multiple years (e.g., 1–3 years post-fire) to assess nutrient dynamics and microbial activity.

7. INTEGRATION OF METHODS

Effective post-fire management often combines field data (e.g., soil cores, hydrophobicity tests) with remote sensing outputs (e.g., NDVI, dNBR) to prioritize restoration efforts. For instance, transitional ecosystems (rangelands, shrublands) show heightened vulnerability to erosion, necessitating targeted interventions.

For further details, consult studies integrating PCA-based minimum data sets (MDS) for soil quality indexing or regional case studies using Sentinel-2 imagery for erosion modeling.

8. CONCLUSIONS

Post-wildfire soil assessments benefit from an integrated strategy combining rapid field indicators, targeted hydrologic tests, erosion monitoring, and laboratory analyses. Standardized protocols and rigorous QA/QC enable comparisons across burn severities, landscapes, and years, ultimately supporting hazard mitigation and ecosystem recovery.

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CHAPTER V

THE UNSEEN HAZARD: A TECHNICAL ANALYSIS OF POST-WILDFIRE SOIL EVOLUTION AND ITS IMPACT ON GEOTECHNICAL STABILITY

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1. INTRODUCTION

Wildfires and agricultural land fires are one of the most important factors threatening people and their habitats in the world. They are increasing in frequency and severity globally, fundamentally altering hydrological and geomorphic processes in burned catchments (Figure 1). A primary post-fire hazard is the generation of destructive debris flows, often triggered by modest rainfall events.

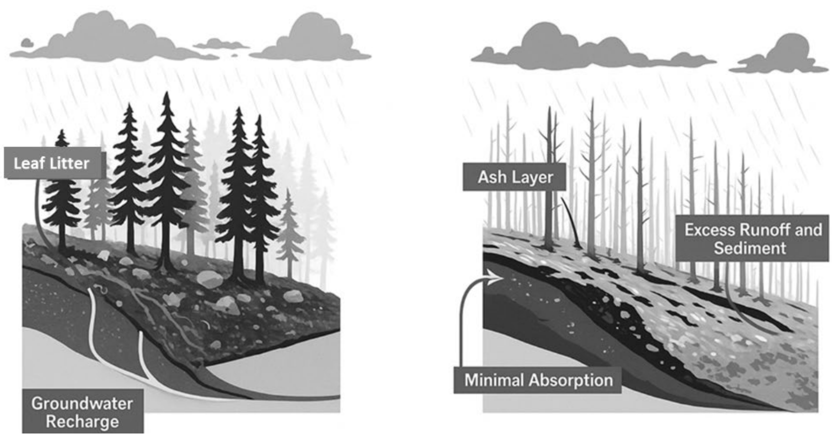

Figure 1. Post-Wildfire Debris Flow Overview – Hydrophobic Soils

After a wildfire hillsides are left bare and unstable, damaged soil and the loss of vegetation make landscapes highly susceptible to erosion. This triggers a sediment cascade. When it rains, a huge amount of soil, ash, and rock gets washed away in a chain reaction called a sediment cascade.

The immediate danger of a wildfire is often followed by a less visible but equally perilous phase of hydrological and geomorphic instability. With the increasing global frequency and severity of wildfires, it is imperative to understand the cascading hazards that emerge long after the fire has been extinguished. When a fire removes vegetation and alters the ground surface, the landscape becomes highly susceptible to erosion and slope failure, fundamentally altering the watershed's hydro-geomorphic response to precipitation.

The escalating trend of large and severe wildfires, driven by climate change and historical land management practices, has created a new urgency in understanding post-fire landscape response (Westerling, 2016). Wildfires dramatically alter watershed characteristics by removing vegetation cover, combusting soil organic matter, and often inducing soil-water repellency (hydrophobicity) (Shakesby & Doerr, 2006). These changes reduce rainfall infiltration and increase surface runoff, leading to accelerated soil erosion and a heightened risk of catastrophic debris flows—rapidly moving slurries of water, sediment, and rock (Cannon et al., 2008).

Post-wildfire debris flows pose a severe threat to life, property, and critical infrastructure located at the base of burned watersheds. The 2018 Montecito, California event, which resulted in 23 fatalities and over $1 billion in damages, stands as a stark reminder of the destructive potential of these phenomena (Kean et al., 2019). Consequently, significant research has focused on developing empirical and physically-based models to predict the probability and volume of debris-flow initiation from burned hillslopes, often based on rainfall intensity-duration (ID) thresholds, burn severity, and soil properties (e.g., Staley et al., 2017).

The primary post-fire hazards are destructive flash floods and debris flows—fast-moving, sediment-rich slurries of water, soil, and rock. These events are the result of a sediment cascade, where rainfall on a bare, damaged landscape triggers a chain reaction of erosion. The 2018 debris flow in Montecito, California, which claimed 23 lives and caused over a billion dollars in damage, serves as a stark reminder of the destructive potential of these post-fire phenomena.

However, debris flows are not isolated hillslope events; they are the initial phase of a larger sediment cascade. Once initiated, a debris flow enters the channel network, where it can bulk (entrain additional sediment from the channel bed and banks), be diluted into a hyperconcentrated flow, or deposit its load due to changes in channel gradient or confinement. The routing of this sediment pulse through the fluvial network determines the ultimate location and magnitude of the downstream hazard. Existing models often treat these two components—initiation and routing—in isolation.

This disconnection represents a critical limitation in our ability to comprehensively forecast post-wildfire geomorphic risk.

Once the smoke clears from a wildfire, the danger is not over. Other hazards, such as flash floods and debris flows, now become the focus. Areas recently burned by wildfires are particularly susceptible to flash floods and debris flows during rainstorms.

Just a short period of moderate rainfall on a burn scar can lead to flash floods and debris flows. Rainfall that is normally absorbed by vegetation can run off almost instantly. This causes creeks and drainage areas to flood much sooner during a storm, and with more water, than normal. Additionally, the soils in a burn scar are highly erodible so flood waters can contain significant amounts of mud, boulders, and vegetation. The powerful force of rushing water, soil, and rock, both within the burned area and downstream, can destroy culverts, bridges, roadways, and structures, and can cause injury or death if care is not taken.

Wildfire is an agent of rapid geomorphic change. By combusting vegetation and organic surficial material, and by driving physical and chemical modifications in soils (e.g., surface sealing, hydrophobicity), wildfires increase surface runoff, reduce infiltration, and liberate sediment that can be transported rapidly downslope during subsequent storms. In steep, burned terrain this process often manifests as debris flows — fast, sediment-rich flows — which can entrain additional channel and hillslope sediment and travel long distances, causing disproportionate damage to downstream communities and infrastructure.

