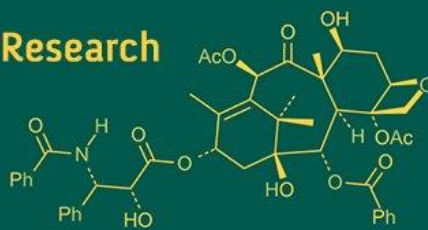


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Digital transformation of integrated pest management in horticultural crops: Integrating artificial intelligence, robotics, digital twins, genomics, remote sensing and big data analytics

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Abstract

Integrated Pest Management (IPM) in horticultural crops is undergoing a profound transformation through the integration of digital technologies. Traditional IPM practices, manual scouting, pheromone traps and biological control are increasingly complemented by innovations such as Artificial Intelligence (AI), robotics, digital twins, genomics, remote sensing and big data analytics. AI-driven diagnostic tools and predictive models enable early detection of pests and diseases, reducing chemical inputs while safeguarding yields. Robotics enhances precision spraying, mechanical weeding and automated monitoring, while robotic pollination offers solutions to declining natural pollinator populations. Digital twins provide virtual replicas of crop systems, allowing farmers to simulate pest-crop interactions and optimize interventions before field application. Genomics contributes molecular insights into pest resistance and virus transmission, with RNA interference (RNAi) and CRISPR-Cas9 technologies paving the way for next-generation biopesticides and resistant cultivars. Remote sensing technologies, including UAV-based hyperspectral and multispectral imaging, deliver non-invasive, real-time monitoring of crop health and pest dynamics. Big data analytics acts as the backbone, integrating diverse datasets from sensors, genomic studies, weather stations and markets to support evidence-based decision making and precision interventions. Together, these technologies shift IPM from reactive to predictive, from chemical-intensive to data-driven and from localized to scalable systems. While challenges remain in cost, accessibility, interoperability and farmer training, the trajectory points toward holistic, sustainable and resilient pest management frameworks. This digital transformation ensures that horticultural crops such as chilli, tomato, banana and citrus can withstand evolving pest pressures and climate variability, aligning productivity with ecological balance.

Keywords: IPM, genomics, remote sensing, robotics and artificial intelligence

1. Introduction

Integrated Pest Management (IPM) emerged in the mid-20th century as a response to ecological crises caused by indiscriminate pesticide use. It integrates biological, cultural, mechanical and chemical strategies to minimize pest damage while safeguarding environmental and human health. Horticultural crops such as chilli, tomato, banana, citrus and mango are particularly vulnerable due to their intensive cultivation and high market value. India, for instance, is a global leader in horticultural production, with chilli and tomato being major export commodities. Yet yield losses due to pests can range from 20-80%. Traditional IPM practices, manual scouting, pheromone traps and biological control agents—have been effective but limited by scale, accuracy and timeliness. The digital transformation of IPM represents a paradigm shift. Emerging technologies such as Artificial Intelligence, robotics, digital twins, genomics, remote sensing and big data analytics are being integrated into pest management systems, enabling precision, scalability and sustainability. AI-driven image recognition tools diagnose crop diseases from farmer-uploaded images within seconds, UAV-based hyperspectral imaging detects thrips damage before visible symptoms appear (Garcia-Ruiz *et al.*, 2013), robotics automates pesticide spraying and mechanical weeding (Blue River Technology, 2019), digital twins simulate crop-pest interactions under varying climatic conditions (Rosen *et al.*, 2015), genomics guides breeding programs and RNAi-based bio pesticides (Xie *et al.*, 2018) and big data analytics

integrates weather, soil and pest data to provide evidence-based decision support systems (Singh *et al.*, 2021) ^[7].

Global challenges underscore the urgency of digital IPM. Climate change alters pest distribution and intensity (Deutsch *et al.*, 2018), pesticide resistance spreads rapidly among key pests (Horowitz *et al.*, 2020) ^[2] and consumer demand for residue-free produce rises. Digital IPM offers solutions by enhancing monitoring, reducing pesticide reliance and supporting integrated approaches aligned with sustainability goals.

2. Artificial Intelligence in IPM

Artificial Intelligence (AI) in horticultural Integrated Pest Management (IPM) represents a convergence of advanced computational techniques with practical crop protection strategies. By encompassing machine learning, deep learning, computer vision and natural language processing, AI provides tools that can learn from vast datasets, recognize complex patterns and deliver actionable insights for farmers. In horticulture, where crops such as tomato, chilli and other vegetables are highly susceptible to pests and viral diseases, AI has become particularly valuable. Mobile applications like Plantix demonstrate this potential by employing deep learning to diagnose over 400 crop diseases from farmer-uploaded images, offering immediate recommendations that empower farmers to act quickly. Similarly, Pest Net uses AI-driven image recognition to identify insect pests, supporting extension services in Asia and Africa. These innovations are crucial in crops like chilli and tomato, where viral diseases spread rapidly through vectors such as thrips and whiteflies and early detection through AI enables timely interventions that reduce yield losses.

