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Organic farming as a sustainable approach to enhanced crop resilience against biotics and abiotic stress

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Abstract
Modern agriculture is increasingly threatened by a combination of biotic stresses such as pests, pathogens, and weeds and abiotic stresses, including drought, salinity, temperature extremes, and nutrient imbalances. These stressors are further intensified by climate change, which alters pest dynamics, increases the frequency of extreme weather events, and heightens crop vulnerability. Organic farming offers a holistic and ecologically grounded approach to mitigate these challenges. Unlike conventional systems reliant on synthetic inputs, organic farming emphasizes soil health, biodiversity, and ecosystem balance through practices like composting, crop rotation, cover cropping, and biological pest control. These practices enhance soil structure, water retention, and microbial diversity, fostering plant resilience to both biotic and abiotic stressors. Mechanisms such as induced systemic resistance (ISR), improved nutrient uptake, and antioxidant activity contribute to enhanced plant defense and physiological stability under stress. Organic systems also support natural pest suppression by promoting habitats for beneficial organisms. However, organic farming faces limitations such as slower nutrient release, labour-intensive weed management, and variable pest control efficacy. Overcoming these challenges requires continued research into biostimulants, climate-resilient crop varieties, and precision organic technologies. Despite these constraints, organic farming presents a sustainable, adaptable pathway for improving agricultural resilience, promoting environmental health, and addressing global food security. This paper reviews the role of organic farming in mitigating biotic and abiotic stresses, examines the underlying ecological mechanisms, and outlines future research priorities to enhance system performance in the face of climate and environmental pressures.

Keywords: Organic farming, biotic stress, abiotic stress, soil health, climate resilience

Introduction

Agriculture today is under escalating pressure from biotic stressors including pests, pathogens, and weeds and abiotic stressors such as drought, salinity, temperature extremes, and nutrient scarcity. Climate change exacerbates these threats by intensifying weather variability, altering pest and disease dynamics, and increasing crop vulnerability (Biswas and Das, 2024). The annual yield losses due to biotic stress alone can reach over 30% in staple crops, with droughts causing severe economic and food security impacts. These pressures are exacerbated by climate change, which not only intensifies abiotic extremes but also facilitates the spread of new or more virulent biotic agents (Asif *et al*., 2023, Dresselhaus and Hückelhoven, 2018) [1, 5].

Abiotic stress refers to non-living environmental pressures, including water scarcity, salinity, temperature extremes, and mineral toxicity. These stresses trigger disruptions in plant water status, ion balance, enzymatic function, and metabolic pathways. Biotic stress involves living threats like fungi, bacteria, viruses, nematodes, and insects. These organisms destabilize plant health by competing for resources, damaging tissues, and diminishing yield potential.

Organic farming is increasingly recognized as a sustainable agricultural approach that not only prioritizes environmental conservation and soil health but also enhances crop resilience to biotic (pests and pathogens) and abiotic (drought, salinity, temperature extremes) stresses. Unlike conventional farming, organic systems promote biodiversity**,** improve soil organic matter, and foster beneficial microbial activity, which collectively contribute to improved plant health and stress tolerance (Lori *et al.*, 2017) [11]. Organic practices such as crop rotation**,** use of organic compost**,** cover cropping, and biological pest control create a robust agroecosystem capable of mitigating the effects of climate variability and pest outbreaks (Pimentel *et al.*, 2005) [23]. Moreover, organic inputs like compost and biofertilizers enhance the physiological and biochemical pathways in crops, strengthening their natural defence mechanisms against environmental stressors (Lal, 2020) [10]. As such, organic farming presents a holistic and ecologically sound method to address agricultural sustainability and food security challenges in the face of growing global environmental pressures. As an ecological alternative to intensive conventional systems, organic farming integrates biodiversity-based practices such as crop rotations, cover crops, composting, biological pest controls, and minimal synthetic inputs to leverage natural ecosystem dynamics. These practices enhance soil health, improve water and nutrient cycling, and foster beneficial biological communities. Meta-analyses demonstrate that diversified rotations and organic amendments significantly boost soil organic carbon, microbial diversity, pest resistance, and system resilience over time. By promoting soil structure, organic organic matter, and microbiome complexity, organic systems bolster the plant's first line of defence roots and rhizosphere enhancing tolerance to drought, salinity, heat, and pathogens (Meel and Saharan 2024) [17]. Long-term trials (e.g., Rodale Institute's Farming Systems Trial) show that, after transition, organic yields match conventional levels and often outperform them during stress years such as droughts . Organic fertilization fosters physiological adaptation via improved leaf water status, nutrient uptake efficiency, antioxidant systems, osmolyte production (e.g., proline), and stress-responsive gene expression.

