

REVIEW PAPER

Soil Health–Driven Strategies for Sustainable and Climate-Resilient Horticulture: A Critical Review with Comparative Insights and Future Directions

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ABSTRACT

Horticulture plays a pivotal role in global food and nutritional security, yet its sustainability is increasingly constrained by soil degradation driven by intensive tillage, mono-cropping, and excessive chemical inputs. This review critically synthesizes soil health–driven strategies as a foundation for resilient horticultural systems, adopting a comparative and systems-based perspective. Soil health is conceptualized as the integrated functioning of physical, chemical, and biological properties that collectively regulate productivity, ecosystem stability, and climate adaptability through services such as nutrient cycling, water regulation, carbon sequestration, and disease suppression. A comparative evaluation of key strategies—including organic matter management, biological interventions, conservation tillage, cropping system diversification, integrated nutrient management, water–soil management, and agroforestry—demonstrates that integrated approaches consistently outperform isolated or input-intensive practices. Organic amendments enhance soil carbon and structure, while microbial inputs improve nutrient cycling but show variable field performance. Conservation tillage and diversification strengthen resilience, though often accompanied by short-term yield fluctuations and management complexity. The review highlights that synergistic interactions among practices are central to long-term sustainability, yet adoption remains limited due to economic constraints, knowledge gaps, inconsistent bioinput performance, and policy biases. Emerging frontiers such as soil microbiome engineering, nanotechnology, precision agriculture, and carbon farming offer promising opportunities but require validation across diverse agro-ecological contexts. Overall, this review underscores that resilience in horticulture is a managed outcome, achievable through holistic, soil-centric strategies supported by interdisciplinary innovation, policy alignment, and region-specific implementation frameworks.

HIGHLIGHTS

- ① Soil health integrates physical, chemical, and biological dimensions to drive resilient and sustainable horticultural systems.
- ② Integrated soil management strategies outperform conventional input-intensive practices through synergistic improvements in soil function and resource-use efficiency.

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- ① Organic matter and microbial interventions play central roles in enhancing nutrient cycling, soil structure, and ecological stability.
- ① Trade-offs between short-term productivity and long-term sustainability necessitate systems-based, context-specific management approaches.
- ① Emerging technologies like microbiome engineering, nanotechnology, and precision agriculture offer new pathways for soil health enhancement.
- ① Adoption barriers highlight the need for policy support, farmer awareness, and region-specific implementation strategies.

Keywords: Horticultural System Resilience, Precision Soil Ecology, Regenerative Soil Intensification, Soil Functionality Integration, Soil–Plant–Microbiome Interface

Horticulture, encompassing the cultivation of fruits, vegetables, ornamentals, plantation crops, and medicinal plants, represents one of the most intensive and nutritionally significant branches of agriculture. It plays a critical role in global food and nutritional security by enhancing dietary diversity, supplying essential micronutrients, generating farm income, and supporting livelihood resilience (Tilman *et al.* 2011). Horticultural sustainability reflects the capacity of horticultural systems to maintain long-term productivity, profitability, ecological balance, and nutritional output while minimizing environmental degradation and resource depletion (Garnett *et al.* 2013; Pretty *et al.* 2018). Given their high-value nature and sensitivity to soil conditions, horticultural systems are inherently dependent on soil quality, making soil health central to sustainable intensification (Bouma, 2014; Kibblewhite *et al.* 2008).

However, modern horticulture is increasingly characterized by high external input dependency, intensive tillage, mono-cropping, and excessive chemical fertilization. While these practices have contributed to short-term yield gains, they have also driven progressive soil degradation (Foley *et al.* 2011; Rockström *et al.* 2017). This degradation is manifested through the depletion of soil organic carbon (SOC), deterioration of soil structure, nutrient imbalances, salinity buildup, and a marked decline in biological activity (Lal, 2020; Montgomery, 2007). Such changes disrupt fundamental soil processes, reduce nutrient-use efficiency, and weaken the soil's buffering capacity against environmental stresses (Congreves and Van Eerd, 2015; Zhang *et al.* 2015). The problem is particularly acute in horticultural systems due to their intensive cultivation cycles and higher demands for water and nutrients compared to staple field crops. Declining soil quality not only reduces yield stability but also directly affects

produce quality—an essential economic parameter in horticulture (FAO, 2022). Moreover, degraded soils exhibit reduced resilience to climatic stresses such as drought, heat waves, and erratic rainfall patterns (IPCC, 2022; Paustian *et al.* 2016). These challenges have necessitated a paradigm shift from input-centric production models toward soil health-centered management approaches that prioritize long-term system stability over short-term productivity gains (Altieri *et al.* 2021; Schipanski *et al.* 2016).

