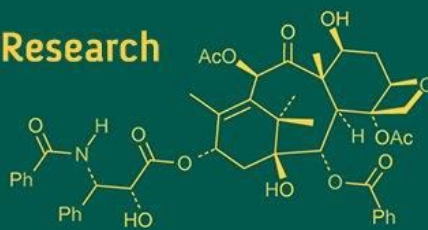


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; 10(3): 569-578
www.biochemjournal.com
Received: 18-01-2026
Accepted: 21-02-2026

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Integrating biotechnology and smart systems for sustainable horticulture: Advances in soil-plant-environment interactions in horticultural ecosystems

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i3g.7928>

Abstract

Horticulture is currently facing a large number of significant sustainability challenges due to global population increases; variable climates; and limited availability of resources. Smart systems and biotechnology (Internet of Things [IoT], artificial intelligence [AI] and precision agriculture) may be able to help solve these problems. In this paper we will look at what current research has found about using biotechnology along with sensor technology to optimize the relationships between the environment, plants and soils in horticultural systems. Specifically we will discuss the potential for CRISPR-Cas9 gene editing as an innovative tool for improving crop resilience and productivity through beneficial microorganisms and real time monitoring of the environment. We also will discuss the dynamic interplay among climate variables, soil microbiota, and plant phenotypes in creating sustainable horticultural practices. The results indicate that the combination of genetic improvements with data-based resource allocation strategies could lead to increased yields (12-20%) and decreased water usage (25-40%). Furthermore, the paper identifies several challenges including regulatory issues, obstacles to farmer adoption, and infrastructural needs associated with scaling-up these biotechnologies in various forms of agricultural settings.

Keywords: CRISPR, IoT sensors, precision horticulture, rhizosphere microbiome, sustainable agriculture, climate-resilient crops, data analytics

1 Introduction

The world's horticultural industry is at a turning point. Demand for fresh produce is going to rise significantly by 2050, so if farmers continue using traditional methods, they will be unable to keep up with the demand without suffering an ecological disaster (Poenaru *et al.*, 2025) [50]. Climate change adds to the uncertainty fluctuations in rainfall, extreme temperatures, new pests and diseases add unpredictability to systems based upon predictability. In addition, soil degradation and lack of water limit cultivation of land in many parts of the world; therefore, in order to expand horticultural crop cultivation into more space, it is necessary to use technology to improve efficiency through intensification. But the story gets more complicated when compared to the optimistic view of technology simply solving problems. Biotechnology has achieved impressive results resistant varieties of crops to diseases and insects, improved nutritional content, and rapid development of new crop varieties yet its application is very different depending on the region or country. Smart farming technologies provide the possibility of precision resource utilization and have a lot of possibilities, yet there are still barriers related to costs, technical capabilities, and available infrastructure (Molina *et al.*, 2025) [40], thus neither of them can accomplish the task independently. Therefore, a combination of both biotechnologies and smart farming technologies may provide a better alternative to achieve sustainability in horticulture.

In this review, we investigate the opportunities to develop more adaptable and efficient horticultural systems using biotechnological innovations and smart monitoring systems to interact with the soil, plants, and environment in a more optimal manner (Zhou *et al.*, 2025) [73]. This review does not focus solely on maximizing yields but also on creating production systems that are resilient enough to withstand climate variability and minimize the impact of environmental damage.