Biotic Stress and Organic Farming

A 20-30% annual loss in worldwide agricultural production is thought to result from biotic stress, which is the harm that living creatures like insects, fungi, bacteria, viruses, nematodes, and weeds impose on crops (Savary *et al.*, 2019) [29]. The intensification of agriculture over recent decades has heavily relied on synthetic agrochemicals, including pesticides, herbicides, and fungicides, as the primary tools to control biotic threats. While initially effective, this strategy has led to the development of resistant pest populations**,** contamination of ecosystems**,** and loss of biodiversity (Pimentel and Burgess, 2014; Goulson, 2013) [24, 7]. Conventional farming systems frequently used on **s**ynthetic pesticides and chemical inputs to manage these threats. However, these inputs can lead to pesticide resistance**,** soil degradation**,** and declining biodiversity (Pimentel and Burgess, 2014) [24]. In contrast, organic farming employs a systems based approach that aims to manage biotic stress by enhancing the resilience of the agroecosystem rather than eradicating specific pests or diseases. It relies on cultural practices**,** biological control agents, and soil health improvement to prevent outbreaks. For example, diverse crop rotations and intercropping help break pest and disease cycles, while compost application and cover cropping foster a healthy soil microbiome that supports plant defence responses (Lori *et al.*, 2017) [11]. Additionally, organic systems enhance above and below-ground biodiversity, providing habitat and resources for natural enemies of pests, such as parasitic wasps, predatory beetles, and entomopathogenic fungi. This approach not only reduces dependence on external inputs but also restores ecological balance in farming landscapes (Letourneau *et al.*, 2011) [12].

Mechanisms in Organic Farming for Managing Biotic Stress

Organic farming employs an ecosystem-based strategy to manage biotic stress by leveraging natural processes and biodiversity. Instead of relying on synthetic pesticides, organic systems utilize biological control agents such as *Trichoderma* spp., *Bacillus thuringiensis*, and *Pseudomonas fluorescens* to suppress pathogens and insect pests effectively (Nicot *et al.*, 2011; Pieterse *et al.*, 2014) [21, 26]. Healthy soil microbiomes, fostered through the application of compost and manure, enhance plant Vigor and create antagonistic conditions unfavourable to harmful organisms (Lori *et al.*, 2017) [11]. Practices like crop rotation**,** intercropping, and habitat diversification reduce host-specific pest outbreaks and encourage populations of natural enemies including predators and parasitoids, thus maintaining ecological balance (Letourneau *et al.*, 2011) [12]. Furthermore, plants benefit from induced systemic resistance (ISR) and systemic acquired resistance (SAR) mechanisms, which are activated by beneficial microbes and organic inputs, leading to increased accumulation of defence proteins and secondary metabolites that boost immunity (Pieterse *et al.*, 2014) [26]. Organic farming also employs natural biopesticides such as neem oil and garlic extracts, which provide targeted and environmentally friendly pest suppression (Isman, 2006) [8]. Together, these integrated mechanisms foster a resilient agroecosystem capable of effectively preventing and mitigating biotic stress.