In the first few months following a wildfire, the condition of the soil is of critical importance. This initial phase is characterized by a dramatic reduction in the soil's ability to absorb water, which directly elevates the risk of surface runoff, flash floods, and severe erosion. Rainfall that would normally soak into the forest floor is instead converted into immediate, powerful overland flow, capable of mobilizing vast quantities of loose ash and sediment.

The resulting pathway of elevated sediment flux from hillslopes to channel networks and ultimately to downstream depositional zones is usefully described as a post-wildfire sediment cascade. Understanding, predicting, and mitigating these cascades requires linking fuel and burn characteristics, short-duration storm triggering, initial sediment mobilization and debris-flow initiation, and network-scale routing and repeated re-mobilization of sediment. The literature documents each of these components, and more recent efforts aim to integrate them into spatially explicit forecasting frameworks.

1. **Landslides Start:** Loose material slides down the burnt hills.
2. **Debris Flows Form:** This material mixes with water in streams, creating fast-moving, destructive debris flows.
3. **Sediment Gets Stuck:** The debris stops in flatter areas, clogging up valleys.
4. **It Moves Again:** Over time, this trapped sediment is slowly washed further downstream into rivers, reservoirs, and eventually the ocean.

To protect people and our water, we need to predict where this sediment is going, how much of it gets stuck, and when it might move again. This requires new models that can track the sediment's entire journey, not just the initial landslide.

After a fire, sediment moves in many different ways—from small trickles of soil to massive debris flows. This material doesn't just flow smoothly downstream; it gets held up by natural **bottlenecks** like tight canyons or where rivers meet. These bottlenecks create a stop-and-go traffic jam for sediment.

Debris flows are one of the most dangerous and destructive consequences of wildfires. These events are often mistaken for simple floods, but they are far more hazardous. A debris flow is a fast-moving, destructive landslide. It's a dense mixture of water, mud, rocks, burned vegetation (like trees and branches), and other debris. These flows destroy homes, and may potentially bury entire communities.

2. WHY WILDFIRES INCREASE DEBRIS-FLOW RISK

Wildfires dramatically alter the landscape, making it highly susceptible to debris flows with two primary reasons:

1. Loss of Vegetation: Wildfires burn away the plants, trees, and leaf litter that normally intercept rainfall and help anchor the soil with their root systems. Without this protective cover, rainwater hits the ground directly and with greater force.

2. Altered Soil Properties: Intense heat from a fire can change the chemical and physical properties of the soil, making it hydrophobic, or water-repellent. This means the ground can no longer absorb water effectively. Instead of soaking into the soil, rainwater quickly accumulates on the surface and begins to run downhill.

2.1. The Trigger: Rainfall

After a fire, an area becomes extremely vulnerable to rainfall. Even a short, intense burst of rain can be enough to trigger a devastating debris flow. As the surface runoff moves down the burned slopes, it gathers loose soil, ash, rocks, and burned logs.

This mixture quickly gains volume, speed, and destructive power, creating a thick, fast-moving slurry. The danger is highest during the first few years after a fire, before vegetation has had a chance to grow back and stabilize the soil.

In the first few months following a wildfire, the condition of the soil is of critical importance. This initial phase is characterized by a dramatic reduction in the soil's ability to absorb water, which directly elevates the risk of surface runoff, flash floods, and severe erosion. Rainfall that would normally soak into the forest floor is instead converted into immediate, powerful overland flow, capable of mobilizing vast quantities of loose ash and sediment.

Scientific analysis of burned soils reveals two primary mechanisms responsible for this initial decrease in soil hydraulic conductivity:

Soil Hydrophobicity: Intense heat from the fire vaporizes organic compounds in the surface litter, which then penetrate the soil profile and condense on cooler soil particles below, creating a waxy, water-repellent layer. Field tests confirm that soil in medium- and high-severity burn areas can transition from having "non-water repellency" to exhibiting "weak and moderate water repellency." This hydrophobic layer acts as a barrier, preventing rainwater from infiltrating the soil.

Ash Clogging: The fire deposits a layer of fine ash and carbon particles on the ground surface. During the first rainfall events, this material is washed into the soil's pores, physically blocking the pathways through which water would normally travel. Observations using scanning electron microscopy confirm that the soil skeleton becomes filled with a large amount of ash, effectively sealing the surface.

The combined effect of these mechanisms is a profound reduction in the soil's infiltration capacity. In studies of medium- and high-severity burn areas, saturated hydraulic conductivity was observed to decrease to 49% and 28%, respectively, of the levels found in unburned soil within the first two months. This impairment of the soil's primary hydrological function creates the perfect conditions for severe surface erosion. However, while these initial changes are significant, the soil undergoes further, less intuitive transformations that redefine the hazard landscape over the following years.

2.2. The Counterintuitive Recovery: Macropore Formation and Increased Infiltration

One to two years after a wildfire, a significant and unexpected shift occurs in the soil's hydrological behavior. Contrary to what might be expected, the soil's ability to absorb water does not simply recover to its previous state; in many cases, it can dramatically exceed its pre-fire capacity. This counterintuitive change creates a new and distinct hazard profile, where the primary risk shifts from surface runoff to deep soil saturation.

The primary mechanism driving this hydrological shift is the formation of large, preferential flow paths, or macropores, within the soil structure. The fire kills the root systems of trees and understory vegetation. Over the subsequent months and years, these dead roots decay and decompose. Microscopic observations of soil profiles clearly show that this process leaves behind a network of hollowed-out channels. These newly formed macropores act as conduits, allowing rainwater to bypass the soil matrix and infiltrate much more rapidly and deeply into this transformation is critical. Over time, rainwater erosion washes away the ash and hydrophobic compounds, eliminating the initial barriers to infiltration. The simultaneous creation of macropores then dramatically increases the overall hydraulic conductivity. This profound increase in infiltration capacity primes the soil mantle for deep saturation, a critical precondition for slope failure, which becomes the dominant threat as the soil's internal reinforcement simultaneously degrades.

2.3. The Unseen Weakness: Progressive Degradation of Soil Shear Strength

The stability of soil on a hillslope is critically dependent on its internal strength, particularly the reinforcement provided by the dense network of plant roots. This soil-root system provides critical apparent cohesion, binding soil particles together and anchoring the soil mantle to the slope. This section analyzes how fire initiates a progressive, time-dependent decay of this natural reinforcement, fundamentally weakening the soil and increasing its susceptibility to landslides.