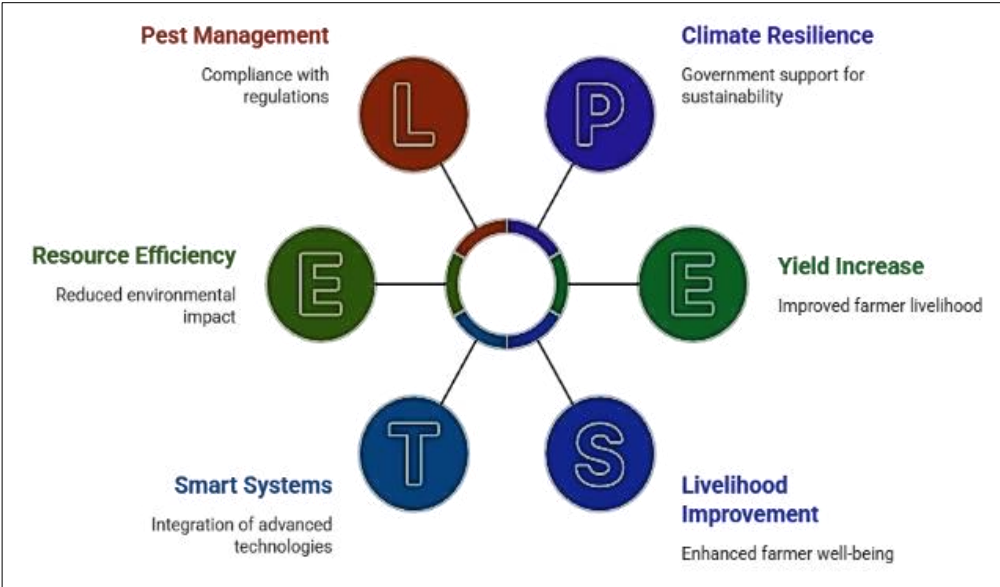


Fig 1: Integrated Framework for Sustainable Horticultural Systems

2.1 Understanding soil-plant-environment interactions in horticulture

Soil provides a physical environment where plants grow, modern studies show that soil is a dynamic living system, composed of microorganisms including bacteria, fungi and fauna that have significant impacts on how well plants are able to grow (Jarvis *et al.*, 2024) ^[23]. Microbial interactions in the soil influence processes like nutrient cycles, pathogens and how plants respond to stressors; many aspects of these processes are still not fully understood despite being studied extensively over the years. Plant roots create a unique ecosystem referred to as the "rhizosphere" which is essentially a microbial hot spot, as plants release organic compounds into this region of their roots and provide them to the microbial community present within this region; the microbes then assist the plants in acquiring nutrients and resisting pathogens (Kuppe *et al.*, 2022) ^[29]. Despite the fact that the rhizosphere is a very unique and defined region around the roots of plants, its composition can be influenced greatly by various factors including plant genetics, soil type, moisture levels, and farming practices. A thorough understanding of how these factors interact is important for managing plants in horticulture. One example of how complex these interactions are includes moisture levels in the soil. Low moisture will limit both photosynthesis and nutrient uptake by the plant while high moisture levels will promote infection of plant roots by pathogens including fungal and oomycetes. However, symbiotic associations between the roots of a plant and certain fungi referred to as mycorrhizae, can help to mitigate the negative effects of drought on plants by increasing the effective surface area of roots and increasing the rate at which water can be absorbed by the roots. Research has

shown that some plants colonized with Arbuscular Mycorrhizal Fungi (AMF) will retain better water status when exposed to drought stress (Manea *et al.*, 2023) ^[34]; however, the effectiveness of this process is dependent upon the species of plant and fungus, as well as the conditions of the soil. The temperature and humidity patterns in the field or greenhouse also impact how diseases develop in horticultural crops. Many common horticultural diseases, including powdery mildew, botrytis, and late blight, have a direct dependence on temperature and humidity patterns in the environment. By monitoring climate variables in real time, growers can use this information to target specific interventions to control or prevent disease outbreaks; however, due to budgetary constraints, traditional extension services do not always have the ability to monitor environmental conditions in real time (R. Kumar *et al.*, 2025). Therefore, the gap between what we know about the factors that contribute to disease development in horticultural crops, and what we practice to manage these diseases, is a significant barrier to controlling disease in both developed and developing countries.

2.2 Biotechnological approaches to horticultural improvement

Biotechnology is a broad term that covers many techniques ranging from mutagenesis to new genome editing technologies. While biotechnologies provide solutions to basic problems of horticulture (e.g., disease susceptibility; abiotic stress; desired traits demanded by the marketplace), they differ widely in their precision and in how acceptable they are to the public.
Genome Editing and Developing Traits.

Table 1: Integration of biotechnology and smart systems in horticultural management

Component	Biotechnology Approach	Smart Systems Application	Integrated Outcome	Stress Tolerance
Drought-resistant varieties via CRISPR (Priyanka <i>et al.</i> , 2025) ^[52]	Soil moisture sensors trigger irrigation (Bindhu & T, 2025) ^[7]	Optimal water use 25-40% reduction (Dakshinamurthy & Mohan, 2025) ^[13]	Nutrient Management	Microbial inoculants enhance uptake (Choudhury <i>et al.</i> , 2022) ^[11]
N-P-K sensors guide application timing (Shukla & Agrawal,	Reduced fertilizer 30-50% (Nardi <i>et al.</i> , 2024) ^[42]	Disease Control	Genetic resistance breeding (Shah, 2024) ^[60]	Predictive models detect pathogen risk (Zhou <i>et al.</i> , 2025) ^[73]

2024) ^[62]				
Proactive intervention reducing 40% losses (Mehmood <i>et al.</i> , 2025) ^[38]	Yield Optimization	High-yielding varieties selection (Shah, 2024) ^[60]	AI-driven varietal recommendation (Manikandababu <i>et al.</i> , 2024) ^[36]	12-20% yield increase potential (Lone <i>et al.</i> , 2024) ^[32]

2.3 Genome editing and trait development

The possibility of altering crops using CRISPR-Cas9 has revolutionized crop development (Priyanka *et al.*, 2025)^[52]. In contrast to older transgenic technologies that used foreign DNA inserted into plants, CRISPR allows users to modify the genome of plants using the plant's own native DNA. Horticulturists have successfully utilized this technology to develop enhanced disease resistant tomatoes, extend the shelf-life of strawberries, and increase the nutritional content of numerous specialty crops (Manik *et al.*, 2024)^[35]. Additionally, the time it takes to produce genetically modified crops has been significantly reduced; what took decades to produce using traditional breeding techniques, can now be produced in 2-3 years (Basu *et al.*, 2023)^[4].