Abiotic Stress and Organic Farming

Abiotic stress, including drought, salinity, extreme temperatures, and nutrient imbalances, is a major constraint to crop productivity worldwide, causing physiological and biochemical disruptions in plants that reduce growth and yield. These stresses induce oxidative damage, disrupt cellular homeostasis, and impair nutrient uptake, ultimately affecting photosynthesis and metabolism (Zhu, 2016) [32]. Organic farming, which avoids synthetic chemicals and emphasizes natural processes, offers effective strategies to mitigate these stresses by improving soil quality and enhancing plant resilience through ecological approaches. One of the key benefits of organic farming is the increased soil organic matter resulting from the application of compost, manure, and cover crops, which enhances soil structure and water-holding capacity, enabling crops to better withstand drought and heat stress (Bhattacharyya *et al.*, 2015) [4]. Organic amendments also improve cation exchange capacity and buffer soil pH, which helps plants manage salinity and heavy metal toxicity (Niu *et al.*, 2018) [20]. Moreover, organic soils often harbour more diverse and active microbial communities that facilitate nutrient cycling and promote plant health through symbiotic relationships such as mycorrhizal fungi and nitrogen-fixing bacteria, thus improving tolerance to abiotic stresses (Reganold and Wachter, 2016) [27]. Crop diversification and rotations common in organic systems also contribute to abiotic stress resilience by reducing pest pressure, breaking disease cycles, and improving soil nutrient balance, which conventional monocultures often fail to achieve (Reganold and Wachter, 2016) [27]. These practices increase biodiversity above and below ground, enhancing ecosystem stability and resource use efficiency. Additionally, the use of green manures and cover crops in organic farming helps maintain soil moisture and prevent erosion, critical factors in managing drought-prone conditions (Bhattacharyya *et al.*, 2015) [4]. However, organic farming faces challenges in rapidly alleviating acute nutrient deficiencies during sudden abiotic stress events because organic nutrients release more slowly than synthetic fertilizers, necessitating careful management and timely application of organic inputs to optimize stress tolerance (Parihar *et al.*, 2015) [22]. To overcome these limitations, integrating biostimulants such as seaweed extracts or microbial inoculants has shown promise in enhancing plant stress tolerance in organic systems. Despite these challenges, the holistic and ecologically sound practices of organic farming provide a sustainable pathway to enhance crop resilience to abiotic stresses while maintaining long-term soil fertility, biodiversity, and environmental health. Such integrated approaches not only improve crop performance under stress but also contribute to climate change mitigation by increasing soil carbon sequestration (Reganold and Wachter, 2016; Niu *et al.*, 2018) [27, 20].

Mechanisms in Organic Farming for Managing Biotic Stress

Organic farming employs multiple ecological and biological mechanisms to manage biotic stress caused by pests, diseases, and weeds, relying on natural processes rather than synthetic pesticides or herbicides. One of the primary strategies is enhancing soil health and biodiversity, which supports populations of beneficial organisms such as predatory insects, parasitoids, and microbial antagonists that naturally suppress pest populations (Reganold &and Wachter, 2016) [27]. Crop diversification through rotations, intercropping, and polycultures reduces the prevalence and spread of pathogens and pests by interrupting their life cycles and reducing host availability (Altieri, 1999) [2]. Additionally, organic farmers use biological control agents such as beneficial fungi (e.g., *Trichoderma* spp.), bacteria (e.g., Bacillus subtilis), and nematodes to target specific pests and diseases, enhancing plant resistance and reducing biotic stress (Larkin and Fravel, 1998) [13]. Organic amendments like compost and green manure not only improve soil fertility but also stimulate the activity of antagonistic microorganisms that compete with or inhibit soil-borne pathogens, thus enhancing disease suppression (Mazzola, 2004) [19]. Furthermore, organic farming promotes the use of resistant or tolerant crop varieties, which inherently reduce the impact of pests and diseases (Pimentel *et al.*, 2005) [23]. The use of natural plant extracts and biostimulants, such as neem oil and seaweed extracts, also strengthens plant defences by activating systemic acquired resistance and induced systemic resistance pathways (Isman, 2006) [8]. Collectively, these integrated approaches build resilient agroecosystems that maintain crop productivity and reduce reliance on chemical inputs, aligning with the principles of sustainability and environmental stewardship.