Synthesized findings from post-fire soil analysis detail several interconnected mechanisms of this mechanical degradation:
Root System Decay: High-temperature fires kill plant roots, initiating a process of decomposition. In medium- and high-severity burn areas, the number of roots was observed to decline by 46%-58% within two years of a wildfire.

Loss of Tensile Strength: The roots that remain in the soil do not retain their strength. As they decompose, their structural integrity weakens. Studies found a 36%-47% reduction in tensile strength for fine roots (those with a diameter less than 2 mm) two years after a fire.

Collapse of Soil Cohesion: Soil cohesion is the force that binds soil particles together, and it is the primary component of shear strength enhanced by roots. The physical loss and weakening of the root system directly translate to a critical loss in soil cohesion, with a reduction of 55% in medium-severity areas and up to 82% in high-severity areas two years after the fire.

Alteration of Soil Composition: High-temperature fires can also alter the soil's texture. The intense heat causes fine clay particles to aggregate into larger, stable sand-sized particles. This change in granulometric composition further reduces the soil's natural cohesion. This textural shift can also contribute to changes in the soil's hydraulic properties, further complicating the long-term recovery.

In stark contrast to the dramatic decline in cohesion, the soil's internal friction angle—a measure of the friction between soil particles—shows negligible changes post-fire. This confirms that the loss of root reinforcement is the dominant factor in the degradation of soil strength. In conclusion, the combination of widespread root decay, reduced root strength, and fire-induced textural changes results in a soil mantle that is substantially weaker and more susceptible to failure than it was before the fire.

3. SYNTHESIS: THE TEMPORAL EVOLUTION OF POST-WILDFIRE GEOHAZARDS

The hydro-mechanical properties of soil do not change in isolation. Their combined evolution creates a distinct, time-dependent hazard profile for burned landscapes, where the nature of the dominant threat shifts significantly from the immediate aftermath to the years that follow. Understanding this temporal evolution is crucial for accurate risk assessment and mitigation.

The post-fire hazard profile can be summarized in two distinct phases:

Phase 1: Immediate Aftermath (0-6 Months): This phase is defined by low infiltration and only the initial stages of root strength loss. The soil surface is sealed by a hydrophobic layer and clogged with ash, causing most rainfall to run off immediately. The dominant hazard is severe surface water runoff because the intact (though dying) root system still provides significant residual cohesion, preventing widespread slope failure despite intense surface erosion. This leads to sheet and gully erosion and generates ash-laden flash floods that can impact downstream areas.

Phase 2: Transition and Deepening Hazard (1-2+ Years): This phase is defined by a hazardous convergence: the formation of macropores creates express pathways for water to reach deeper soil layers, while the near-total loss of root-derived cohesion means those same layers have lost their ability to resist failure once saturated. This combination of high infiltration and critically low soil cohesion significantly increases the risk of deep-seated soil saturation, which can trigger shallow landslides and destructive debris flows, even from modest rainfall events.

It is essential for emergency planners and land managers to recognize that the primary geohazard threat is not static. Risk assessment must account for this temporal evolution, as a landscape initially prone to surface flooding can become highly susceptible to catastrophic slope failure within just a few years.

4. CONCLUSION AND IMPLICATIONS FOR RISK MANAGEMENT

This analysis demonstrates that the aftermath of a wildfire is a period of dynamic and escalating geotechnical risk. The core finding is that the temporal evolution of soil properties creates a hazardous landscape that shifts from being dominated by surface runoff and erosion in the first year to being highly susceptible to deep infiltration and slope failure in the subsequent one to two years. This transition from flood risk to landslide risk demands a more sophisticated and time-aware approach to post-fire management.

The technical findings presented in this paper translate directly into several key implications for effective risk management:

Dynamic Hazard Assessment: Debris-Flow Hazard Assessment (DFHA) maps must consider the time elapsed since the fire. A hazard map produced three months post-fire may underestimate the landslide risk that will exist at the two-year mark, as the triggers and failure mechanisms evolve.

Informed Monitoring: Post-fire monitoring should track not only vegetation regrowth but also geomorphic signs of instability, leveraging satellite and airborne imaging to monitor metrics such as surface displacement, vertical land motion, and surface disturbance.

Targeted Early Warnings: Early-warning systems, such as the demonstration project operated by NOAA and the USGS, must adapt their alert criteria over time. Consequently, rainfall intensity-duration thresholds for debris-flow initiation are not static; they are likely to decrease as soil cohesion diminishes, meaning less intense storms can trigger catastrophic failures in subsequent years.

Ultimately, treating post-wildfire landscapes as static systems is a critical error in risk assessment. The findings herein demand a move towards adaptive management frameworks where hazard models, monitoring priorities, and public warnings evolve in lockstep with the predictable, dangerous evolution of the soil itself.

4.1. What do we do?

Hazard Assessments: For major wildfires, Debris-Flow Hazard Assessment (DFHA) maps should be developed. These maps include data on basin topography, soil properties, burn severity, and local rainfall patterns to predict the likelihood and potential size (volume) of a debris flow from a specific drainage basin. This information is crucial for emergency managers, officials, and residents to take protective measures.

Post-Fire Monitoring: The relevant agencies conduct research by monitoring burned areas over time. This helps them understand how the risk of debris flows changes as the landscape recovers and vegetation regrows.

Debris-Flow Flume Research and Inundation Modeling: In order to create more accurate predictive models, researchers may focus on building and operating a large-scale experimental facility (for example a "flume") to study the physics of how debris flows start and move. Scientists may also develop advanced models to predict not just where a debris flow might start, but also how far it will travel and which areas it will inundate (flood). Current satellite/airborne imaging technologies may be efficiently used (Figure 2).