However, there are many issues with implementing CRISPR technology that go beyond its capability to perform edits. Globally, regulatory environments are very different regarding genetically modified crops; while some countries restrict all gene edited crops to prohibitions against transgenic crops, other countries allow distinctions between the method of editing and genetic modification (Shah, 2024)^[60]. Additionally, consumer attitudes towards genetic modification are also a concern, especially in Europe; much of the European population has historically expressed significant reservations about genetic modification (Shah, 2024)^[60].

Microbial biotechnology and plant-microbe associations

Table 2: Soil-Plant-Microbe Interaction Dynamics and Management Strategies

Interaction Type	Key Organisms	Environmental Influence	Management Impact	Nutrient cycling
PGPR, AMF, Trichoderma (Barea <i>et al.</i> , 2005) ^[3]	Soil pH, moisture, temperature (Jarvis <i>et al.</i> , 2024) ^[23]	Enhanced uptake efficiency (Choudhury <i>et al.</i> , 2022) ^[11]	Disease suppression	Antagonistic bacteria, fungi (Frc <i>et al.</i> , 2022) ^[16]
Competition, antibiotic production (Szczaba <i>et al.</i> , 2019) ^[67]	Reduced chemical inputs (Mehmood <i>et al.</i> , 2025) ^[38]	Stress tolerance	Mycorrhizal associations (Begum <i>et al.</i> , 2019) ^[5]	Drought, salinity, toxicity conditions (Zulfiqar <i>et al.</i> , 2023) ^[74]
Improved resilience under stress (Ngongolo & Mmbando, 2024) ^[44]	Organic matter cycling	Saprobic microbes, invertebrates (Frc <i>et al.</i> , 2022) ^[16]	Carbon availability, moisture regime (Jarvis <i>et al.</i> , 2024) ^[23]	Soil carbon sequestration (Joseph <i>et al.</i> , 2021) ^[24]

Plant-associated microorganisms offer a vast untapped resource for developing sustainable horticultural practices. Many types of plant growth promoting bacteria (PGPR) enhance the availability of essential nutrients, reduce the presence of plant pathogens, and aid plants in overcoming stresses due to several mechanisms (i.e. nitrogen fixation, phosphate solubilization, VOC production, induced systemic resistance); PGPR generally occupy either the rhizosphere of plant tissues and establish a symbiotic relationship with the plant that improves the fitness of the plant (Choudhury *et al.*, 2022)^[11]. Arbuscular mycorrhizal fungi (AMF) are also another useful group. Since these obligate symbionts establish extensive hyphal networks beyond the roots of their hosts, they create "extended root systems" for the acquisition of nutrients from areas of the soil that roots cannot easily access (Szczaba *et al.*, 2019)^[67]. Several studies conducted in Mediterranean and semi-arid climates have shown that when AMF is applied to plants, phosphorus fertilizer usage can be reduced by 50-75% with no negative impact on yields (Nardi *et al.*, 2024)^[42]; as such, research findings such as those above may have beneficial effects on environmental quality and on the economics of farmers.

Trichoderma spp. (filamentous fungi) serve as dual-purpose organisms capable of serving as both biological control agents and as biofertilizers/plant growth promoters (Woo *et al.*, 2014)^[70]. Trichoderma spp. are capable of degrading complex organic molecules which enhances soil health and the production of secondary metabolites to inhibit the presence of plant pathogens. However, the widespread application of Trichoderma spp. is limited by the need for formulations stable over long periods of storage and the

variability in effectiveness of applications made under diverse climatic/soil conditions.

3 Smart systems for real-time horticultural monitoring

Data collection is an innovative method in horticulture that utilizes IoT (Kumar *et al.* 2025) rather than the traditional way of collecting data through visual inspections on a periodic basis as well as sampling the soil from time-to-time. The data collected by IoT systems is a series of variable data streams (such as; soil moisture, temperature, humidity, electrical conductivity, nitrogen-phosphorus-potassium levels), Bindhu & T (2025)^[7] are sent into the Cloud system and can be used by algorithms to identify discrepancies and provide the grower with management suggestions for correcting any issues detected.

