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Insect pest and plant disease management in horticultural crop production: recent insights provide opportunities for improved control

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With the world population projected to increase to approximately 8 billion people by 2030, tremendous efforts are needed to produce enough food to feed the population with a decreasing land available for agricultural production. Horticultural crops, characterized by very diverse production systems, continue to play a significant role in food security and safety. However, plant pests and plant diseases continue to negatively impact the production of healthy and safe food in horticultural cropping systems, by affecting produce quality, quantity, and safety. Furthermore, the emergence and re-emergence of pests and pathogens coupled with the rapid development of resistance to available pesticides further exacerbate the challenges of pest and disease control in horticultural systems. Given the recognized need to mitigate climate-change risks, novel pest and disease management strategies are required to achieve net-zero emissions for more sustainable horticultural production. This perspective highlights some recent research insights that could provide opportunities for the improved management of insect pests and plant diseases in horticultural crop production systems.

KEYWORDS
artificial intelligence (AI), endophyte, Internet of Things (IoT), integrated pest management, nanotechnology, smart agriculture

Introduction

Insect pests and diseases in horticultural cropping systems are primarily controlled through an integration of control strategies for a more effective outcome. Most of these strategies rely on monitoring, detection, and decision support systems that evaluate the need to apply pesticides and fungicides based on the anticipated risk of disease or pest outbreak (Gent et al., 2013; Wallhead and Zhu, 2017). These weather-driven decision support systems have placed informed decisions on pesticide and fungicide application in growers' hands. Pests and diseases also cause superficial damage to fruits and vegetables, which is unacceptable to consumers, and there is a tremendous desire for no pesticide residue in and on the produce (Xu, 2022). This need to balance aesthetics, food safety, and improved yields in the presence of pests and diseases necessitates the development and use of new and emerging solutions that will ensure plant health and the production of safe fruits and vegetables. In this perspective, we highlight below some recent research insights that could provide opportunities to improve the control and management of insect pests and plant pathogens in horticultural crop production systems. Where appropriate, we highlight how these insights provide a path toward achieving net-zero emission in an effort to mitigate risks associated with climate change for a more sustainable horticulture production system.

Nanomaterials and nanotechnology

Management and control of insect pests and plant pathogens is of primary importance in several fruit and vegetable production systems. Pesticides and fungicides are perhaps one of the most common options used to control pests and pathogens in the field and greenhouse settings in commercial horticulture crop production. While pesticide application is effective, there are concerns about its ecological impact on the environment and beneficial microorganisms. Furthermore, pests and pathogens are continually developing resistance, rendering pesticides less effective following their introduction to the market. The production of insecticides and fungicides is energy-intensive, and greenhouse gases are emitted during the process (Rose and Gabrielli, 2023). Pesticide resistance and climate change impacts are expected to lead to increased needs in pesticide use (Deutsch et al., 2018), creating a vicious cycle between chemical dependency and intensifying global warming (Choudhury and Saha, 2020). Thus, approaches that improve farming efficiency by accurately delivering pesticides to improve pest and disease control while mitigating emissions from pesticide use are receiving increasing attention.