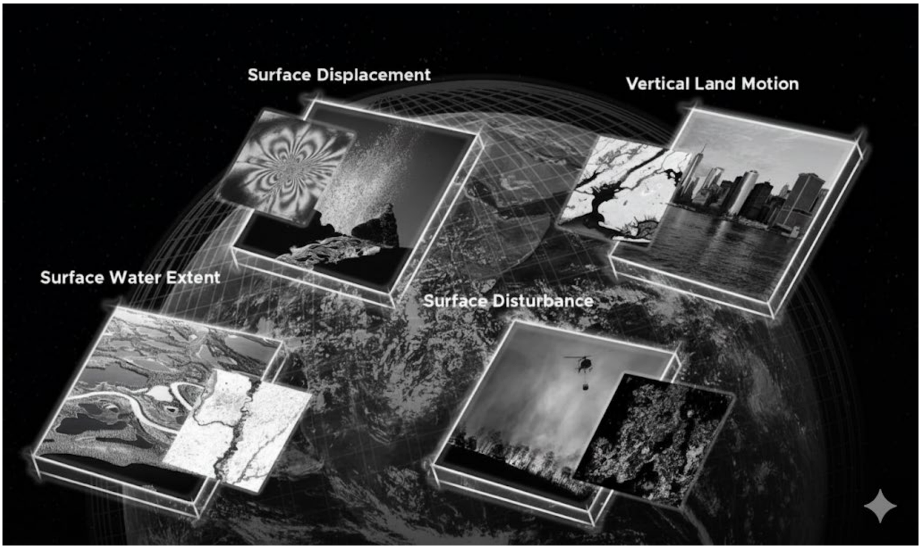

Figure 2. Imaging Technology. (Source https://www.jpl.nasa.gov/go/opera/)

This are essential for accurately identifying the specific communities and infrastructure at risk.

4.2. Early Warning

The National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) have established a demonstration flash-flood and debris-flow early-warning system for recently burned areas in southern California. The demonstration project covers eight counties within Southern

California and utilizes the National Weather Service's (NWS) Flash Flood Monitoring and Prediction (FFMP) system. FFMP identifies when both flash floods and debris flows are likely to occur based on comparisons between radar precipitation estimates and established rainfall intensity-duration threshold values. Beginning in autumn 2005, advisory Outlooks, Watches, and Warnings are disseminated to emergency management personnel through the NWS Advanced Weather Information Processing System.

4.3. Use of GIS in PFDFA:
Where Do Post-Wildfire Debris Flows Occur?

Post-wildfire debris flows are most common in areas that combine steep slopes, intense rainfall, and recent wildfire disturbance. Globally, they occur in mountainous and fire-prone regions such as California (USA), Mediterranean Europe (Spain, Greece, Portugal), and Australia.

Key Conditions Favoring Debris Flows

- Steep terrain → gravity accelerates runoff and sediment transport.
- Loss of vegetation → roots and canopy no longer stabilize soils.
- Hydrophobic soils → fire-induced water repellency reduces infiltration and increases surface runoff.

- Intense rainfall → short-duration storms mobilize ash, soil, and rock material.
- Convergent valleys and channels → concentrate runoff and debris.

4.4. Post-Wildfire Debris Flows in Turkey

Turkey is highly vulnerable due to its Mediterranean climate, rugged topography, and frequent wildfires. The risk is greatest in regions where wildfires are followed by sudden autumn rainstorms.

In Turkey, post-wildfire debris flows are most likely in the Mediterranean and Aegean regions (Antalya, Muğla, Mersin), with smaller-scale risks in Marmara (Çanakkale, Balıkesir). The highest risk occurs within the first 1–3 years after major wildfires, especially when intense rainfall events follow.

1. Mediterranean Region is the most wildfire-prone region of Turkey. Toros Mountains rise sharply behind the coast, creating steep slopes.xAfter the 2021 Antalya-Manavgat wildfire, researchers documented severe soil hydrophobicity and increased surface runoff, raising debris flow risk in local valleys. In Mersin-Gülnar, small-scale post-fire debris flows were observed in stream channels after heavy rainfall.

2. Aegean Region is characterized by hot, dry summers and sudden intense rainfall in autumn. The Muğla-Marmaris wildfires (2021) burned vast areas on steep slopes. Subsequent rainstorms caused ash and sediment-laden flows in streambeds, resembling debris flow precursors. Studies found that post-fire soils here exhibited 2–3 times higher runoff rates than unburned soils.

3. Marmara Region has smaller wildfires, but steep slopes in Çanakkale and Balıkesir-Gömeç have produced local debris-flow-like events after intense rainfall.

4. Southeastern Anatolia (limited but possible) although has less documented, mountainous districts could face post-fire debris flows when rangelands burn and are followed by convective storms.

4.5. Why in Turkey?

1. Mediterranean climate: hot, dry summers → severe fires → sudden intense autumn storms.

2. Topography: steep mountain–coast transitions (especially in Mediterrenian and Egean Seas).

3 Soil changes: fire-induced hydrophobicity, loss of organic matter, accumulation of ash.

4. Sediment availability: loose ash, rocks, and organic debris easily mobilized.

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CHAPTER VI

DIGITAL TRANSFORMATION IN IRRIGATION: EFFICIENCY AND SUSTAINABILITY IN WATER MANAGEMENT THROUGH SMART TECHNOLOGIES

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1. INTRODUCTION

1.1. Global Importance of Water Resources and Increasing Water Demand

Agriculture plays a vital role in sustaining global food security; however, the accelerating growth of the world's population, the adverse effects of climate change, and the progressive reduction of freshwater reserves have introduced substantial constraints on agricultural production systems. Projections for the year 2050 suggest that the gap between available water resources and global water demand may reach nearly 40%, which is particularly critical for the agricultural sector due to its high dependency on sufficient water supply (Lawal, 2025). At present, irrigation activities in agriculture are responsible for approximately 70% of global freshwater consumption and occupy nearly 34% of the world's land surface, thereby imposing increasing and unsustainable pressure on natural ecosystems and resource availability (Lee, 2019; Chen et al., 2021; Abioye et al., 2022; Pandya and Sharma, 2023; Lawal, 2025).

Global water resources exhibit significant variations in terms of spatial distribution, quantity, and quality. The global hydrological cycle is a dynamic system composed of interconnected surface and groundwater resources, linked through processes such as infiltration, precipitation, evaporation, and sublimation. More than 90% of the circulating water is associated with the continuous exchange of water among oceans, seas, lakes, rivers, and streams. A substantial portion of the remaining approximately 10% of the circulating water enters the atmosphere through plant transpiration, surface evaporation, and the sublimation of snow cover in mountainous regions (Koç, 2024). Although the Earth possesses vast water reserves, only a small fraction of these resources is accessible and suitable for human consumption and agricultural production. Consequently, water is regarded as an essential natural asset for sustaining human existence and maintaining ecological balance. Despite this importance, freshwater represents less than 3% of the planet's total water resources, while the remaining 97% is composed of saline water. Furthermore, this limited freshwater portion is unevenly distributed among glaciers and ice sheets, groundwater bodies, surface waters such as rivers and lakes, and atmospheric moisture (Borden et al., 2017; Turan and Bayrakdar, 2020). The strategic significance of freshwater for global water security and food production has become increasingly evident in the context of climate change. Climate change amplifies the frequency and severity of hydrometeorological extremes such as droughts, floods, heatwaves, irregular precipitation regimes, and the decline of water supplies thereby deepening existing vulnerabilities. This situation imposes additional stress on agricultural systems and ecosystem resilience through mechanisms including seawater intrusion into groundwater reserves, reduced soil moisture availability, and heightened irrigation demands (Mahato et al., 2022).