3.1 Sensor technologies and data architecture

The improvement in the size reduction of semiconductors makes it possible for a growing number of advanced sensors to be created at lower costs (Schlagmann *et al.*, 2023)^[59]. Today's soil moisture sensors are able to tell how much water is available to the roots of the plants verses the overall amount of moisture in the soil. Nitrate concentration can be measured using electrochemical sensors, thus making it possible to avoid the need for other measures of nitrate such as chlorophyll levels or visual assessments of the health of the canopy (Bristow *et al.*, 2022)^[8]. Hyperspectral imagery obtained from aerial drone platforms provides a detailed view of the crop's spectral signature which allows for an accurate determination of the level of stress and/or disease present in the plant prior to when visual signs become apparent.

However, there are numerous practical problems associated with deploying sensors that are often overlooked in the description of technology. The physical properties of the soil (e.g. clay, sand, compaction) create spatial variability in the physical environment that cannot be captured by evenly spaced sensors. Calibration of sensors will also degrade over time, especially in highly reactive chemical environments. The lifespan of batteries and the range of wireless transmissions creates limits on the placement of sensors in the field (Shukla & Agrawal, 2024) ^[62]. In addition, field conditions present challenges including vandalism, wildlife damage, and water infiltration that do not exist in laboratory conditions.

3.2 Data processing and artificial intelligence

Data from sensor networks is so large that humans can't analyze it all. Machine learning helps find relationships between a variety of factors and how they relate to how crops grow and if they are at risk for disease (Zhou *et al.*, 2025) ^[73]. Deep learning is used to train machines on past data, and once they are trained, they can then be used to make decisions such as when to irrigate your crops, when pests will emerge, and what your yields will be; in some cases better than an experienced agronomist (Dakshinamurthy & Mohan, 2025) ^[13].

However, there are also challenges to using data-driven decision support systems. In general, models developed based on data collected in one area do poorly in other areas where the soil is different or the climate is different. As the amount of digitalization and centralization of farm data increases, security risks increase because hackers have access to sensitive information about farms including details about the irrigation system and growing conditions of crops. Hackers could potentially use this access to hack into the irrigation system or to lie about growing conditions of the crops. Additionally, many deep-learning models produce recommendations without providing explanation (rationale) to the user for why the recommendation was made, which may further reduce farmers' trust in the model and decision-making process (Saraswathi *et al.*, 2024) ^[58].

4 Integration pathways: bridging biotechnology and smart systems: True innovation emerges where

biotechnology and smart systems reinforce each other rather than operating in parallel. Several promising integration pathways are emerging.

4.1 Genotype-by-environment optimization

The same environmental conditions result in different growth responses from various crops. For example a drought tolerant variety of tomatoes may perform less than a standard variety when there is ample water. Smart systems that continue to monitor and report the conditions in an agricultural field as they occur, are capable of making "real time" decisions for which variety to plant in each location within a field with varying environmental conditions (Zhou *et al.*, 2025) ^[73]. Data collected by the Internet of Things (IoT) regarding limited water conditions would be used to automatically grow drought resistant varieties in those locations, while growing higher yielding, standard varieties in the wetter areas. This type of adaptive, variable planting strategy is theoretically possible at this point; however it represents a very plausible option for future development.

4.2 Microbiome engineering via data-driven inoculation

The variation in soil microbiota composition is an important factor that determines both the amount of nutrients available for plants to utilize and how much of a disease suppressive effect there is. Microbial communities are affected by soil properties, management practices, and past environmental exposures. Therefore, smart systems capable of measuring and describing soil conditions can inform when it would be most appropriate to apply targeted inoculants (e.g. apply AMF if there is evidence of phosphorus limitation; apply PGPR if there is evidence of nitrogen stress) (S *et al.*, 2024). The described process of using data to make informed decisions about when to apply inoculants is fundamentally different than the traditional method of making "blanket" inoculum applications.

4.3 Precision phenotyping for accelerated breeding

The combination of speed breeding the use of controlled environments to dramatically accelerate the number of generations per year and AI-based phenotyping can create a new paradigm for the time it takes to complete the breeding cycle in the development of horticultural crops.

Table 3: IoT sensor technologies for horticultural monitoring and performance metrics

Sensor type	Variables monitored	Detection accuracy	Cost estimate (usd)	Deployment scale
Soil moisture (Bindhu & T, 2025) ^[7]	Water content, matric potential	±2-5% accuracy (Placidi <i>et al.</i> , 2021) ^[49]	\$50-200/unit	Plot to field
Environmental (R. Kumar <i>et al.</i> , 2025)	Temperature, humidity, light	±0.5°C, ±3% humidity (Srinivasan <i>et al.</i> , 2024) ^[66]	\$30-150/unit	Greenhouse, field
Electrochemical (Bristow <i>et al.</i> , 2022) ^[8]	Nitrate, phosphate, pH	±5-10% for nutrients (Schlagmann <i>et al.</i> , 2023) ^[59]	\$200-500/unit	Field, intensive
Multispectral imaging (Tsouros <i>et al.</i> , 2019) ^[68]	Vegetation index, disease symptoms	85-95% disease detection (Zhou <i>et al.</i> , 2025) ^[73]	\$300-5000/system	Regional coverage

The continuous feed of phenotypic data provided by IoT sensors monitoring a variety of attributes including the architectural characteristics of plants, their pigments, growth rate and response to environmental conditions, are used as inputs to machine learning models that allow for identification of the superior genotypes much faster than is possible using the naked eye. As such, the potential exists to

reduce the length of the breeding cycle from years to months (Patel & Gurjar, 2024) ^[47].