The application of nanotechnology and nanomaterials in horticulture is now providing an opportunity to improve the efficacy, accuracy, and targeting of insecticides and fungicides (An et al., 2022; Atanda et al., 2025). Nanopesticides utilize nanomaterials engineered within 1–200 nm in size to serve as carriers for pesticide active ingredients. Wang et al. (2022) synthesized literature and identified two major types of nanopesticides. Type 1 nanopesticides are metal-based (e.g., Ag, Cu, and Ti) products that have a strong antimicrobial activity rendered by adhesion, dissolution, cytotoxicity, and oxidative stress. Type 2 nanopesticides include materials in which the active ingredient is encapsulated by nanocarriers such as polymers and clays and zein nanoparticles (Wang et al., 2022). Thus, nanosized particles, with their unique shape and properties, are being explored in nanocarrier-based pesticide formulations. These innovative formulations utilize a variety of materials, such as silica, lipids, polymers, copolymers, ceramics, metals, and carbon (Agostini et al., 2012). They can be transported in dissolved and colloidal states, a mechanism that accords them different behavior than those for conventional solutes of the same particles (Kumpiene et al., 2008). The delivery of pesticides via nanomaterials also reduces runoff and alleviates concerns about negative ecological impacts on the environment and beneficial microorganisms (Li et al., 2021). Furthermore, pesticide delivery via nanomaterials improves the bioavailability of active ingredients and, thus, reduces the opportunities of sublethal doses that can encourage the development of insecticide and fungicide resistance. These nanopesticides have been found to control plant pathogens such as *Ralstonia solanacearum* that causes bacterial wilt in tomato (Liang et al., 2022) and *Macrophomina phaseolina* that affects beans (Kumar et al., 2016). Nanopesticides have also been used to improve the efficacy of microbial pesticides against the larvae of the potato leafworm moth *Spodoptera litura* (Hersanti et al., 2020) and several sucking insects (Usman et al., 2020). Researchers are now paying special attention to the field of nanopesticides and nanocarriers based on smart pesticide delivery systems (Jiang et al., 2024; Singh et al., 2021) (Figure 1).

Attract-and-kill through pheromones is one of the most potent approaches to insect pest control that requires the continuous release of pheromone active substances during the pest capture period (Gregg et al., 2018). Nanomaterial-loaded pheromones with environment-friendly properties have shown excellent properties in field conditions compared to traditional pheromone traps for agricultural pests (An et al., 2022). Production costs, evaluation standards, and registration policy are some of the factors that influence the production of nanomaterials for insect pest and plant disease control. Promoting awareness and enactment of policies that facilitate testing and registration of nanopesticides could promote the use of this technology for the effective control of insect pests and diseases. Robots are also being developed to reduce pesticide use and improve farming efficiency by accurately delivering pesticides, thereby reducing emissions associated with pesticide use (Jacquet et al., 2022). Autonomous robots can perform temporal and spatial high-resolution monitoring to detect disease or pest outbreak early and deliver pesticides to treat only the affected areas before pests and diseases become widespread. Early detection and intervention provides growers time to select their control options and, when effective, limit insect pest and plant disease pressure from reaching undesirable thresholds. While promising in improving the efficacy, accuracy, and targeting of pesticides, there are concerns on how nanopesticides may affect the environment and public health (Atanda et al., 2025; Zainab et al., 2024; Usman et al., 2020). Future research should focus on understanding nanopesticide toxicity, developing robust risk assessment frameworks, and promoting sustainable agricultural practices. Furthermore, high production costs make the use of nanopesticides in agriculture a low-margin industry (Younis et al., 2021) and, thus, a major constraint to their large-scale application.

Precision tools, smart farming, and Internet-of-Things

Automation of expert tasks in entomology and plant pathology is gaining interest in insect pest and disease monitoring, pest and