A considerable amount of water is currently wasted, particularly as a result of inefficient practices in agricultural irrigation. The increasing volume of water lost before being effectively utilized highlights the necessity of managing water resources more efficiently and sustainably. In this regard, the advancement of innovative technologies and modern water management strategies is crucial for minimizing water losses, improving utilization efficiency, and securing the long-term sustainability of existing water resources. Efficient water management constitutes a core element of sustainable agricultural production systems, as it significantly contributes to cost reduction, productivity enhancement, and the rational use of natural resources. Moreover, the feasibility and success of projects implemented at various scales depend on the adoption of accurate and holistic water management strategies. Effective water management, as one of the fundamental components of sustainable agriculture, holds strategic importance in the face of increasing water scarcity and the pressures imposed by climate changeIn this context, optimizing agricultural water utilization necessitates the integrated deployment of contemporary technologies, including precision irrigation systems, soil moisture monitoring sensors, and real-time data-driven analytical tools.

Global forecasts indicate that by 2050, nearly half of the world's population will reside in regions experiencing a high risk of severe water scarcity. This projection underscores the increasing urgency and necessity of implementing sustainable water management strategies. Within the framework of the Sustainable Development Goals, which emphasize equitable access to water resources and the rational utilization of natural assets, the integration of digital technologies facilitates the effective monitoring, regulation, optimization, and prediction of freshwater use and pollution patterns. In this regard, innovative technological applications including sensor-based systems, the Internet of Things (IoT), machine learning algorithms, and big data analytics are playing a pivotal role in reshaping water management practices by enabling more intelligent, adaptive, and data-driven decision-making processes (Aivazidou et al., 2021).

1.2. Impacts of Climate Change, Drought, and Water Scarcity on Agriculture

In recent years, the concept of water security has increasingly become central to sustainable development policies, alongside food security. Despite the availability of freshwater from various sources including precipitation, rivers, lakes, groundwater aquifers, glaciers, reclaimed wastewater, and desalinated water ensuring safe and equitable access to water is becoming progressively more challenging on a global scale. This situation is driven by multiple interconnected factors such as drought trends associated with climate change, rapid population growth, the decline in per capita water availability, inequalities in water access, the expansion of water-stressed basins, inefficient water use practices in agriculture and industry, excessive groundwater extraction, and the increasing water demand accompanying economic growth.

These conditions pose significant risks to the sustainable management of available freshwater resources and disturb the global equilibrium between water demand and supply (Pandya and Sharma, 2023). When this imbalance is further intensified by soil degradation, biodiversity decline, and the effects of climate change, the rate of yield improvement in agricultural systems is markedly reduced. As a result, there is increasing concern that existing agricultural production capacities may be insufficient to satisfy the growing global food requirements in the coming decades.

Climate change has substantially altered the global hydrological cycle, leading to an increase in both the frequency and intensity of drought occurrences (Hussain et al., 2022). As a result, the sustainable and efficient management of water resources within agricultural systems has emerged as a central priority in contemporary resource management. Each year, extensive agricultural regions across the world are exposed to the risk of severe water shortages, posing significant threats to crop productivity and overall food security. The depletion of water reserves further undermines social welfare and economic stability particularly in arid and semi-arid zones and presents structural obstacles to the attainment of sustainable development objectives.

The sector most profoundly influenced by this process is agriculture, which utilizes nearly 80% of the world's available freshwater resources (Dalezios et al., 2018). The substantial reliance of agricultural production on water transforms water scarcity from a purely environmental concern into a global challenge with significant socio-economic implications. In a study published by Luo et al. (2015), global water stress projections for the year 2040 are presented in Figure 1.

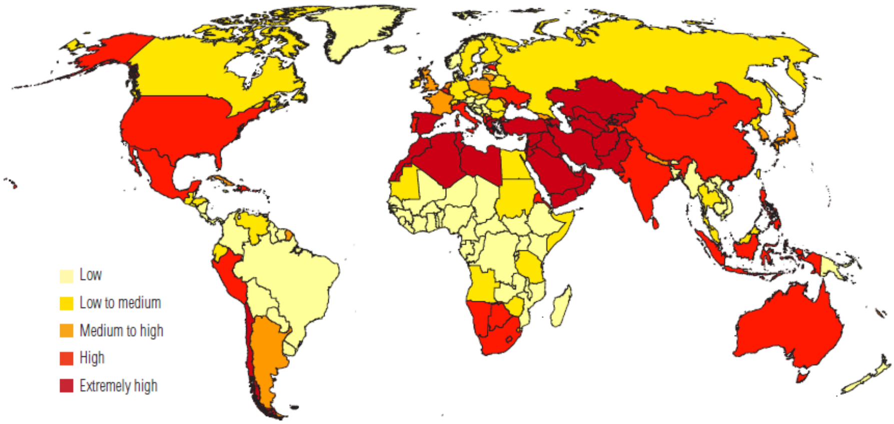

Figure 1. Forecasted regional water stress levels across the world by 2040 (Luo et al., 2015)

Overall, forecasts for the year 2040 suggest that a considerable share of the global population will inhabit areas exposed to high or very high-water stress. This circumstance underscores the necessity of developing digital and data-informed water management strategies that can effectively respond to the consequences of climate change. In particular, the adoption of smart sensor technologies, artificial intelligence-based predictive modeling, and integrated water governance frameworks in agricultural irrigation systems is essential for safeguarding water resources, enhancing their efficient use, and supporting sustainable agricultural production models in the future.

1.3. Efficiency Challenges in Agricultural Irrigation and the Need for Digital Transformation

The rapid growth of the global population has rendered the expansion of agricultural production capacity a strategic imperative, particularly in arid and semi-arid climatic regions. In these areas, the limited availability of water resources heightens the sensitivity of agricultural production systems to climatic variability and underscores the need for water to be managed in a more systematic, data-oriented, and sustainable framework. Therefore, ensuring food security depends not only on increasing production output but also on the efficient and intelligent utilization of existing water resources. In this context, smart irrigation strategies that utilize sensor-based data acquisition, automated control systems, and real-time decision-support mechanisms play a crucial role in improving agricultural productivity while promoting the efficient use of water resources.