5. Case study: precision horticulture implementation

Real world implementation shows a combination of potential as well as continued challenges. An example of integrated technology implementation at a small scale is the Parcelas 5.0 project in Mexico.

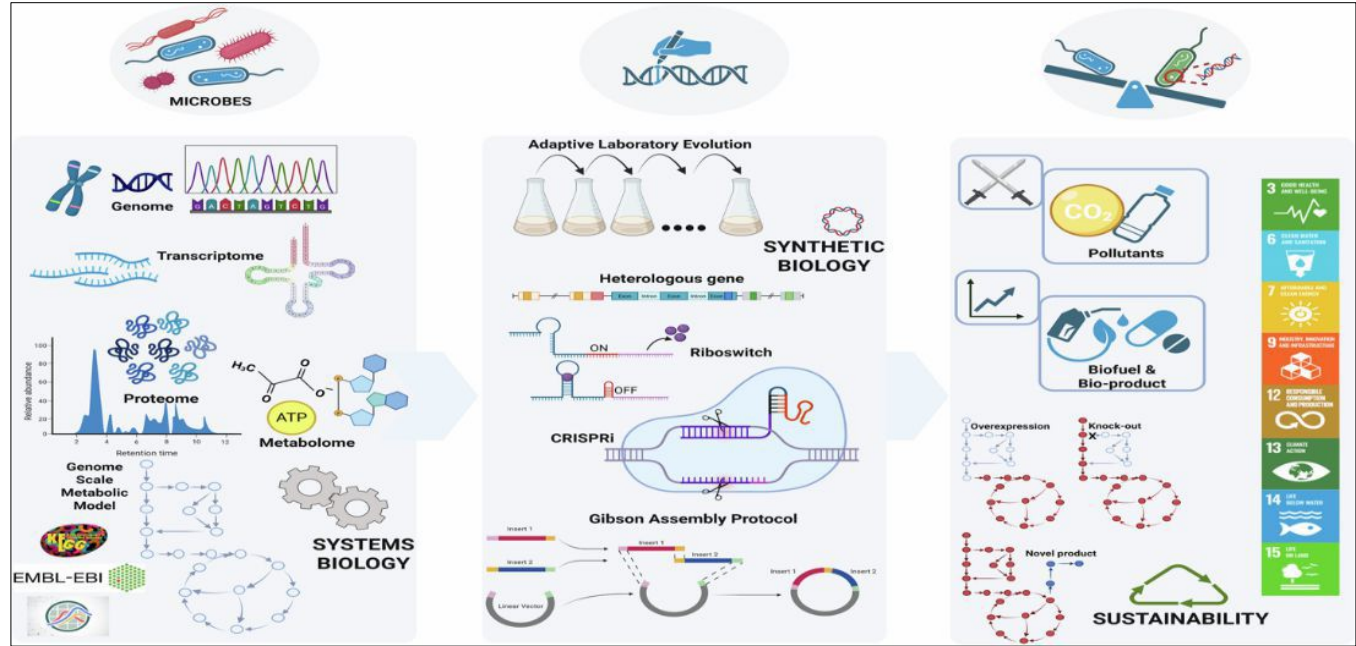


Fig 2: Microbiome engineering via data-driven inoculation

This vertical farm is powered by solar, uses rainwater collection, precision agriculture, and microbial inoculants to grow crops (Molina *et al.*, 2025) [40]. The Parcelas 5.0 system has an array of IoT sensors that measure various environmental parameters. It also includes automated irrigation systems that can react to changes in soil moisture on a real time basis. Production takes place vertically within the parcels, allowing farmers to produce more per unit area where land is limited. Results from this study indicate that there are several improvements over previous practices: crop yield was significantly greater than those produced using the prior methods of growing crops, the amount of water used for irrigation was dramatically more efficient (28% less water was used during a recent trial) and costs were decreased through the use of lower amounts of fertilizers due to the targeted inoculation of microbes. There are significant barriers to implementing systems like Parcelas 5.0 at larger scales. The initial cost of infrastructure will be beyond the financial capacity of many small-scale farmers. Additionally, operating the technical aspects of the Parcelas 5.0 system requires a level of literacy and mathematical ability that may not be possessed by all potential target populations (Rehman *et al.*, 2022) [55]. Finally, supply chains for high-quality inoculants and sensors have been limited in many geographic areas.

