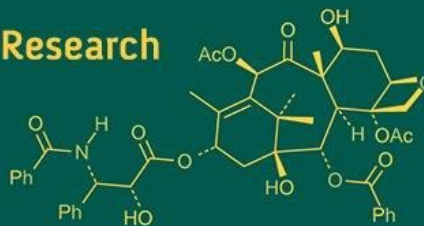


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Naval Kishore Meena
Department of Horticulture Fruit
Science, Rajasthan College of
Agriculture, MPUAT, Udaipur,
Rajasthan, India

Ashish Kumar
Department of Horticulture Fruit
Science, Rajasthan College of
Agriculture, MPUAT, Udaipur,
Rajasthan, India

Vicky Yadav
Department of Horticulture Fruit
Science, College of Agriculture,
Sanskaram University, Kheri
Taluka, Patauda, Jhajjar,
Haryana, India

Subhajit Panigrahi
Department of Vegetable Science,
College of Horticulture, Bermiok,
Sikkim CAU, Imphal, Manipur,
India

Thusharreddy Jaganathan
Department of Vegetable Science,
College of Horticulture, Bermiok,
Sikkim CAU, Imphal, Manipur,
India

Dr. Gargi Shekhar
Assistant Professor, Department of
School of Agriculture, Dev Bhoomi
Uttarakhand University,
Dehradun, Uttarakhand, India

ER Happy Narang
Assistant Professor, Department of
School of Agriculture, Maya Devi
University, Dehradun,
Uttarakhand, India

Harendra
Assistant Professor, Department of
Horticulture, School of Agricultural
Sciences, GD Goenka University
Sohna Gurugram, Haryana, India

Corresponding Author:
Naval Kishore Meena
Department of Horticulture Fruit
Science, Rajasthan College of
Agriculture, MPUAT, Udaipur,
Rajasthan, India

Emerging trends in precision horticulture integrating digital technologies for smart crop management

Naval Kishore Meena, Ashish Kumar, Vicky Yadav, Subhajit Panigrahi, Thusharreddy Jaganathan, Gargi Shekhar, ER Happy Narang and Harendra

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Abstract

Precision horticulture constitutes a new paradigm of crop production, which utilizes digital, geospatial, and automation technologies to manage spatial and temporal variability in fruits, vegetables, and ornamentals. In this regard, this review focused on the development, features, and exploitation of digital tools, which are differentiating existing and emerging smart horticultural systems. Among these, a number of key enabling technologies exist including IoT, remote sensing, drones, Artificial Intelligence (AI), Machine Learning (ML), and robotics which facilitate technology convergence to realize the continuous sensing, predictive analysis, and data-driven decisions related to irrigation, fertigation, pest management and postharvest handling. GIS-based zoning, sensor networks, Variable-Rate Technologies (VRT) and cloud-based Decision Support System (DSS) are integrated to improve resource use efficiency, crop yield, and environmental protection. Furthermore, developments such as blockchain-based traceability and autonomous greenhouse and orchard solutions signify the increasing influence of digitization in horticulture. Still, challenges pertaining to technology costs, data interoperability, infrastructure, and access for smallholder farmers continue to pose major roadblocks for comprehensive uptake. It is anticipated that future development will depend on AIoT convergence, digital twins, climate smart analytics, and the realization of economically feasible and scalable solutions. In the end, precision horticulture, through the convergence of technologic innovation, data intelligence, and ecological stewardship, perhaps best embodies a sustainable pathway to resilient, productive, and climate-adaptive horticultural systems within the concept of Agriculture 5.0.

Keywords: Precision horticulture, digital agriculture, Internet of Things (IoT), artificial intelligence (AI), remote sensing, variable-rate technology, decision-support systems, automation

Introduction

Concept and Scope of Precision Horticulture

Precision horticulture is a novel, information-intensive management system applicable to fruit, vegetable, and ornamental crop production. Based on geographic information system (GIS), sensing and automation systems, it addresses site-specific monitoring and management of crop variability at various spatial scales to maximize input efficiency of water, nutrient, labour, and agrochemicals while improving output in terms of productivity, quality and sustainability (Nabi *et al.*, 2017) ^[25].