In recent years, the depletion of water resources has emerged as a critical environmental issue that constrains agricultural production capacity and threatens sustainable development goals (Huang et al., 2021). This reduction in water availability necessitates the adoption of integrated water management principles and the implementation of technological transformations that prioritize resource efficiency in agricultural enterprises. In this context, digital and automation-based applications, which enable higher yields per unit area while using less water, have become fundamental components of modern agricultural systems. These systems not only contribute to water and energy savings but also support lowering production expenses and mitigating environmental impacts. In this regard, increasing urbanization, difficulties in accessing a qualified agricultural workforce, the pressures of global competition, and rising expectations for reliable food have further emphasized the importance of adopting innovative technologies in agriculture. Digital agriculture technologies provide substantial potential for optimizing production processes, minimizing losses, enhancing overall efficiency, and improving product quality standards. In particular, the integrated application of Internet of Things (IoT) infrastructures with artificial intelligence–based analytics and decision-making systems strengthens field-level traceability and supports the development of sustainable agricultural production models (Dertli and Dertli, 2023).

Considering all these dynamics, accelerating digital transformation in the agricultural sector holds strategic importance in terms of safeguarding food security and increasing the capacity to adapt to the environmental risks driven by climate change. However, rising food demand, increasing production costs, the depletion of water and soil resources, and the degradation of ecosystems continue to threaten agricultural sustainability. Therefore, the development of data-driven, technology-supported production models that preserve ecological balance has become a fundamental requirement for establishing secure and sustainable agricultural production systems in the future (Çakmakçı and Çakmakçı, 2023). In this context, the design program developed by Ayberkin (2025) presents a holistic solution approach that supports digital transformation in the agricultural sector. The system is grounded in objectives such as increasing agricultural productivity, ensuring the sustainable use of natural resources, reducing environmental impacts, strengthening producers' decision-making processes, and enhancing food safety and product quality. At the same time, it contributes to the widespread adoption of data-driven practices and the acceleration of digitalization in agricultural production processes.

2. THE CONCEPT AND DEVELOPMENT OF DIGITAL AGRICULTURE

2.1. Agriculture 4.0 and the Foundations of Digital Transformation

Agriculture 4.0 represents a contemporary production model in which a variety of digital and intelligent systems are utilized throughout agricultural operations. These include technologies that enable advanced data processing, artificial intelligence–based interpretation, interconnected communication among devices, automated and robotic agricultural machinery, sensor-supported monitoring structures, aerial observation platforms, and satellite or remote ground-based imaging methods (Wolfert et al., 2017; Çakır and İşlek, 2021; Dayıoğlu and Turker, 2021; Sevli, 2023; Ali et al., 2025). In their study, Araújo et al. (2021) identified four principal technological domains within this framework and explained the specific functional roles associated with each domain. This classification provides a structured foundation for understanding how digital technologies contribute to agricultural planning, production, monitoring, and decision-making processes (Table 1). This approach conceptually explains the contribution of digital transformation to agricultural decision-making, production planning, resource management, and monitoring processes.

Table 1. Components and application areas of Agriculture 4.0

(modified from Araújo et al., 2021)

Component	Application Areas	Component	Application Areas
Monitoring	Weather and greenhouse condition monitoring; crop growth observation; soil condition assessment; water usage tracking; livestock health and movement monitoring	**Prediction**	-Forecasting weather conditions - Estimating agricultural product yield - Modeling crop growth and development stages, - Market demand trends
Control	-Smart greenhouses - Irrigation systems - Fertigation systems - Weed, pest, and disease management -Harvesting sytems	**Logistics**	-Handling and storage -Transport and distribution -Supply chain management -Provenance tracebility

2.2. Smart Agriculture Technologies: IoT, Sensor Systems, Big Data, Artificial Intelligence

Çakır et al. (2022) describe smart agriculture as an advanced form of production management in which continuously updated data streams are rapidly and comprehensively analyzed to guide agricultural operations. This approach enhances resource-use efficiency and enables producers to make timely and informed decisions based on real-time information. In recent years, digital technologies have gained prominence as strategically significant tools for achieving sustainable water management. Technologies such as sensor networks, the Internet of Things (IoT), machine learning techniques, big data analytics, and artificial intelligence (AI) facilitate the integrated execution of monitoring, forecasting, control, and optimization functions across multiple stages of the water cycle (Liu et al., 2019; Bharti et al., 2020; Ramírez-Agudelo et al., 2020). The real-time data transmission and analytical capabilities provided by these tools support the efficient utilization of water resources, minimize system losses, and contribute to the development of climate-resilient management strategies.

A key dimension of this technological shift is the combined use of Artificial Intelligence (AI) and Internet of Things (IoT) infrastructures. According to Lawal (2025), the convergence of these technologies enables intelligent, sustainable, and data-oriented solutions to the growing challenges of water scarcity and agricultural productivity across the globe. Environmental data obtained from IoT-based sensor networks are processed by AI algorithms to automate processes such as irrigation scheduling, water quantity adjustment, and dynamic control based on plant needs. In this way, real-time analysis and predictive decision-making mechanisms significantly enhance water savings and production efficiencyWithin this framework, digital agriculture emerges as a central concept that integrates precision agriculture practices with big data analytics, IoT infrastructures, and artificial intelligence applications. Such systems support farmers in optimizing the use of inputs, enhancing production efficiency, and minimizing environmental pressures. Data-oriented decision-making becomes possible through information obtained from sensors, satellite observation, unmanned aerial vehicles, and various smart monitoring devices, enabling more accurate and informed agricultural management strategies (Arijit et al., 2025). In this regard, IoT, artificial intelligence, remote sensing, drones, robotic systems, and blockchain technologies have the potential to transform agricultural production processes into a more precise, efficient, and sustainable structure (Wolfert et al., 2017; Kamilaris and Prenafeta-Boldú, 2018). With the digital capabilities brought by the computer age, Internet of Things (IoT) technologies and new-generation precision agriculture methods have initiated a profound transformation in agricultural production systems. Among the primary benefits provided by IoT systems in irrigation applications are the reduction of water consumption, the lowering of operational costs, the improvement of system performance, the minimization of energy use, and the prevention of yield losses (García et al., 2020). These advantages are achieved through sensor-based monitoring and data analytics infrastructures, which enable irrigation operations to be conducted with accurate timing and appropriate quantities. In this way, water is used only at the level required by the plant, thereby preventing resource waste and increasing efficiency within production processes.