Soil Health as a Foundation for Resilience

Soil health serves as the cornerstone of resilient agricultural systems by providing the physical, chemical, and biological conditions necessary for sustainable crop production and ecosystem stability. Healthy soils exhibit a balanced soil structure, rich organic matter content, and diverse microbial communities that collectively enhance soil fertility, water retention, and nutrient cycling (Lal, 2015) [14]. The improved soil structure increases porosity and aggregate stability, which reduces erosion and enhances infiltration of rainwater, thereby mitigating the impacts of drought and heavy rainfall events (Bronick and Lal, 2005) [3]. This physical buffering capacity is essential for crops to maintain physiological functions during periods of water deficit or flooding. Biologically, soils with high microbial diversity foster symbiotic relationships, such as those with mycorrhizal fungi and nitrogen-fixing bacteria, which improve nutrient uptake and enhance plant growth under stressful conditions (Van der Heijden *et al.*, 2008) [8]. These microbial communities also compete with or antagonize soil pathogens, providing a natural disease-suppressive environment that reduces the incidence of soil-borne diseases (Kibblewhite *et al.*, 2008) [9]. Soil microorganisms play a vital role in decomposing organic residues and recycling nutrients, making them available in forms accessible to plants, thus supporting productivity even under nutrient-poor conditions. Agricultural management practices that prioritize soil health such as minimal tillage, cover cropping, crop rotation, and organic amendments build soil organic carbon stocks and stimulate microbial activity, further enhancing resilience to biotic and abiotic stresses (Lal, 2015) [14]. For instance, cover crops protect soil from erosion, improve soil moisture retention, and add biomass that serves as a substrate for soil microbes (Kibblewhite *et al.*, 2008) [9]. Reduced tillage preserves soil structure and microbial habitats, preventing disruption of soil food webs critical for nutrient cycling and pest regulation. In addition to improving productivity, healthy soils contribute significantly to climate change mitigation by sequestering atmospheric carbon, thus reducing greenhouse gas concentrations (Lal, 2015) [14]. Soils with robust organic matter stores act as carbon sinks, helping stabilize the climate while maintaining the resilience of agroecosystems. Ultimately, soil health not only supports plant and microbial life but also strengthens the entire agricultural ecosystem's ability to withstand shocks such as drought, salinity, pest outbreaks, and nutrient imbalances, ensuring long-term sustainability and food security (Van der Heijden *et al.*, 2008) [8].

Challenges and Limitations in Organic Farming

While organic farming presents many ecological and sustainability benefits, it also faces several challenges and limitations that can impact productivity and stress resilience. One major limitation is the slower nutrient release from organic amendments such as compost and manure, which may not meet the immediate nutritional demands of crops during critical growth periods or under acute abiotic stress like drought or salinity (Parihar *et al.*, 2015) [22]. Unlike synthetic fertilizers, organic inputs depend heavily on microbial decomposition, which is temperature-and moisture-dependent, making nutrient availability less predictable, especially under extreme environmental conditions (Reganold and Wachter, 2016) [27]. Additionally, organic farms often face lower yields compared to conventional systems, particularly in the short term, due to limitations in nutrient availability, pest control, and weed management (Seufert *et al.*, 2012) [28]. Another challenge is the management of biotic stress, such as pests and diseases, without synthetic pesticides. Organic systems rely on biological control and cultural practices, which may be less effective during severe infestations or when pest pressure is high. Inconsistent efficacy of biocontrol agents and limited availability of organic-approved solutions can further constrain pest management options (Pimentel *et al.*, 2005) [23]. Moreover, weed control in organic farming remains labour-intensive and often requires mechanical weeding, which can lead to soil structure degradation if not managed carefully (Lichtfouse *et al.*, 2009) [15]. Organic certification also brings economic and bureaucratic barriers**,** especially for smallholder farmers, due to the cost and complexity of compliance and record-keeping. Access to certified organic inputs, knowledge, and infrastructure is limited in many regions, particularly in developing countries (FAO, 2021) [6]. Additionally, organic farming may demand higher labor input, particularly during transitional periods or when implementing practices like crop rotation, composting, and intercropping (Ponisio *et al.*, 2015) [25]. These constraints can affect scalability and adoption rates, despite growing consumer demand. Hence, while organic farming offers a sustainable approach to managing stress and promoting soil and plant health, overcoming these limitations requires continued research, policy support, and education to make it more viable and accessible on a larger scale.