Soil health is broadly defined as the capacity of soil to function as a living system that sustains plants, animals, and humans (Doran and Zeiss, 2000). It is governed by three interdependent components: (i) physical properties, including soil structure, porosity, aggregation, and water-holding capacity; (ii) chemical properties, such as nutrient availability, pH balance, and salinity status; and (iii) biological properties, encompassing microbial diversity, enzymatic activity, and soil fauna interactions (Kibblewhite *et al.* 2008; Wall *et al.* 2015). The integration of these components determines soil functionality and its ability to deliver essential ecosystem services, including nutrient cycling, water regulation, carbon sequestration, and disease suppression (Keshyagol *et al.* 2026; Drinkwater and Snapp, 2020).

Historically, soil science in horticulture evolved through distinct phases. Early approaches were largely reductionist and chemically oriented, focusing on correcting nutrient deficiencies through synthetic fertilizers and managing soil pH. While these interventions significantly enhanced productivity during the Green Revolution era, they often overlooked the long-term implications for soil structure and biology (Six *et al.* 2004). Subsequently, integrated nutrient management practices emerged, incorporating organic amendments and crop



residues. In recent decades, advances in soil microbiology, carbon dynamics, and precision agriculture have further transformed the discipline into a holistic science that integrates physical, chemical, and biological dimensions (Bender *et al.* 2021). This evolution reflects a broader transition from ‘feeding the plant’ to ‘managing the soil as a living system’.

In this context, the concept of ‘cultivating resilience’ has gained prominence. Soil resilience refers to the ability of soil systems to resist and recover from disturbances while maintaining functional integrity (Lal, 2004; Smith *et al.* 2020). A wide range of soil science–based strategies contribute to this resilience in horticulture, including organic matter management, soil biological enhancement, conservation tillage and soil structure management, cover cropping and crop diversification, efficient water and moisture management, integrated nutrient management, integrated pest and disease management (IPM), soil erosion and degradation control, agroforestry and perennial systems, soil health monitoring and precision management, chemical load reduction, and climate-resilient practices (Giller *et al.* 2015; Reganold and Wachter, 2016). Emerging approaches such as nanotechnology, bioengineered inputs, and digital soil diagnostics are further expanding the scope of sustainable interventions (Goel and Kumar, 2024; Joshi *et al.* 2026).

This review aims to: (a) critically evaluate soil health–driven strategies in horticultural systems; (b) provide a comparative analysis of their effectiveness across different agro-ecological contexts; (c) identify key trade-offs, constraints, and knowledge gaps associated with their adoption; and (d) highlight emerging technologies and future research directions that can enhance system resilience. The uniqueness of this review lies in its integrative and comparative perspective. Rather than presenting strategies in isolation, it systematically contrasts conventional

input-intensive practices with sustainable and regenerative alternatives, evaluating them based on efficiency, environmental impact, economic feasibility, and long-term soil functionality. Furthermore, it emphasizes context-specific applicability, recognizing that the performance of soil management strategies varies across climatic zones, crop types, and socio-economic conditions. By bridging traditional knowledge with cutting-edge innovations, this review provides a comprehensive and critical framework for advancing resilient horticultural systems in the face of global challenges such as climate change, land degradation, and resource scarcity.

Conceptual framework of soil health in horticulture

Soil health in horticulture is increasingly conceptualized as a dynamic, integrated system rather than a static checklist of properties. The physical, chemical, and biological dimensions do not function independently; instead, they interact continuously to regulate soil processes, crop performance, and long-term sustainability (Kibblewhite *et al.* 2008; Doran and Zeiss, 2000). A critical limitation of conventional horticulture is its reductionist bias toward chemical fertility, often overlooking how physical degradation and biological decline undermine nutrient-use efficiency itself (Drinkwater & Snapp, 2020). Thus, a systems-based understanding is essential for cultivating resilient production systems (Table 1).

1. Physical dimension

The physical structure of soil forms the foundation for root growth and resource acquisition. Parameters such as aggregation, bulk density, porosity, and pore continuity govern water infiltration, aeration, and mechanical resistance to roots (Six *et al.* 2004). In intensive horticulture, repeated tillage and machinery traffic disrupt soil aggregates,

Table 1: Comparative perspective of different dimensions

Dimension	Conventional Focus	Sustainable Approach	Key Limitation
Physical	Intensive tillage, mechanical preparation	Reduced tillage, organic matter inputs	Trade-offs in crop-specific suitability
Chemical	High synthetic fertilizer input	Integrated nutrient management	Balancing yield vs sustainability
Biological	Often neglected or suppressed	Microbial restoration, organic amendments	Variability in field performance

leading to compaction, crusting, and reduced hydraulic conductivity (Montgomery, 2007). While conventional tillage may provide short-term benefits, it accelerates structural instability and carbon loss (Roy *et al.* 2021; Lal, 2020). In contrast, organic matter incorporation and reduced tillage enhance aggregation via microbial binding agents (Gupta and Germida, 2015).