Although the concept is based on precision agriculture, precision horticulture is adapted to the small-scale, high-value and spatially dissimilar systems which characterize horticultural production. In contrast to broad-acre farming, horticultural crops can vary at much finer scales, on occasion even down to individual plants, rows, or canopy zones, and so require management decisions and data at high levels of resolution (Kumar *et al.*, 2024) ^[17].

The main components of precision horticulture are remote sensing, internet of things (IoT) based sensor networks, automated irrigation and fertigation systems, unmanned aerial vehicles (drones), mobile platforms (robots), and big data analytics. Collectively, these technologies form a comprehensive system that growers can use to observe the crop, identify stress or disease at an early stage, and implement timely, science-based management decisions. Ultimately, it aims to resource-efficient, climate-resilient and environmentally sound production system for higher horticultural production (Haque *et al.*, 2025) ^[14].

Need for digital transformation in horticulture

The horticulture industry is undergoing an unprecedented challenge due to climate variability, resource constraints, increasing cost of inputs, and the growing demand from consumers for quality, safety, and traceability. Drastically changing environmental conditions are rendering traditional growing methods—generally organized around fixed calendars and accumulated experience—insufficient to sustain productivity and profitability.

Digital transformation provides a paradigm shift by giving access to real-time monitoring, predictive decisions, and accurate administration. By incorporating digital technologies including IoT sensors, Artificial Intelligence (AI), Unmanned Aerial Vehicles (UAVs), Machine Learning (ML), and big data analytics, growers are able to collect and analyze field data on an ongoing basis. These automated techniques enable the generation of smart crop management systems, which can modify irrigation, nutrient supply, pest control, and harvest procedures according to real-time information from the field environment (Miller *et al.*, 2025) ^[22].

Evolution of precision horticulture

Historical Background and Technological Milestones

The roots of precision agriculture can be traced to the end of the 20th century, with the developments of Global Positioning System (GPS) and Geographic Information System (GIS) in the 1980s and 1990s. These tools made it possible for farmers to map their fields spatially, log yield information, and use inputs at variable rates a revolutionary departure from standard, uniform management. The combination of yield monitors, soil probes, and variable rate application equipment initiated site-specific crop management (SSCM), which was designed to enhance resource use efficiency and environmental sustainability (Mulla and Khosla, 2016) ^[24].

With technology evolution, the PA principles were later applied in horticultural systems, leading to modern precision horticulture. In contrast to field crops, horticultural production takes place in smaller plots of land that is high value, and it needs to be managed over much finer spatial and temporal scales. The application of GPS-based mapping, remote sensing, and automated irrigation systems allowed the monitoring of plant variability in orchards, vineyards, greenhouses, and vegetable farms (Mehta and Masdekar, 2018) ^[21].

Over the past 20 years, a series of milestones have defined the development of precision horticulture. Integration of remote sensing and GIS for orchard zoning in 2000s, and now, sensor-based fertigation and irrigation scheduling in greenhouse system has been employed. More recently, technological advances have led to the development of unmanned aerial vehicles (UAVs), Internet of Things (IoT) platforms, artificial intelligence (AI), and machine learning (ML) that allow for real-time monitoring, predictive analytics, and automation of decision-making processes (Halder *et al.*, 2024) ^[13].

Transition from traditional to data-driven horticulture

Conventional horticultural production systems have historically been based on experience and calendar date, with irrigation, nutrient application, pest management, and harvest timing decisions influenced largely by farmer gut-feeling and general weather patterns (Ferreira *et al.*, 2024)

^[8]. Although these methods work well in predictable environments, they tend to neglect the intrinsic variability of soil, plant and microclimatic conditions, resulting in input use inefficiencies and yield variability.