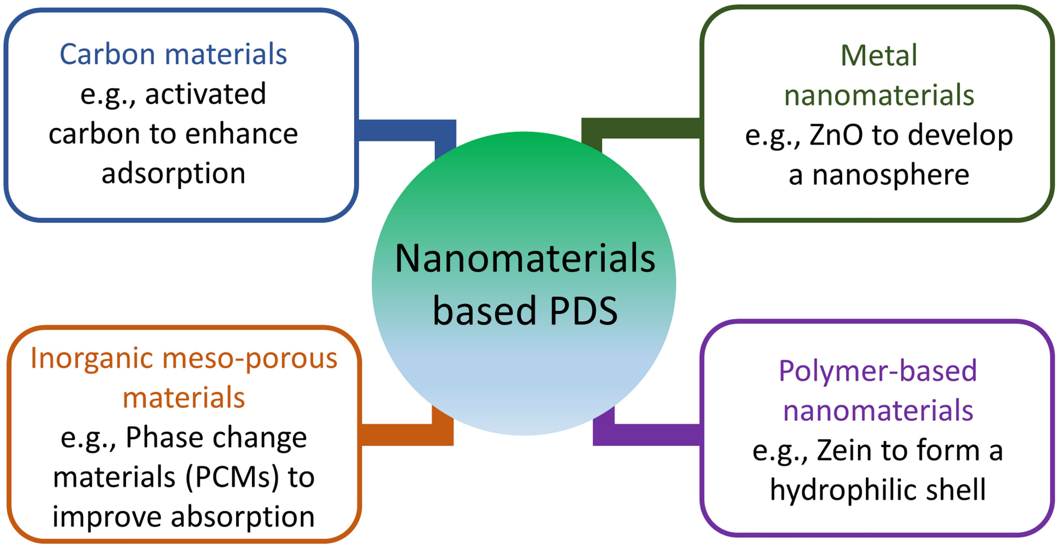

FIGURE 1
A schematic representation of nanomaterial (e.g., zinc oxide, ZnO)-based pesticide delivery systems (PDS) for multifunctional delivery and application of pesticides for a more effective and precise control of insect pests and plant pathogens.

disease detection, and plant disease measurement. Advances in artificial intelligence (AI) and machine learning (ML) coupled with the connectivity of network products based on the Internet of Things (IoT) are fueling the application of precision tools in horticultural crop production (Ali et al., 2023; Vidya Madhuri et al., 2025). The use of decision support systems has been instrumental to allow growers make decisions such as when to apply pesticides and in what areas within their fields where early onset of disease or insect infestation has been detected. Decision support systems utilizing AI/ML technologies have been developed to control anthracnose (*Colletotrichum acutatum*) and *Botrytis* (*Botrytis cinerea*) fruit rots in strawberry (Hu et al., 2021) and codling moth (*Cydia pomonella*) and pear leaf blister moth (*Leucoptera maifoliella*) in apple (Čirjak et al., 2022). The increasing interest of ML is primarily due to the difficulties associated with pest and disease diagnosis, challenges associated with early disease detection, and the need to improve the accuracy of disease assessments using robotics and autonomous systems. Hyperspectral measurements coupled with drone technology have been used for the early detection of early (*Alternaria solani*) and late blight (*Phytophthora infestans*) in potato (Gold et al., 2020). Electronic nose (E-nose) systems combined with fluorescence imaging are also being used to predict the severity of gray mold (*B. cinerea*) and early blight (*A. solani*) in tomato (Sun and Zheng, 2024). Many diseases of horticultural crops exhibit common symptoms and signs produced by the leaves, stems, or roots that are caused by different pathogens. Furthermore, disease images often do not possess sufficient details to assist in the diagnosis and can potentially lead to an incorrect diagnosis. There is thus a need to incorporate ML in disease detection and measurement with traditional integrated disease management for effective diagnosis and timely pest and disease control. With the increasing number of ML approaches, there is a need to establish which techniques are appropriate to specific systems and how they perform when compared to traditional approaches to justify the additional investment needed to use these technologies (Omaye et al., 2024). System-specific ML approaches are critical, given the diverse nature of commercial horticultural production systems. In this regard, AI can integrate critical spatiotemporal data into models describing the effects of weather and/or climate on emerging pest and disease risk, generate maps of geographic priorities for surveillance and mitigation strategies, and translate these analyses into practical decision support systems for farmers and crop consultants (Garrett et al., 2022).