2. Chemical dimension

The chemical dimension governs nutrient dynamics, availability, and potential toxicity. Horticultural systems depend heavily on synthetic fertilizers, often leading to nutrient imbalances, acidification, and salinity buildup (Zhang *et al.* 2015). A key issue is inefficient nutrient-use efficiency (NUE), where inputs exceed plant uptake capacity. Integrated nutrient management (INM) improves synchronization of nutrient supply and demand (Rathi *et al.* 2024), although complete substitution of chemical inputs remains impractical in intensive systems (Garnett *et al.* 2013).

3. Biological dimension

The biological component represents the most dynamic indicator of soil health. Soil organisms regulate nutrient cycling, organic matter turnover, and disease suppression (van der Heijden *et al.* 2008). Intensive systems often suppress microbial diversity due to pesticide overuse and low organic inputs. Although microbial inoculants are widely promoted, their field performance remains inconsistent (Bender *et al.* 2021). Therefore, restoring native microbial communities is more sustainable than external inoculation alone (Wall *et al.* 2015).

4. Functional integration

Soil functionality emerges from the interaction of all three dimensions, enabling ecosystem services such as nutrient cycling, water regulation, carbon sequestration, and disease suppression (Paustian *et al.* 2016). Biological processes act as a bridge linking chemical transformations and physical structure formation (van der Heijden *et al.* 2008). Thus, degradation in one domain cascades into others, reinforcing the need for integrated management (Bouma, 2014).

A key insight is that biological processes mediate both chemical transformations and physical

structure formation, acting as a bridge between the other two dimensions. Therefore, degradation in one domain inevitably cascades into others. A major limitation in current horticultural systems is the overemphasis on chemical inputs as a proxy for soil fertility, neglecting the foundational roles of structure and biology. This imbalance creates a cycle of dependency where declining soil function necessitates increasing external inputs. Breaking this cycle requires a holistic soil health framework, where all three dimensions are managed synergistically rather than in isolation.

Comparative analysis of soil health-driven strategies

1. Organic matter management

Organic matter (OM) remains the central driver of soil multifunctionality in horticultural systems, linking physical stability, chemical buffering, and biological activity (Lal, 2004). Its role extends beyond nutrient supply to regulating soil resilience under stress conditions, particularly drought and intensive cultivation. While widely acknowledged, its management is often fragmented and inconsistent across production systems.

OM enhances aggregate stability through microbial binding agents, improves water-holding capacity by increasing microporosity, and acts as a slow-release nutrient reservoir (Lehmann and Joseph, 2015). More importantly, it fuels soil biota, thereby indirectly regulating nutrient mineralization and disease suppression. However, the rate and pathway of these benefits vary significantly depending on the type of organic input (Table 2) (Rathi *et al.* 2024).

No single organic amendment is sufficient to sustain intensive horticulture. Compost ensures stability, green manure provides immediacy, and biochar offers persistence—but their isolated use creates functional gaps (Dey and Mondal, 2020; Dey *et al.* 2023). An integrated OM strategy can generate synergistic effects, optimizing both short-term productivity and long-term soil health (Pretty *et al.* 2018). However, a key bottleneck lies in standardization and scalability. Variability in raw materials, decomposition stages, and nutrient composition leads to inconsistent outcomes. Thus, future progress depends on quality-controlled organic inputs and site-specific OM

Table 2: Comparative evaluation of different amendments

Amendment Type	Strengths	Limitations	Functional Role
Compost / FYM	Stable carbon, long-term fertility	Slow nutrient release, bulk requirement	Structural improvement, microbial habitat
Green Manure	Rapid nutrient release, N fixation	Low persistence, seasonal dependency	Short-term fertility boost
Biochar	High stability, carbon sequestration, CEC enhancement	Variable yield response, cost constraints	Long-term carbon storage, soil buffering

Table 3: Comparative evaluation of different biological approaches

Intervention Type	Strengths	Limitations	Functional Role
Biofertilizers	Eco-friendly, improve nutrient cycling	Inconsistent field performance	Nutrient mobilization
Mycorrhizae	Stable symbiosis, efficient P uptake	Sensitive to soil disturbance	Root extension, stress tolerance
Biocontrol Agents	Targeted disease suppression	Require specific soil conditions	Pathogen regulation

management frameworks, rather than generalized recommendations.