AI also plays a pivotal role in predictive modeling, integrating climatic, soil and crop data to forecast pest outbreaks. Predictive analytics has shown remarkable results, reducing pesticide use by 25% in tomato crops while maintaining yields. This proactive approach allows farmers to anticipate pest pressures and apply control measures only when necessary, aligning with IPM principles of minimizing chemical inputs while safeguarding productivity. Decision support systems further extend AI's utility. Platforms like IBM Watson Agriculture analyze millions of data points to recommend pest management strategies tailored to specific regions. By combining real-time sensor data, satellite imagery and farmer inputs, these systems guide farmers on when to spray, what to spray and how much to spray, thereby reducing unnecessary pesticide applications, lowering costs and minimizing environmental impact (Singh *et al.*, 2021) ^[7].

The benefits of AI in horticultural IPM are multifaceted. Early detection prevents widespread crop damage, while reduced pesticide use lowers both costs and environmental contamination. Farmers gain cost efficiency by avoiding unnecessary sprays and environmental sustainability is enhanced through reduced chemical residues in soil and water. Importantly, mobile apps democratize access to expert-level diagnosis, making AI tools accessible even to smallholders in remote areas.

Despite these advantages, challenges remain. AI models depend heavily on data quality and poor images or incomplete datasets can reduce accuracy. Algorithm transparency is another issue, as farmers may not fully trust

systems they cannot understand. Accessibility for smallholders is limited by digital literacy and smartphone availability, while the cost of advanced AI systems and IoT sensors can be prohibitive.

Future directions in AI for horticultural IPM involve open-source platforms that encourage collaborative development, IoT integration for real-time monitoring and policy support to subsidize adoption and promote digital literacy. Scalable solutions that run on basic smartphones without requiring high-speed internet will further enhance accessibility. By integrating AI into IPM, horticulture can achieve a balance between productivity and environmental stewardship, ensuring resilient crop protection in the face of evolving pest pressures and climate change.

In essence, AI is not just a technological innovation but a practical ally in horticultural IPM, blending theory with application. It transforms pest management from reactive to predictive, from chemical-intensive to data-driven and from expert-dependent to farmer-empowered. This integration of AI into horticultural systems represents a paradigm shift toward sustainable, efficient and intelligent agriculture.

3. Robotics in IPM

Robotics in horticultural Integrated Pest Management (IPM) refers to the use of automated machines capable of performing agricultural tasks with minimal human intervention and it is increasingly reshaping how pest and disease management is carried out. In IPM, robotics plays a crucial role in precision spraying, mechanical weeding, automated monitoring and even pollination. These technologies enhance precision, reduce labor dependency and support sustainable crop protection strategies. For instance, the "See & Spray" robot developed by Blue River Technology uses AI-driven cameras to distinguish weeds from crops, reducing chemical use by up to 90%. Similarly, EcoRobotix has created solar-powered robots that autonomously navigate fields, identifying and removing weeds with mechanical arms (Zhang *et al.*, 2022) ^[10]. UAV-based robotic systems are also being deployed to monitor thrips populations in chilli crops, providing real-time data for pest forecasting (Patil *et al.*, 2020) ^[4].

Pollination is another critical area where robotics is making an impact. Over 75% of major food crops depend on animal-mediated pollination (Klein *et al.*, 2007), but declines in pollinator populations have created significant challenges for horticulture. Projects like Harvard's RoboBee explore miniature robotic insects capable of pollinating crops (Ma *et al.*, 2013), offering potential solutions to pollinator shortages. By integrating robotics into pollination, horticulture can safeguard yields and reduce reliance on declining natural pollinator populations.

The advantages of robotics in IPM are clear: precision spraying reduces pesticide waste, mechanical weeding minimizes herbicide use, automated monitoring provides continuous pest surveillance and robotic pollination addresses ecological challenges. These innovations contribute to sustainable horticulture by lowering chemical inputs, reducing environmental impact and improving efficiency. However, challenges remain, including cost, infrastructure, technical training and the need for policy support to scale adoption.