With the help of modern digital and Internet-assisted tools and smart applications, the IoT is now assisting farmers' decision-making by readily availing information related to insect pest and disease monitoring, thereby enabling farmers to adopt precautionary measures and customize their pest management approaches (Kanuru et al., 2021). As such, IoT and smart farming techniques can help simulate and predict yield production under forecasted climatic conditions and, thus, assist farmers in decision-making for various crop management practices such as insecticide and fungicide applications. A typical IoT, for example, disease control in strawberry production, would consist of the following: i) measurement device (powered sensor for disease detection), ii) data transmission, iii) data storage and analytics (algorithms for disease threshold), iv) feedback and implementation, and v) project structure and support. The device layer consists of a sensor to measure the parameter of interest (e.g., anthracnose fruit) and the electronics necessary to support its functions. Devices would be arranged in a topology and connected to a gateway using a communication protocol in the data transmission layer. A broad coverage of cellular networks would allow for frequent and, in some cases, near real-time, data transmission. Individual or aggregated measurements are then received by a server where they can be queried, cleaned, and analyzed. Relevant insights are fed back to an end user or other IoT devices to inform decisions and prompt actions (e.g., fungicide application). While smart farming and IoT have the potential to transform the horticultural sector, with it comes a series of various challenges to crop advisors and farmers (Idoje et al., 2021). Data security is one of the major problems associated with IoT (Jia et al., 2020). The IoT devices accumulate huge data from an agricultural IoT system, which can be viewed or accessed by an unauthorized personnel due to the lack of the necessary security protocols by some of the IoT providers (Neshenko et al., 2019). Hence, collected data may be prone to manipulation or present other ownership-related problems. Furthermore, various countries pose a series of regulations and paperwork for the farmers who are willing to adopt new technologies (Ali et al., 2023). While this serves to ensure compliance, it may also deter potential adopters of these new technologies. Development and enactment of policies that promote data security, addressing regulations that hinder the adoption of technology, and promoting grower education will be vital to fully exploit the potential of precision tools, smart farming, and IoT in horticultural crop production.

Microbiome and soil health in insect pest and disease management

The plant microbiome consists primarily of the rhizosphere, phyllosphere, and endophytic microbial communities. Beneficial microbes, a key group in the plant microbiome, can suppress plant diseases by initiating the plant immune system, inducing the synthesis of antibiotic compounds, and competing with pathogens for nutrient resources (Wang et al., 2023). Endophytic microbes are ubiquitous, and their potential in pest and disease management in horticulture crop production is increasingly being recognized (Lastochkina et al., 2022). Microbial endophytes can activate defense mechanisms against a variety of postharvest diseases in fruits and vegetables including tomato, pepper, apple, and cucurbits (Lastochkina et al., 2019; Tran et al., 2019). For example, endophytes have been demonstrated to prevent the growth of postharvest gray mold caused by *B. cinerea* on grape berries (Nifakos et al., 2021). It has also been shown that *Bacillus subtilis* reduces potato late blight (caused by *P. infestans*) severity and associated symptoms in stored potato tubers (Lastochkina et al., 2022). Some endophytes have been reported to control insects in potato, and these operate through the production of alkaloid and neurotoxins that result in insect behavioral disorders and mortality (Song et al., 2020; Tooker and Giron, 2020).

Microbial endophytes have the potential to replace some synthetic pesticides in horticulture, but exploiting these microbes to increase crop resilience against insect pests and diseases is a challenge. Identifying the most effective strain or combination of strains is still the main bottleneck with the use of microbial endophytes. More than 80% of endophytes are not detected when cultured on conventional nutrient media (Lastochkina et al., 2022), which creates difficulties in obtaining a pure culture, identifying and using many potentially effective strains. Furthermore, many artificially unculturable microbial resources within plant tissues may play an equally important role in increasing crop resilience against pests and diseases. Recent studies on alternative agar substitutes provide promising options for culturing unculturable microorganisms (Demin et al., 2024). The efficacy of endophytes also depends on their compatibility and interaction with their plant hosts since endophytes isolated from one plant species may not interact with plants from another species. Thus, research on the intricate relationships between plants, insect pests, pathogens, and microbial communities is required to better harness the potential of beneficial microorganisms for pest and disease control. The most relevant studies on plant-associated microbes for biocontrol have focused on rhizosphere microbial communities (Wang et al., 2023), and a systematic understanding of the structure and function of endophytic microbial communities under pathogen invasion is not well known and needs to be established.