2 Biological interventions

Biological interventions in horticulture aim to re-activate soil as a living system, enhancing nutrient cycling, plant growth, and resilience through microbial processes (Bender *et al.* 2021). Unlike chemical inputs, these approaches rely on functional interactions between plants and microorganisms, making their performance inherently context-dependent.

Biofertilizers such as *Rhizobium*, *Azotobacter*, and phosphate-solubilizing bacteria (PSB) improve nutrient availability through biological nitrogen fixation and solubilization of bound phosphorus. Mycorrhizal fungi, particularly arbuscular mycorrhizae (AMF), extend root absorptive capacity and enhance phosphorus and micronutrient uptake. Biocontrol agents like *Trichoderma* and *Pseudomonas* contribute to disease suppression via competition, antibiosis, and induced systemic resistance (Table 3).

A major limitation of biological inputs is their variability under field conditions, driven by soil type, climate, and native microbiota competition. Single-strain inoculants often fail to establish consistently, reducing reliability (van der Heijden *et al.* 2008). In contrast, microbial consortia offer functional redundancy and resilience, improving

adaptability across environments. However, their success depends on ecological compatibility and habitat suitability, which are often overlooked in commercial applications. Thus, future strategies should prioritize site-specific microbial engineering and soil habitat restoration, rather than mere inoculation, to ensure sustained biological functionality.

3. Conservation tillage

Conservation tillage represents a shift from mechanical soil manipulation to biological structuring, aiming to preserve aggregation, minimize erosion, and enhance soil organic carbon (SOC) (Pittelkow *et al.* 2015). In horticulture, its adoption is complex due to crop-specific requirements, yet its long-term benefits for soil resilience are increasingly evident. Conventional tillage temporarily improves aeration and root penetration but disrupts soil aggregates, accelerates organic matter oxidation, and weakens microbial habitats. In contrast, conservation tillage promotes carbon stabilization, pore continuity, and biological activity, leading to improved water retention and reduced erosion over time (Table 4).

Despite its benefits, conservation tillage often leads to increased weed pressure and initial yield variability, particularly during the transition phase (Giller *et al.* 2015). In high-value horticultural crops, this can pose economic risks, limiting adoption.

Table 4: Comparative evaluation of different tillage systems

Tillage System	Short-Term Effects	Long-Term Impacts	System Implication
Conventional Tillage	Better seedbed, immediate yield gains	SOC loss, compaction, structural decline	Input-dependent system
Conservation Tillage	Slower initial establishment	Improved aggregation, SOC, moisture	Resilient system

Table 5: Comparative evaluation of different cropping systems

System Types	Advantages	Limitations	Soil Health Impact
Mono-cropping	High uniform yield, easy mechanization	High pest risk, nutrient depletion	Soil degradation over time
Crop Rotation	Breaks pest cycles, improves nutrient balance	Requires planning, crop compatibility	Moderate improvement
Intercropping	Efficient resource use, niche complementarity	Management complexity	Enhanced biological activity
Polyculture	High resilience, biodiversity enrichment	Difficult mechanization, market constraints	Strong soil restoration

The effectiveness of conservation tillage is context-dependent rather than universally applicable. Its benefits are significantly amplified when integrated with cover cropping and organic inputs, which compensate for reduced soil disturbance by enhancing biological activity and surface protection (Thapa *et al.* 2024). Thus, conservation tillage should not be viewed as a standalone practice but as part of a systems-based soil management strategy, where short-term trade-offs are strategically managed to achieve long-term sustainability and resilience.

4. Cropping system diversification

Cropping system diversification is a core ecological strategy that enhances soil resilience by optimizing resource use, stabilizing productivity, and reducing systemic risks. In horticulture —where mono-cropping is prevalent due to market demand — diversification introduces functional heterogeneity, improving both above- and below-ground interactions (Altieri *et al.* 2021). Diversification operates through crop rotation (temporal diversity), intercropping (spatial complementarity), and polyculture (multi-species integration). These systems influence root architecture, nutrient uptake patterns, and microbial diversity, thereby strengthening soil processes (Schipanski *et al.* 2016). Mono-cropping maximizes short-term productivity but leads to nutrient mining, pest buildup, and reduced microbial diversity. Diversified systems, in contrast, improve nutrient cycling, soil structure,

and biological interactions, contributing to long-term sustainability (Table 5).