Future Prospects and Research Directions

The future of organic farming lies in addressing existing challenges while harnessing innovation to improve productivity, sustainability, and resilience to both abiotic and biotic stresses. As climate change intensifies, one key research direction is the development of climate-smart organic practices, including adaptive crop management and drought-or heat-tolerant varieties bred specifically under low-input, organic conditions (Lammerts van Bueren *et al.*, 2011; Seufert *et al.*, 2012) [16, 28]. Unlike conventional breeding, which often targets high-input systems, organic crop breeding must consider traits like nutrient-use efficiency, pest resistance, and compatibility with beneficial soil organisms. The enhancement of soil microbial ecology is another important matter. Microbiome engineering through inoculation of beneficial bacteria, fungi, and other microbes can significantly boost nutrient cycling and plant resilience, especially in stressed environments (Van der Heijden *et al.*, 2008; Reganold and Wachter, 2016) [8, 27]. Biofertilizers and microbial consortia tailored for specific crops and climates are under active research to replace or complement traditional organic inputs like compost and manure (Isman, 2006; FAO, 2021) [8, 6]. Likewise, biopesticides and biostimulants are emerging as eco-friendly tools for managing pests and improving plant Vigor, though their formulation and delivery methods need further standardization and scale-up (Lichtfouse, 2009) [15]. Technological integration in organic systems is another promising frontier. Digital agriculture tools, such as remote sensing, AI-based pest identification, and precision compost application, can enhance decision-making and resource-use efficiency without violating organic standards (Lal, 2015) [14]. Research is also needed into reduced-tillage methods that maintain soil health and carbon stocks while controlling weeds in organic systems, potentially addressing one of the system's persistent challenges (Ponisio *et al.*, 2015) [25]. From a policy and socio-economic perspective, future research must explore institutional support mechanisms such as crop insurance, credit access, and fair trade networks for organic producers especially smallholders in developing countries who face high entry barriers (FAO, 2021) [6]. Building local capacity through farmer-led innovation platforms and participatory research can accelerate the spread of regionally adapted organic practices and technologies (Seufert *et al.*, 2012; Lammerts van Bueren *et al.*, 2011) [16, 28]. Finally, long-term, multi-location organic trials are essential to evaluate the true sustainability of organic systems over time and under variable environmental conditions. These should assess not only yield but also biodiversity outcomes, ecosystem services, carbon sequestration, and socio-economic viability (Lal, 2015; Reganold and Wachter, 2016) [14, 27]. The future of organic farming thus hinges on an interdisciplinary, systems-based approach that integrates ecological science, agronomy, technology, and social innovation.

Conclusion

This review paper has revealed that organic farming offers a sustainable and resilient approach to managing biotic and abiotic stresses in agriculture. By enhancing soil health, biodiversity, and natural defense mechanisms, it reduces reliance on synthetic inputs and supports long-term productivity. While challenges remain, including nutrient availability and pest control, ongoing research and innovation can help overcome these barriers. As climate change intensifies, organic farming stands out as a viable strategy for building resilient, eco-friendly food systems.

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Competing Interest

The authors have declared that there are no competing interest.

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