5.1 Soil-microbe-plant dynamics in horticulture

More recent studies have emphasized a lot about how soil microbiota directly influences plant phenotype (Habteweld *et al.*, 2024) [21]. Plants with the same genetics are affected by the presence of microbes which significantly impact their phenotype. In turn, when the same microbes colonize different plant genotypes they develop significantly different microbial community compositions based upon selective

pressure from the host plant. The plant-microbial co-evolution is multi-faceted and occurs through many routes. Plants use root exudate to selectively favor microbial populations that can benefit the plant (providing carbon and energy in an amount that favors those organisms that will improve plant performance). As well as providing nutrients and carbon to the microorganisms, the metabolic byproducts of the microorganisms also affect the root structure and capacity of the root to absorb nutrients and make the plant susceptible or resistant to disease (Smith, 2002) [64]. This creates a system level property that cannot be reduced to an understanding of its components. Horticulture now increasingly recognizes this dynamic. Succession cropping (cropping different plant species one after another) intentionally changes the composition of the microbial communities in the soil and reduces the likelihood of pathogens developing and establishing themselves in the soil (Abbas *et al.*, 2024) [1]. Mulching and cover cropping increase the amounts of organic matter in the soil which in-turn increases the number of beneficial fungi (Manea *et al.*, 2023) [34]. Also, using reduced tillage to grow crops preserves the hyphal network necessary for effective mycorrhizal functioning and soil structure stability. However, it has been shown that when horticulturists implement management practices that increase the health of the soil microbial community; there are usually trade-offs in terms of short term productivity. For example, if a farmer decides to reduce the amount of fertilizers used on his/her farm, he/she may need to rely more heavily on the ability of microbes to mobilize nutrients, which could temporarily stunt crop growth. Suppression of pathogens by increasing the diversity of microbes does so probabilistically and not with absolute certainty (Ratnadass *et al.*, 2011) [53].

Table 4: Case study comparisons: technology integration in horticultural systems

System Type	Location	Key technologies	Productivity gain	Water reduction
Economic Return	Precision greenhouse (Molina et al., 2025) [40]	Mexico	IoT + vertical farming + microbial inoculants	30-45% (Molina et al., 2025) [40]
28-35% (Bindhu & T, 2025)	Positive ROI 2 years (Goda et al., 2025) [18]	Smart irrigation (Monchusi et al., 2024) [41]	South Africa	ML scheduling + PGPR inoculants

25% (Monchusi et al., 2024) ^[41]	35% (Dakshinamurthy & Mohan, 2025) ^[13]	40% cost reduction (Monchusi et al., 2024) ^[41]	Aquaponic system (Goda et al., 2025) ^[18]	Egypt
Integrated IMTA + AI monitoring	20-30% (Goda et al., 2025) ^[18]	50% water reuse (Goda et al., 2025) ^[18]	Higher profitability vs conventional (Goda et al., 2025) ^[18]	Digital twin optimization (Postolache et al., 2025) ^[51]
Multiple sites	AI-driven resource allocation	15-20% potential (Costa et al., 2024) ^[12]	20-30% potential (Postolache et al., 2025) ^[51]	Under evaluation

Therefore, for farmers to adopt these types of management strategies, they would need to feel confident that the biological processes involved in them are understandable and predictable even though they are not yet fully understood and do include uncertainties.

5.2 Climate resilience and environmental interactions

Horticulture is significantly impacted by climate change which fundamentally impacts the dynamic of ecosystems of horticulture. In some climates, warmer temperatures will continue to grow crops for longer periods of time; however, in hotter climates, warmer temperatures can cause excessive heat stress. The changing rainfall patterns create unstable droughts with periodic heavy rainfall, and this creates a new habitat for many pests that were once unable to live in those locations. The effects of these changes have a cascading effect on soil/plants, but biotechnology and smart systems can work together better than they can individually to respond to these effects. Biotechnologists are developing plants for traits that are beneficial for climate resiliency such as drought tolerant, resistant to heat, and able to survive waterlogged conditions (Ngongolo & Mmbando, 2024) ^[44]. However, the expression of the traits in a plant vary greatly due to the differences in the soil characteristics, the type and abundance of microorganisms, and the nutrients available in the soil. For example, a tomato variety that has been developed for drought tolerance will be unsuccessful if it does not also develop sufficient mycorrhizae that will provide an efficient means to obtain water (Begum *et al.*, 2019) ^[5]. Smart systems allow for adaptive responses to changes in climate. IoT based irrigation systems do not use pre-determined schedules for irrigation, instead, they adjust their irrigation application based on the current status of the soil moisture and forecasted weather data to minimize waste of water during unanticipated dry spells, while maximizing applications of water during times of drought stress (Manikandababu *et al.*, 2024) ^[36]. Climate control systems in greenhouses automatically adjust the temperature and humidity in response to disease risk models to prevent pathogens from developing into infections (Srinivasan *et al.*, 2024) ^[66].