Despite clear ecological advantages, diversification faces practical barriers, including mechanization limitations, labor intensity, and market preferences for uniform produce. Moreover, benefits are often context-specific and knowledge-intensive, requiring precise crop combinations and management timing. Thus, the transition toward diversification must integrate technological innovation (e.g., adaptive machinery) and market restructuring, ensuring that ecological benefits translate into economic viability for horticultural producers (Pretty *et al.* 2018).

5. Water–Soil management

Water management in horticulture is not merely about irrigation efficiency; it fundamentally regulates soil physical stability, chemical dynamics, and biological activity. The interaction between water and soil determines aeration, nutrient mobility, salinity risk, and microbial functioning, making it a critical axis of soil health management (Table 6). Flood irrigation, though widely practiced, often leads to waterlogging, salt accumulation, and nutrient loss, thereby degrading soil structure and reducing root efficiency. In contrast, drip irrigation enables precise water delivery, maintaining optimal moisture conditions without disturbing soil aggregates. Mulching further complements this by stabilizing soil temperature, reducing evaporation, and promoting microbial activity (Lal, 2020).

**Table 6:** Comparative evaluation of different soil water management systems

Practice	Advantages	Limitations	Soil Health Impact
Flood Irrigation	Low initial cost, simple operation	Water loss, salinity buildup, nutrient leaching	Structural degradation, poor aeration
Drip Irrigation	High water-use efficiency, targeted delivery	Higher installation cost, maintenance	Preserves structure, reduces leaching
Mulching	Reduces evaporation, moderates temperature	Material availability, management effort	Enhances moisture retention, supports microbes

Table 7: Comparative evaluation of different nutrient release approaches

Approaches	Strengths	Limitations	Long-Term Impact
Chemical Fertilization	Immediate nutrient availability, high yield	Nutrient imbalance, soil degradation	Declining soil function
Organic-Only Systems	Soil restoration, ecological sustainability	Slow nutrient release, yield constraints	Improved soil health
INM	Balanced nutrition, improved NUE	Requires management precision	Sustainable productivity

A key limitation in current systems is the fragmented adoption of water management practices, where irrigation methods are not integrated with soil health strategies. The synergy between drip irrigation and organic mulching, for instance, can significantly enhance moisture-use efficiency and biological activity, yet remains underutilized (Zhang *et al.* 2015). Thus, water–soil management should be approached as a coupled system, where optimizing one without the other leads to suboptimal outcomes. Future strategies must emphasize integrated, precision-based water–soil frameworks to enhance both productivity and resilience.

6. Integrated nutrient management (INM)

Integrated Nutrient Management (INM) represents a transitional paradigm between conventional input-intensive agriculture and fully regenerative systems. By combining organic amendments, inorganic fertilizers, and biological inputs, INM aims to optimize nutrient availability while maintaining soil functionality and minimizing environmental externalities (Congreves and Van Eerd, 2015). INM improves nutrient use efficiency (NUE) by synchronizing nutrient release with crop demand, thereby reducing losses through leaching, volatilization, and fixation (Rathi *et al.* 2024). The inclusion of organic inputs enhances soil organic carbon, aggregation, and microbial activity, while biofertilizers facilitate nutrient mobilization. Collectively, these effects contribute to reduced

environmental impact and improved soil health (Table 7).

INM outperforms purely chemical systems by reducing dependency on synthetic inputs and improving soil buffering capacity. However, it is not without limitations. The complexity of managing multiple inputs, variability in organic sources, and site-specific nutrient dynamics can affect consistency (Garnett *et al.* 2013). While INM is widely promoted as a sustainable solution, it often remains input-optimization rather than system transformation. It improves efficiency but may not fully restore ecological processes to the level achieved by regenerative systems. Therefore, INM should be viewed as a strategic intermediate approach, bridging productivity goals with long-term soil regeneration, rather than an endpoint in sustainable horticulture.

7. Agroforestry and perennial systems

Agroforestry and perennial-based systems represent a structural reconfiguration of horticulture, shifting from short-term, input-driven production to ecologically regulated, and self-sustaining systems. By integrating trees with crops, these systems create multilayered canopies and deeper rooting networks that fundamentally alter soil processes and landscape stability (Paustian *et al.* 2016). The presence of perennial components enhances carbon sequestration through continuous biomass input and reduced soil disturbance. Deep-rooted trees