Future directions involve developing affordable robotic systems, integrating robotics with AI and IoT sensors for real-time decision-making and designing energy-efficient

machines that can operate sustainably in diverse horticultural environments (Singh *et al.*, 2021; Yamanaka *et al.*, 2026) [7, 9]. As robotics continues to evolve, its role in IPM will expand from task automation to intelligent, adaptive systems that not only reduce labor dependency but also enhance resilience against pest and disease pressures. By blending robotics with AI-driven analytics, horticulture is moving toward a future where pest management is precise, sustainable and less reliant on chemical interventions, ensuring both productivity and ecological balance.

4. Digital Twins in IPM

A digital twin in horticultural IPM is essentially a virtual replica of a crop system that continuously receives data from sensors, models and external inputs to simulate real-time processes. This allows farmers and researchers to understand and predict pest population dynamics, crop-pest interactions and climate impacts with high precision. For example, a digital twin of a chilli crop in Andhra Pradesh can integrate data on thrips populations, humidity and virus prevalence to predict outbreaks of Groundnut Bud Necrosis Virus (GBNV). Farmers can then test interventions virtually before applying them in the field, reducing risks and costs.

Greenhouse horticulture is particularly suited to digital twin applications because of its controlled environment. In European greenhouses, digital twins have been used to simulate whitefly infestations in tomato crops, enabling growers to optimize biological control strategies (Jones *et al.*, 2020) [3]. These systems go beyond simple monitoring by integrating genomic data, remote sensing and big data analytics, creating holistic IPM frameworks that enhance precision and scalability (Patil *et al.*, 2022) [5].

The benefits are clear: digital twins allow for virtual experimentation, where farmers can test pest management strategies without risking actual crop losses. They also improve forecasting accuracy, reduce pesticide dependency and support sustainable practices. However, challenges remain in terms of data integration, cost, accessibility, technical expertise and the need for policy support.

5. Genomics in IPM

Genomics in horticultural Integrated Pest Management (IPM) provides powerful insights into pest biology, host-pathogen interactions and crop resistance mechanisms, enabling precision strategies that go beyond conventional approaches. By identifying genetic markers for pest resistance, understanding vector biology and developing molecular diagnostics, genomics allows researchers and farmers to design highly targeted interventions. Advanced tools such as RNA interference (RNAi) and CRISPR-Cas9 are being explored to create biopesticides and resistant crop varieties, marking a new era of molecular pest management (Patil *et al.*, 2022) [5].

Genome sequencing of *Bemisia tabaci*, a notorious whitefly pest, has revealed genes associated with insecticide resistance. This knowledge helps in designing strategies to overcome resistance and improve chemical efficacy. Similarly, genomic studies of thrips have identified genes linked to virus transmission, supporting diagnostics for Groundnut Bud Necrosis Virus (GBNV) (Zhang *et al.*, 2024) [11]. In chilli crops, molecular markers have been identified for resistance to Chilli Leaf Curl Virus (ChiLCV), enabling breeders to develop resistant varieties (Reddy *et*

al., 2020) [6]. RNAi has been successfully applied to silence genes in *Bemisia tabaci*, reducing virus transmission (Singh *et al.*, 2025), while CRISPR-Cas9 has been used to edit tomato genomes for resistance to Tomato Yellow Leaf Curl Virus (TYLCV). These examples highlight how genomics directly contributes to pest management by targeting the molecular basis of resistance and transmission.

The integration of genomics into IPM supports precision, sustainability and innovation. Precision comes from the ability to design interventions at the genetic level, sustainability is achieved by reducing reliance on broad-spectrum pesticides and innovation is reflected in the development of next-generation biopesticides and resistant cultivars. However, challenges remain, including cost of sequencing and molecular tools, infrastructure for data analysis, regulation of gene-editing technologies and adoption among farmers who may lack awareness or technical expertise.

Future directions involve developing affordable genomic tools, integrating genomics with digital twins for real-time pest modeling, establishing clear regulatory frameworks for RNAi and CRISPR applications and investing in capacity building to train farmers and extension workers. By embedding genomics into horticultural IPM, pest management becomes more predictive, targeted and resilient, ensuring that crops like chilli and tomato can withstand evolving pest pressures while reducing chemical dependency. This molecular dimension of IPM represents a paradigm shift, where pest control is not only about managing populations in the field but also about understanding and manipulating their genetic foundations for long-term sustainability.

6. Remote Sensing in IPM

Remote sensing in horticultural Integrated Pest Management (IPM) refers to the collection of data from satellites, drones, or ground-based sensors without direct contact, enabling continuous monitoring of crop health, pest infestations and environmental conditions. This technology provides farmers with early warning systems and precise insights into pest dynamics. For example, UAV-based hyperspectral imaging has been used to detect thrips damage in chilli crops before visible symptoms appear. Similarly, multispectral imaging identifies early signs of *Tuta absoluta* infestations in tomato crops (Zhang *et al.*, 2020), while thermal imaging detects *Fusarium wilt* infections in banana plants. These applications highlight how remote sensing can capture subtle physiological changes in crops that are invisible to the naked eye, allowing for timely interventions.