6 Challenges and barriers to integration

Despite compelling benefits, widespread integration faces substantive obstacles spanning technical, economic, social, and regulatory domains.

6.1 Infrastructure and cost limitations

The smart systems are expensive to develop in terms of initial capital outlays. The cost includes sensors, the communication infrastructure needed for data transmission between devices and into the "cloud", the costs associated with the use of cloud computing services to provide the processing power needed for big data analytics and to support remote access to the software platforms developed to support the other components of a smart system. Because most of the world's horticultural producers are smallholders

who do not have large amounts of capital to invest, these costs typically are prohibitive. In addition, many rural areas in which smallholders tend to live, lack reliable electricity service or reliable connectivity required to deploy an Internet of Things (IoT) network. Thus, although there is likely the greatest opportunity to increase the productivity of smallholder farming operations located in rural areas of developing countries, they are faced with the highest barriers to entry relative to other types of agriculture.

6.2 Knowledge and capacity constraints

The ability to implement biotechnology and smart system technologies effectively requires a high level of sophistication in order to use these technologies properly. For example; farmers need to be able to interpret sensor data, have an understanding of microbial ecology, assess the output from disease risk models, and make highly complex decisions regarding their management practices. Unfortunately extension services that can provide this type of education are limited, especially outside of wealthy countries (Rehman *et al.*, 2022) ^[55]. The educational challenges facing farmers add to the economic challenges they face and create a cycle of poverty and lack of access to information, where the farmer's ability to gain access to information is directly correlated to the size of his/her operation and the resources available to them.

6.3 Regulatory uncertainty

The various national and international regulatory systems create inconsistencies and un-certainties, especially for genome edited crops. For example some nations will completely ban all genetic modification while other nations may allow it with certain constraints on how it is used. Most jurisdictions have different approval processes for biotech derived crop varieties compared to conventional crop improvements (Tvora *et al.*, 2022) ^[69], which creates trade barriers and disincentives for investment.

7 Data governance and ownership issues

The increased reliance of agriculture on advanced technologies raises questions concerning who owns the collected data as well as the use and privacy implications (Gupta *et al.*, 2020) ^[20]. The larger tech companies gathering data from farms could be using this data to gain a competitive advantage over farmers. In addition, while the issue of algorithmic bias is emerging in the context of systems that are systematically biased against certain geographic areas or producer types, there has been limited research in this area; however, these concerns need to be addressed for building trust among farmers and fair distribution of benefits.

7.1 Emerging technologies and future directions

Several frontier technologies promise to further advance sustainable horticulture by more tightly integrating biotechnology and smart systems.

7.1.1 Artificial intelligence and autonomous systems

The use of AI to drive autonomous robots for farming will allow for such activities as field monitoring, targeted spraying of pests, selective harvesting, and precision application of nutrients without a farmer's involvement (Costa *et al.*, 2024) ^[12]. The computer vision that is used by these robots can quickly and accurately identify diseases on crops and insect infestations which would allow farmers to respond rapidly to potential problems before they become major issues. These same computer vision systems can also be trained using reinforcement learning to continually improve their decision making process based on what happens in the field (Dakshinamurthy & Mohan, 2025) ^[13]. However, autonomous farming systems have been hindered from being deployed widely because of regulatory uncertainty and legal liabilities. A primary concern has been who is liable if an autonomous robot makes an error in its decision-making processes leading to damage to crops or other property. In addition, there are environmental concerns that relate to potential unintended consequences from the actions of an autonomous farm agent in the complex environment of nature.

7.2 Synthetic biology and microbiome engineering

New research is applying concepts from synthetic biology to horticultural microbiome systems. The new research engineers bacteria and fungi that have higher capacities for suppressing diseases; more efficient in fixing nitrogen; or produce secondary metabolites with a novel application to improve nutritional status of plants or as pesticides (Kaul *et al.*, 2021) ^[25]. If these are used as inoculants they would be likely to provide more consistent biocontrol and nutrient cycling than wild-type microbial populations. However, there are legitimate biosafety issues related to the potential for the environmental release of the genetically modified organisms (GMOs) that include horizontal gene transfer that could potentially allow GMO traits to be transferred to wild microbe populations with unforeseen results. The public's acceptance of the use of genetically modified organisms also will depend on how well the public accepts biotechnology generally.

7.3 Digital twin technology

The potential for digital twin technologies to assist in optimizing the horticulture industry developing a virtual model of a real-world system that simulates and predicts its behavior is demonstrated by Postolache *et al.* (2025) ^[51]. A comprehensive model integrating all relevant biological processes (plant physiology), environmental processes (soil dynamics, microbe ecology), and climatic factors will allow for testing of different management strategies prior to actual field application, thus minimizing experimentation risk and cost. The use of continuous real-time sensor input from the environment allows the accuracy of the digital twin predictions to increase over time.