Table 8: Comparative evaluation of different nutrient release approaches

System Type	Strengths	Limitations	Soil Health Impact
Annual Systems	Quick returns, flexible cropping	High disturbance, lower stability	Declining SOC, higher erosion
Perennial Systems	Long-term stability, continuous cover	High initial investment, delayed returns	Improved carbon storage, structure
Agroforestry	Multifunctionality, biodiversity enhancement	Complex design, management challenges	Strong ecosystem resilience

improve nutrient recycling by accessing subsoil reserves, while permanent ground cover reduces erosion and runoff losses (Lal, 2004). Additionally, increased plant diversity supports rich microbial and faunal communities, strengthening biological resilience and ecosystem services. Perennial systems inherently provide temporal stability, while agroforestry adds spatial and functional diversity, making them superior in long-term soil restoration compared to annual mono-cropping. Despite their ecological advantages, adoption remains limited due to economic and managerial constraints, including delayed profitability and lack of standardized models (Reganold & Wachter, 2016). Moreover, poorly designed agroforestry systems may lead to resource competition (light, water, nutrients) (Table 8). Thus, their success depends on context-specific design, species compatibility, and policy support, positioning agroforestry not merely as a practice but as a holistic land-use strategy for resilient horticulture.

Synthesis: synergies and trade-offs

Soil health-driven strategies in horticulture do not function as isolated interventions; rather, they form a complex, interactive network where outcomes are shaped by synergies, feedback loops, and inherent trade-offs (Fig. 1). A fragmented adoption of individual practices often leads to suboptimal or even contradictory results, whereas a systems-based integration can unlock cumulative benefits that exceed the sum of individual components (Pretty *et al.* 2018).

One of the most compelling aspects of soil health management is the emergence of functional synergies. For instance, the combination of organic matter inputs with microbial inoculants enhances nutrient cycling beyond additive effects. Organic substrates provide energy sources and habitat, enabling introduced or native microbes to establish

and function effectively, thereby improving nutrient mineralization and availability (Bender *et al.* 2021). Similarly, conservation tillage coupled with cover cropping creates a reinforcing cycle of soil protection and regeneration. Reduced disturbance preserves soil aggregates, while cover crops contribute biomass, root exudates, and surface protection. Together, they enhance soil organic carbon accumulation, aggregation, and moisture retention, ultimately improving resilience to climatic stress (Pittelkow *et al.* 2015). Another critical synergy is observed between integrated nutrient management (INM) and precision irrigation. Efficient water delivery systems, such as drip irrigation, ensure that nutrients are retained within the root zone, reducing losses and improving nutrient-use efficiency. This integrated approach aligns resource availability with plant demand, minimizing environmental impacts while sustaining productivity.

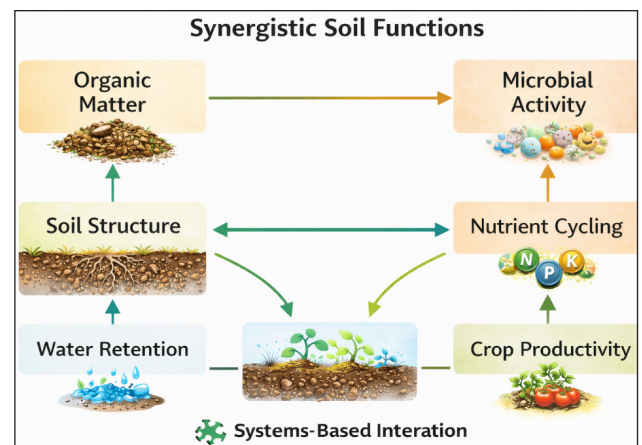


Fig. 1: Simplified interaction network illustrating synergistic soil functions

Despite these synergies, soil health strategies are not without trade-offs. A fundamental tension exists between short-term productivity and long-term sustainability (Giller *et al.* 2015). Practices such as reduced tillage or organic amendments may initially



result in yield fluctuations or slower nutrient availability, posing risks for farmers dependent on immediate returns. Labor and management complexity present another significant constraint. Diversified systems, organic matter management, and biological interventions often require greater knowledge, monitoring, and manual inputs, making them less compatible with conventional mechanized systems. This creates a trade-off between ecological benefits and operational feasibility. Economic considerations further complicate adoption. Many soil health practices involve high initial investments — for example, drip irrigation systems, bioinputs, or agroforestry establishment — while their benefits accrue gradually over time. This temporal mismatch between cost and return can deter adoption, particularly among smallholder farmers (Rockström *et al.* 2017).

A key limitation in current horticultural practice is the piecemeal implementation of soil health strategies, often driven by input substitution rather than system redesign. This approach fails to capture the interactive benefits and may even create inefficiencies. Therefore, a holistic systems approach is essential—one that strategically integrates practices to maximize synergies while explicitly managing trade-offs. Future research and policy must focus on context-specific optimization frameworks, enabling farmers to balance productivity, sustainability, and economic viability.