Remote sensing does not operate in isolation; it integrates seamlessly with AI, robotics, digital twins and big data analytics to create holistic IPM systems. AI algorithms process the massive datasets generated by sensors, robotics provide automated responses such as precision spraying or mechanical weeding and digital twins simulate pest-crop interactions using real-time sensor inputs. Together, these technologies enhance precision, reduce pesticide use and support sustainable horticulture. The advantages of remote sensing in IPM include early detection of pest and disease outbreaks, non-invasive monitoring of crop health and large-scale environmental assessment. However, challenges remain in terms of data integration, cost of advanced imaging systems, technical expertise required for interpretation and policy support for scaling adoption.

Future directions involve developing affordable remote sensing platforms, improving interoperability across devices and training farmers to use these tools effectively. By embedding remote sensing into horticultural IPM, pest management becomes predictive, adaptive and highly efficient, ensuring both productivity and ecological sustainability.

7. Big Data Analytics in IPM

Big data analytics in horticultural Integrated Pest Management (IPM) integrates diverse information streams from weather stations, soil sensors, genomic studies, pest monitoring systems and market data, creating a comprehensive foundation for evidence-based decision making. By processing these large datasets, big data enables predictive modeling and precision interventions that improve both crop productivity and sustainability (Patil *et al.*, 2020)^[5].

Decision support systems are a key application, combining big data analytics to suggest interventions tailored to specific crops and regions. For instance, IBM Watson Agriculture analyzes millions of data points to recommend pest management strategies, ensuring that farmers receive region-specific and crop-specific guidance (Singh *et al.*, 2021; Zhang *et al.*, 2022)^[7, 11].

Predictive models built on big data have been particularly effective in forecasting pest outbreaks. In chilli crops, big data-driven models can predict thrips infestation, allowing farmers to act before populations reach damaging levels, thereby reducing yield losses (Singh *et al.*, 2021)^[7]. Similarly, integrating genomic data with pest monitoring systems helps identify resistance markers and track vector biology, while soil and climate data improve the accuracy of pest population dynamics modeling (Sun *et al.*, 2026)^[8]. This holistic approach ensures that interventions are not only timely but also optimized to minimize pesticide use and environmental impact.

The advantages of big data analytics in IPM include precision interventions, where treatments are applied only when necessary; evidence-based decision making, which reduces reliance on guesswork; and scalability, as systems can be applied across diverse crops and regions. However, challenges remain in terms of data integration, ensuring that information from multiple sources is harmonized, cost of advanced analytics platforms, technical expertise required to interpret outputs and the need for policy support to make these tools accessible to smallholders.

Future directions involve developing affordable big data platforms, enhancing interoperability across devices and datasets and integrating big data with AI, robotics, digital twins and remote sensing to create holistic IPM systems. Farmer training and capacity building will also be essential to ensure adoption and effective use. By embedding big data analytics into horticultural IPM, pest management becomes predictive, adaptive and highly efficient, supporting both productivity and ecological sustainability. This integration represents a shift from reactive pest control to proactive, data-driven crop protection, ensuring resilience against evolving pest pressures and climate variability.

Conclusion

Bringing together the different strands of technology explored in horticultural IPM, it becomes clear that big data analytics acts as the backbone that connects and strengthens other innovations such as AI, robotics, digital twins,

genomics and remote sensing. By integrating information from weather stations, soil sensors, genomic studies, pest monitoring systems and even market data, big data enables a shift from reactive pest control to predictive and precision-based interventions. This interconnected system allows farmers to anticipate outbreaks, tailor strategies to specific crops and regions and minimize chemical use while safeguarding yields.

The synergy of these technologies demonstrates how horticultural IPM is evolving into a holistic, data-driven ecosystem. Big data analytics ensures that the massive flow of information from sensors, drones, sequencing labs and decision support platforms is not only collected but transformed into actionable insights. This strengthens sustainability by reducing pesticide dependency, enhances resilience against climate variability and empowers farmers with evidence-based tools. While challenges such as cost, accessibility and technical expertise remain, the trajectory points toward affordable, interoperable platforms supported by policy frameworks and farmer training.

In essence, big data analytics is the central nervous system of modern IPM, coordinating diverse technologies into a unified strategy. Its integration with AI, robotics, genomics, digital twins and remote sensing ensures that horticulture moves toward a future of precision, sustainability and innovation, where pest management is smarter, more efficient and deeply aligned with ecological balance.

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