The use of Internet of Things (IoT) technologies in agricultural production enables advanced agricultural management approaches, reduces resource waste, minimizes environmental impacts, and increases crop yield (Goel et al., 2021). IoT-based agricultural infrastructures allow continuous monitoring of production processes through real time data streams, strengthen decision support systems with the information obtained, and encourage the establishment of sustainable production models. In this regard, digital technologies such as wireless sensor networks, radio frequency identification systems, communication between machines, cloud based computing environments, and data analytics contribute to making agricultural processes more efficient, transparent, and sustainable (Kumar et al., 2024). Overall, this comprehensive digital transformation not only reshapes approaches to water management but also redefines production efficiency, system resilience, and sustainability in agriculture. It provides the foundation for agricultural systems that are adaptable to climate conditions, effective in the use of resources, and guided by data driven decision making.

2.3. Strategic Impacts of Digital Transformation on Water Management

The environmental pressures induced by climate change, coupled with rapidly growing population levels and the increasing demand on industrial and agricultural production processes, necessitate the adoption of sustainable approaches in water resource management. This situation requires the efficient, controlled, and reusable management of water, both in closed production systems (such as greenhouses) and in open agricultural areas.

According to Zeng et al. (2023), irrigation patterns that are inadequately planned or poorly managed increase the risk of waterlogging caused by excessive water accumulation in the field, as well as drought stress resulting from insufficient irrigation. These conditions negatively influence both water use efficiency and crop productivity. Precision irrigation practices aim to optimize water utilization in agricultural systems by employing an integrated management structure that incorporates soil moisture data collection and analysis, automated irrigation control, and real time climatic information.

Morchid et al. (2024) examined the difficulties associated with water management in areas characterized by scarce water availability or severe climatic conditions. The research examines the effectiveness of predictive algorithms in estimating soil moisture and highlights how these technologies are contributing to a transformation in water management practices. Predictive algorithms combine historical data on parameters such as temperature, humidity, and soil moisture with current climatic conditions in order to estimate future irrigation requirements of crops with high accuracy. As a result, irrigation practices can be implemented in a timely and targeted manner, which significantly reduces water wastage. Similarly, while traditional irrigation methods often result in inefficiencies due to improper timing or excessive water application, smart irrigation systems optimize resource use by applying water when the moisture level in the root zone falls below a specified threshold. The study conducted by Subeesh and Mehta (2021) demonstrates that such sensor-based systems can reduce water consumption by approximately 30 percent depending on environmental conditions, without causing any reduction in crop growth or yield performance. When these findings are considered together, the studies by Morchid et al. (2024) and Subeesh and Mehta (2021) clearly demonstrate that digital and data-driven irrigation technologies play a critical role in enhancing agricultural water-use efficiency, strengthening resilience to climate change, and supporting the development of sustainable agricultural production models.

2.4. Digitalization and Smart Application Models in Agricultural Irrigation Systems

Shanthakumari et al. (2024) conducted a comprehensive analysis of the transformative potential of machine learning and Internet of Things (IoT) technologies in agricultural applications. The study demonstrates that optimizing irrigation schedules through real-time data significantly improves water use efficiency while also enhancing agricultural productivity. These findings highlight that data-driven decision support systems constitute a critical component of smart irrigation management.

Irrigation scheduling based on soil moisture is updated using real-time data with the aim of increasing crop yield and reducing plant water stress. The water requirement of plants is determined through evapotranspiration (ET), which consists of the combined processes of evaporation (E) and transpiration (T). However, excessive irrigation may negatively affect plant development by causing oxygen deficiency in the root zone. Water needs vary depending on the plant growth stage, climatic conditions, and plant species. Therefore, irrigation systems designed to improve water use efficiency are planned by considering these variables and applying water at appropriate intervals (Gu et al., 2021). The multi-layer data monitoring approach in smart agriculture establishes a holistic management model by evaluating soil, water, and plant interactions together with environmental variables through sensor-based systems. Through the integration of data obtained from different sources, this model enables accurate decision-making, enhances resource-use efficiency, and supports the achievement of sustainable production objectives. This multidimensional monitoring approach enables the accurate determination of irrigation timing and water application amounts through the analysis of information obtained from sensor-based data collection systems. In this way, irrigation is optimized based on actual crop requirements, water wastage is prevented, and production efficiency is enhanced. Consequently, smart irrigation systems emerge as an advanced irrigation strategy that supports sustainable water management and automates decision-making processes in agricultural production.

In this context, the study conducted by Gamal et al. (2023) schematically illustrates the monitoring technologies used in smart irrigation systems, as presented in Figure 2. The figure identifies the fundamental monitoring techniques employed in smart irrigation systems. These techniques are categorized into three main groups: soil monitoring, plant monitoring, and environmental monitoring. Soil monitoring involves measuring parameters such as moisture, temperature, and pH; plant monitoring focuses on assessing water stress, disease detection, and vegetation indices; and environmental monitoring includes tracking climatic factors such as temperature, humidity, radiation, and precipitation. This multidimensional monitoring approach enables the accurate determination of irrigation timing and water application amounts through the analysis of information obtained from sensor-based data collection systems. Accordingly, irrigation is optimized based on actual crop requirements, water wastage is prevented, and production efficiency is enhanced. In conclusion, smart irrigation systems represent an advanced irrigation strategy that supports sustainable water management and automates decision-making processes in agricultural production.

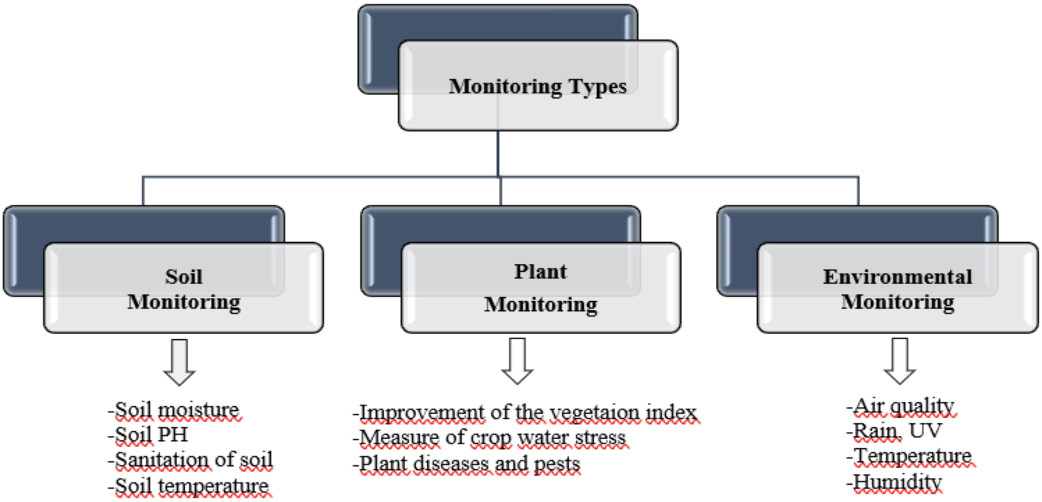

Figure 2. Monitoring Types in Smart Agriculture Systems

(modified from Gamal et al., 2023)