Constraints and adoption barriers

Despite compelling scientific evidence supporting soil health–driven strategies, their large-scale adoption in horticulture remains uneven and often limited. This gap reflects not a lack of technological solutions, but a misalignment between innovation, economics, knowledge systems, and policy frameworks. Economic barriers are among the most significant impediments. Many soil health practices—such as drip irrigation, bioinputs, or agroforestry establishment—require high upfront investment, while benefits such as improved soil structure or carbon sequestration accrue gradually. This temporal mismatch between cost and return discourages adoption, particularly among smallholders operating under tight financial constraints (Falcon *et al.* 2022). Knowledge and capacity gaps further exacerbate the issue. Soil health

management is inherently knowledge-intensive and site-specific, requiring an understanding of soil biology, nutrient dynamics, and system interactions. In contrast, conventional input-based agriculture offers standardized, easily replicable solutions. As a result, farmers often lack the technical guidance needed to implement integrated strategies effectively.

Another critical limitation is the inconsistent performance of biological inputs. Biofertilizers and biocontrol agents frequently show variable results under field conditions due to environmental fluctuations and competition with native microbiota. This unpredictability undermines farmer confidence and reinforces reliance on chemical inputs perceived as more reliable. Policy frameworks also play a decisive role. In many regions, subsidies and institutional support remain biased toward synthetic fertilizers and conventional practices, creating structural disincentives for adopting sustainable alternatives (IPCC, 2022).

A central insight is that technological innovation alone cannot drive transformation. Soil health strategies require supportive ecosystems involving extension services, financial incentives, and policy realignment. Without these, even the most effective practices remain confined to experimental or niche applications. Therefore, the transition toward resilient horticulture demands a systems-level intervention, where scientific advances are complemented by institutional reforms, farmer-centric knowledge dissemination, and economic mechanisms that de-risk adoption.

Emerging frontiers

The next phase of soil health–driven horticulture is being shaped by interdisciplinary convergence, where advances in biology, materials science, and digital technologies are redefining how soil systems are understood and managed. These emerging frontiers aim not only to enhance productivity but also to engineer resilience at multiple scales, from the rhizosphere to the landscape (Fig. 2).

1. Soil microbiome engineering

Recent progress in microbial ecology has opened avenues for targeted manipulation of soil microbiomes to enhance nutrient acquisition, stress

tolerance, and disease resistance. Unlike conventional inoculation approaches, microbiome engineering focuses on designing stable, functional microbial communities that can persist under field conditions (Bender *et al.* 2021). However, soil ecosystems are highly complex and context-dependent; introduced consortia often face competition from native microbiota. Thus, the challenge lies in achieving ecological compatibility and functional stability, rather than merely increasing microbial diversity.

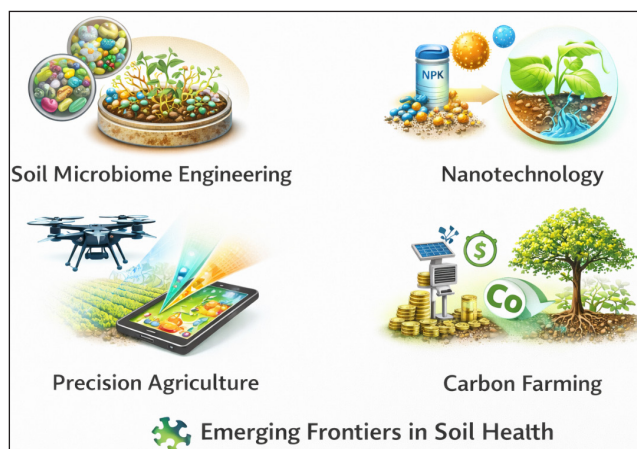


Fig. 2: Emerging frontiers in soil health

2. Nanotechnology

Nanotechnology offers transformative potential through nano-fertilizers and nano-carriers that enable controlled and targeted nutrient release. These inputs can significantly improve nutrient-use efficiency (NUE) while reducing environmental losses such as leaching and volatilization. Nevertheless, concerns remain regarding long-term soil accumulation, potential toxicity, and regulatory gaps, which must be addressed before widespread adoption (Roy and Mondal, 2023).

3. Precision agriculture

The integration of sensors, artificial intelligence (AI), and geographic information systems (GIS) is enabling real-time monitoring of soil moisture, nutrient status, and biological activity. Precision agriculture facilitates site-specific management, reducing input waste and enhancing decision-making accuracy (Kumar *et al.* 2024). However, its scalability is constrained by high costs, data complexity, and limited accessibility for smallholder farmers, particularly in developing regions.