IPM adoption and implementation at different spatial scales

Insect pests and pathogens significantly reduce crop productivity and thus pose a challenge to achieving global food security. The tenet of integrated pest management (IPM) is the use of various pest and disease control strategies (e.g., cultural, biological, genetic, physical, legislative, and mechanical constraints) into one program to keep pest levels below a certain economic threshold (Prokopy and Kogan, 2009; Oguh et al., 2019). This approach has the intention of reducing pesticide use and managing pesticide resistance using strategies that are practical and affordable and minimize damage to the environment (Dara, 2019; Oguh et al., 2019). Studies have shown that IPM-managed pests rarely reach economic threshold, resulting in 95% lower insecticide use (Pecenka et al., 2021). However, significant challenges remain toward improving IPM adoption (Magarey et al., 2019) to exploit its full potential. Efforts to increase IPM adoption have been hindered by poor coordination and prioritization of IPM strategies, lack of a clear methodology to measure the environmental and economic benefits of IPM (Greitens and Day, 2007), and lack of communication with the general public (Magarey et al., 2019). A study conducted in the UK reported positive correlations between IPM adoption and farmed area and familiarity with IPM (Creissen et al., 2021). As such, policies that promote awareness of IPM approaches and encourage farmers to greater levels of engagement with pest issues should be expected to promote IPM adoption (Lane et al., 2023; Creissen et al., 2021).

The IoT is improving farmers' decision-making by readily providing information related to pest and disease monitoring, and this represents a significant advancement in IPM. A novel approach that integrates automatic pest management is being developed by combining the rational behavior of intelligent agents and IoT technologies (Ahmed et al., 2024). This approach allows real-time information acquisition through electronic traps connected to a wireless sensor network, enabling efficient spatiotemporal monitoring of pests and diseases, for the identification and location of infestation hotspots in the field. The precise and focused detection capacity of such systems reduces the need to apply pesticides throughout an area, thus optimizing the use of resources and minimizing the environmental impact of pesticide use. Lewis et al. (1997) proposed a "total system approach" as an alternative to the "silver bullet" solutions for pest control to counteract the increasing environmental consequences of pest control in agriculture. However, a compartmentalized approach is still prevailing, where IPM projects focus on one or two critical control strategies rather than its entirety (Falkenberg et al., 2022). Regenerative agriculture based on sustainable intensification (Giller et al., 2021) is now providing an avenue to integrate the various compartmentalized approaches to IPM into a more holistic One Health framework (Falkenberg et al., 2022).

Conclusion

Horticulture crop production is now at a technological crossroads, fighting climate change while simultaneously feeding the world. Advancements in horticulture production systems are important to maximize crop protection, productivity, and food quality and safety especially under changing environmental conditions. In this perspective, some selected emerging, affordable, fast, eco-friendly, and effective approaches that can contribute to the successful management of pests and diseases in horticultural crop production were highlighted. The exogenous use of beneficial strains of endophytic microbes and nanoparticles, in particular, has a huge potential to replace some agrochemicals, and they are used in plant protection formulations to increase plant resilience, crop productivity, and quality. Robotics and autonomous systems are now emerging as next horizon technologies with considerable potential to transform diverse horticultural activities including minimizing on-farm greenhouse emissions and food and farm waste and improving the efficiency of decision support systems. While promising, certain challenges still exist and need to be addressed to fully harness the potential of these emerging technologies in pest and disease control. Global coordination of multidisciplinary researchers, investors, consumers, farmers, and policy regulators will be vital for driving a paradigm shift in net-zero agriculture and to increase IPM adoption. The use of IoT in conjunction with the current pest management techniques opens new opportunities for IPM to achieve a new milestone in horticultural crop production.

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