Raj et al. (2021) showed that irrigation operations can be controlled automatically through the use of soil moisture sensor data, allowing systems to start and stop without manual intervention. The findings indicated that this form of automation can reduce water use by approximately 30 to 40 percent while simultaneously improving plant growth performance. This result shows that sensor-based irrigation management holds significant potential for enhancing resource efficiency and supporting agricultural productivity. In another study employing sensor technology, average water consumption was projected to decrease by approximately 50 percent (Majsztrik et al., 2013). Field studies conducted by Gupta et al. (2025) further revealed that irrigation applications using IoT-based automation systems consumed about 30 percent less water compared to traditional irrigation practices. These results suggest that irrigation management supported by Internet of Things (IoT) technologies offers a significant benefit in enhancing the efficiency of water utilization.

In the research carried out by Alibabaei et al. (2022) on tomato cultivation, a Deep Learning-based method was utilized to design an intelligent irrigation scheduling system. In the research, soil moisture, climatic parameters, and irrigation water volume were monitored using sensors, and the collected data were analyzed through artificial intelligence-based models. The findings revealed that using the proposed system resulted in an approximate 11 percent improvement in crop yield. This finding demonstrates that deep learning-based approaches can serve as an effective tool in optimizing agricultural irrigation practices. In the study conducted by Gong et al. (2022), a smart irrigation system developed using a fuzzy logic (FL) approach was evaluated. According to the research findings, this method resulted in approximately 95 percent water use efficiency. The results indicate that fuzzy logic-based control systems provide high accuracy and resource efficiency in irrigation management.

3. FINDINGS AND DISCUSSION

This study evaluated the influence of digital transformation on agricultural water management, with a particular emphasis on sensor-based monitoring systems, Internet of Things (IoT) infrastructures, artificial intelligence applications, big data analytics, and machine learning-driven decision support frameworks utilized in smart irrigation practices. The overall findings demonstrate that digital technologies hold considerable strategic value in enhancing water-use efficiency within agricultural irrigation, minimizing resource losses, and improving the ability of production systems to cope with climate-induced risks. Water scarcity, which is increasingly intensified by the effects of climate change, poses a significant challenge to the long-term sustainability of agricultural production. The rising pressure on water resources, especially in regions with arid and semi-arid climatic conditions, highlights the limitations of traditional irrigation approaches. Inefficiencies commonly encountered in traditional irrigation practices, such as excessive water use, drainage problems, and soil salinization, highlight the growing importance of data-driven management systems that ensure the precise timing and appropriate quantity of water application.

In this regard, soil moisture sensors, automated control systems, multi-layer monitoring frameworks, and artificial intelligence-supported prediction models offer significant advantages for improving water use efficiency (Subeesh and Mehta, 2021; Morchid et al., 2024). Within this framework, the study conducted by Yılmazer and Tunalıoğlu (2024) emphasizes that, in order to promote the widespread adoption of smart agricultural technologies, application-oriented projects must be strengthened at national and regional levels, and research and development activities should be accelerated to enhance domestic technology production capacity. However, despite the significant advantages of smart agricultural practices in terms of input savings and environmental sustainability, high initial investment costs limit their adoption among producers. Therefore, the activation of government support mechanisms, the revision of agricultural extension and organizational models, the widespread provision of digital literacy training for farmers, and the acceleration of land consolidation processes are critically important for ensuring that these technologies are applied sustainably and efficiently.

The literature demonstrates that smart irrigation systems contribute not only to reductions in water consumption but also to improvements in crop productivity by regulating plant growth conditions in a more precise manner. For instance, Alibabaei et al. (2022) reported that irrigation optimization supported by deep learning techniques led to approximately an 11 percent increase in crop yield. Similarly, the fuzzy logic-based control systems evaluated by Gong et al. (2022) demonstrated improvements in water use efficiency of up to 95 percent, revealing that digital control mechanisms can provide high accuracy and effectiveness in irrigation management.

These findings indicate that agricultural water management can no longer be explained solely through hydraulic, agronomic, or meteorological parameters; rather, it requires a holistic systems approach based on multi-layer data integration. The effectiveness of smart irrigation systems depends on factors such as the reliability of sensor data, the continuity of data transmission infrastructure, the digital literacy level of farmers, and the economic accessibility of the systems. Therefore, the effective implementation of digital transformation should be evaluated in conjunction with institutional capacity, educational programs, and policy regulations that support the use of technology.

4. CONCLUSION

The findings indicate that monitoring soil moisture through sensors, implementing automated control of irrigation systems, and utilizing artificial intelligence-based prediction models can significantly reduce water consumption and enhance crop yield performance compared to traditional irrigation practices. Algorithms based on deep learning, fuzzy logic, and decision support mechanisms enable irrigation decisions to shift from fixed and repetitive applications to dynamic, real-time management strategies that can adapt to environmental variations. This technical advancement represents an important adaptation strategy, particularly in enhancing the resilience of agricultural production systems under stress conditions associated with climate change, such as irregular precipitation, rising temperatures, and increasing drought intensity. However, the large-scale implementation of smart irrigation practices depends on certain infrastructural and socioeconomic conditions. Relatively high installation costs, limited levels of digital technology competency among farmers, interruptions in communication networks in rural areas, and the need for guidance regarding the use of new technologies constitute key constraints in this context. Therefore, the widespread adoption of smart irrigation technologies requires the strengthening of public support mechanisms, the enhancement of domestic technology production and software development capacity, the continuity of research and development activities, and the restructuring of agricultural extension and advisory services toward digitalization. In conclusion, digital irrigation practices aimed at the rational use of water are regarded not merely as technological innovations, but as one of the fundamental pillars of sustainable agriculture in contemporary production systems. The widespread adoption of automation-based irrigation approaches that rely on real-time data analytics and adapt to environmental conditions is critically important both for securing agricultural production processes and for preserving existing water resources for the future. In this respect, the future of agriculture will depend on the implementation of digital decision-support systems that place water at the center, are adaptable to climate variability, and possess high operational flexibility.

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