4. Carbon farming

Carbon farming introduces an economic dimension to soil health by incentivizing carbon sequestration through carbon credit mechanisms (Smith *et al.* 2020). Practices such as cover cropping, reduced tillage, and agroforestry can generate measurable carbon gains, linking soil management with climate mitigation (Kabato *et al.* 2025). Yet, measurement uncertainties, verification costs, and policy standardization remain significant barriers.

While these innovations hold substantial promise, their success depends on rigorous validation across diverse agro-climatic conditions and farming systems. A key risk is the technological oversimplification of complex soil processes, which may lead to inconsistent outcomes. Therefore, future progress must integrate these advanced tools with ecological principles and local knowledge, ensuring that innovation translates into sustainable and scalable horticultural practices.

Research gaps

Despite rapid advances in soil health research, several critical knowledge gaps continue to limit the effective translation of science into horticultural practice. A major limitation is the lack of long-term, multi-location trials, which restricts our understanding of how soil health strategies perform under diverse agro-climatic conditions and over extended periods (Timilsina *et al.* 2025). Most existing studies are short-term and site-specific, often overestimating benefits while failing to capture cumulative effects such as carbon stabilization, structural resilience, and system adaptability. Another key gap is the limited integration of biological indicators into soil health assessment frameworks (Wall *et al.* 2015). While physical and chemical parameters are routinely measured, biological metrics—such as microbial diversity, functional genes, and enzymatic activity—remain underutilized due to methodological complexity and lack of standard protocols. This creates an incomplete understanding of soil functionality.

Furthermore, the soil–plant–microbiome interface remains insufficiently understood. Interactions among root exudates, microbial communities, and soil properties are highly dynamic and context-dependent, yet current research often isolates these



components rather than examining their integrated behavior. Finally, the lack of standardization in bioinputs—including biofertilizers and biocontrol agents—leads to inconsistent performance and low farmer confidence (Joshi *et al.* 2026). Variability in strain selection, formulation, and application methods further complicates reproducibility. Collectively, these gaps highlight the need for systems-based, interdisciplinary research frameworks that integrate long-term experimentation, standardized methodologies, and holistic analysis to advance soil health–driven horticulture.

Future directions

Advancing soil health–driven horticulture requires a decisive shift from fragmented interventions to systems-based research and implementation frameworks. Future studies must integrate physical, chemical, and biological dimensions within long-term, multi-scale experimental designs, capturing interactions, feedback mechanisms, and resilience outcomes under real farming conditions. Such approaches will move beyond input optimization toward system redesign, enabling sustainable intensification. A promising frontier lies in the integration of omics technologies—including genomics, metagenomics, transcriptomics, and metabolomics—to decode complex soil–plant–microbiome interactions. These tools can identify functional microbial traits, nutrient cycling pathways, and stress-response mechanisms. However, their practical application remains limited by high costs, data complexity, and the challenge of translating molecular insights into field-level interventions.

Policy support is equally critical. Current agricultural policies often prioritize yield-centric approaches, with limited incentives for soil health improvement. Future frameworks must promote soil-centric subsidies, carbon credit mechanisms, and support for regenerative practices, aligning economic incentives with ecological sustainability. Finally, the development of region-specific management strategies is essential, given the variability in soil types, climate, and cropping systems. Universal recommendations are often ineffective; instead, context-driven, locally adaptive solutions must be prioritized.

Collectively, these directions emphasize that the future of horticulture lies in integrating advanced science with practical, policy-backed, and location-specific solutions for resilient soil management.

CONCLUSION

Soil health emerges as the central determinant of resilience and sustainability in horticultural systems, underpinning productivity, quality, and ecological stability. This review demonstrates that no single intervention can adequately address the complex challenges of soil degradation and climate stress. Instead, integrated soil science strategies — encompassing organic matter management, biological interventions, conservation tillage, diversified cropping, and efficient water–nutrient use — consistently outperform isolated approaches by generating synergistic benefits across physical, chemical, and biological domains. However, the transition from conventional to soil health–driven systems is constrained by economic, institutional, and knowledge barriers. Bridging this gap requires not only technological innovation but also policy alignment, farmer-centric capacity building, and context-specific adaptation frameworks. Resilience should not be viewed as an inherent property, but rather as a managed outcome cultivated through deliberate soil-centric practices. Future progress depends on advancing systems-level understanding, integrating emerging technologies with ecological principles, and ensuring that sustainability is both scientifically robust and practically achievable.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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