8. Recommendations and pathways forward

Realizing sustainable horticulture's potential through integrated biotechnology and smart systems requires coordinated action across multiple domains.

8.1 Research and development priorities

Ongoing studies in the area of interaction between plant-microbe-soil-climate will continue to be important for

understanding how different types of microbial communities interact with crop improvement technologies as well as how genetically modified crops affect functioning of a soil ecosystem (Narra *et al.*, 2025) ^[43]. Laboratory studies are needed to accompany field based studies to verify results in complex real world systems (Gonzalez Guzmán *et al.*, 2021) ^[19]. In addition, there is a need to develop affordable and accessible technologies. Affordable sensor options, low cost, open source software, and decentralized processing of data may allow for the use of these by small holder farmers. Solutions that can meet the needs of limited resources should take precedence over developing products based on what will happen in wealthy markets (Narra *et al.*, 2025) ^[43].

8.2 Policy and governance frameworks

Harmonization of regulations, even within a regional context, would help diminish uncertainty that hinders the use of new technologies. The establishment of clear science-based regulatory guidelines to distinguish between different types of genetic modification techniques and their respective risk profiles, along with transparent regulation approval processes, should lead to faster beneficial innovation and maintain necessary protections. It is imperative that countries establish data governance policies, such as giving farmers ownership of their own data, to prevent companies from using algorithms to unfairly discriminate against them. International collaboration is also required to develop these policies. In addition to public investment in research, infrastructure, and the education/training of farmers; private sector innovation alone will not be sufficient to resolve the issues facing areas with little or no immediate profit potential. There is a need for public investment to support the restoration and enhancement of the capacity of public extension services to educate farmers about biotechnology and smart systems, as well as to provide knowledge transfer on both topics (Layek *et al.*, 2023) ^[31].

8.3 Farmer engagement and participatory innovation

The need for successful scaling of new technologies is that they be developed and adapted using the active participation of farmers as a key part of this process. Farmers have valuable knowledge about the local environment; how local crops are sold and bought; and real-world, practical limitations on their ability to manage new technologies. When participatory research approaches are used to develop new innovations together with farmer groups, it increases the likelihood of the adoption of these new technologies by farmers. Additionally, when the suitability of new technologies to the actual realities of the local farming environment are ensured through participatory research approaches (i.e. co-designing innovations), the adoption of new technologies will be increased (Larasati *et al.*, 2024) ^[30]. Farmer-to-farmer demonstration trials, farmer field school and peer learning networks facilitate the transfer of knowledge about new technologies from one group of farmers to another, far better than top-down extension approaches. The use of peer-to-peer methods of technology transfer (e.g., farmers learn from other farmers in their neighborhood or community who have successfully adopted a new technology) results in much greater technology adoption rates compared to the use of technology transfer based upon expert advice provided to farmers from outside their local area (A. Kumar *et al.*, 2024) ^[27].

9. Conclusions

The challenges facing sustainable horticulture are greater than ever before; they necessitate simultaneous innovation across a range of areas. While neither biotech alone nor smart systems alone provide sufficient solutions, integrating them can produce synergies which may address the three key elements of sustainability (productivity, resilience and environmental sustainability). Optimized genome edited crop varieties for specific soil microbial climate conditions, paired with real time IoT data, may offer possible near term opportunities for horticulturists. In the longer term, synthetic biological approaches to designing microbiomes may be used in conjunction with autonomous systems and digital twinning to provide significant gains in productivity at significantly reduced use of resources and environmental impact. However, the technological potential to implement these innovations is limited by the constraints of regulatory uncertainty, capital availability, knowledge gaps, and the need for infrastructure development. These constraints are most pronounced in developing countries where there is the greatest potential for innovative developments to occur. To overcome these challenges, there needs to be coordinated action amongst scientific researchers, policymakers, investors, and stakeholders who work directly with farmers and are able to provide a framework for innovation beyond the capabilities of any single scientist or technology company. Horticultural systems of the year 2050 will include biotechnologies, smart sensors/monitoring systems and refined understandings of the relationships between plants, soil and microbes that have yet to be envisioned. Sustained commitment to the development of new horticultural innovations is required but it is also important to recognize that technology is merely an enabler of sustainable agriculture outcomes - it is not the end goal of sustainable agriculture outcomes. Long-lasting progress toward enhancing global food security, supporting the livelihoods of farmers and ensuring environmental quality for future generations will depend on our ability to develop sustainable horticultural systems with wisdom, through collaborative endeavors, and through an awareness of the continued uncertainty surrounding the development of those systems.

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