The emergence of data-driven horticulture is a shift in the paradigm from traditional methods to on-the-spot, facts-based decisions. With the fusion of sensor networks, remote imaging and predictive analytics, next-generation systems at very fine scales monitor variability of soil moisture, temperature, canopy health, and pest pressure. This enables farmers to make differential application of resources, by ensuring that water, nutrients and pesticides are applied only where and when they are needed (Soussi *et al.*, 2024) ^[37].

Key components of precision horticulture systems

Current precision horticulture is the integration of digital, mechanical, and analytical technologies to enable data-driven crop management. They are intended to acquire, process and apply data in real time, so as to optimize water, nutrient and agrochemical use under high yield and quality standards. The combination of multiple tools, (e.g. in-field sensors, cloud-based analytics) creates a cyber-physical system that enables real-time decision making and control. The key elements of a Precision Horticulture system can be categorized into six interconnected areas: sensing technologies, geospatial tools, imaging systems, variable-rate technologies, decision-support systems (DSS), and automation & robotics. Combined, they form a measurement-analysis-action feedback loop, which is the hallmark of today's intelligent smart horticultural management. The key elements include:

Sensors: Sensors are the basis of precision horticulture, as they give incessant and location-specific data about the crop and the environment in which it is grown. An array of in-field sensors are nowadays employed to quantify soil moisture, temperature, electrical conductivity (salinity), pH, and levels of nutrients, infrequently by one sensor but more commonly in a multi-sensor platform, typically linked via Internet of Things (IoT) networks enabling real-time monitoring (Getahun *et al.*, 2024) ^[12].

Soil (e.g., tensiometer, TDR probe) temalahn is important for root zone management and irrigation scheduling, and plant (e.g., leaf wetness sensor, zchlorophyll meter, canopy temperature sensor) seimalahns measure physiological responses to environmental stress (Chappell *et al.*, 2013) ^[5]. Such data inputs make it possible to apply precision fertigation, guide the best use of resources and enhance efficiency of use of water in crops such as mango, grape and tomato.

Recent developments are wireless sensor networks (WSN), low-power wide-area networks (LPWAN), and edge computing frameworks that can transmit large data sets with high efficiency while the potential overhead of system maintenance is also reduced (Palianny *et al.*, 2024) ^[26]. These systems are now connected to AI-based dashboards that translate data from the sensors into information farmers and researchers can act on.

Geospatial Tools (GIS and GPS): Geospatial technology, especially geographic information systems (GIS) and global positioning systems (GPS) are in important in mapping and monitoring spatial heterogeneity within horticultural fields. The combination of soil maps, topographic information,

yield maps, and climatic data using GIS can be applied to identify management zones within an orchard or a greenhouse (Longchamps *et al.*, 2022) ^[18].

By GIS analysis, the farmer has information to clearly see the diversity of soil texture, the variability of nutrient contents and microclimatic conditions within fields. GPS-based systems also improve site-specific operations, allowing proper navigation during application of sprays, fertilizers, and during harvesting. When GIS and GPS are used together it is possible to apply input at variable rates, allowing for greater precision and less wastage of resources (Singh, 2022) ^[32].

These tools have been especially transformative in orchard systems where plant spacing, canopy architecture, and topography differ widely and in viticulture, in which GIS-based zoning is employed to match management to terroir-specific attributes (Mansoor *et al.*, 2025) ^[19].

Imaging Systems: Imaging technologies now lead precision horticulture by enabling crop health, canopy development, and stress detection to be assessed on a large scale without destruction. Imaging data are acquired by satellite, UAVs, or ground sensors and processed through multispectral, hyperspectral, or thermal imaging (Di Gennaro *et al.*, 2022 ^[7]; Aasen *et al.*, 2018) ^[1].

Multispectral imaging makes it possible to distinguish vegetation vigor through indices such as Normalized Difference Vegetation Index (NDVI), and hyperspectral sensors have a finer spectral resolution for disease detection, nutrient deficiency identification, and phenotyping (Sadka *et al.*, 2023) ^[29]. Thermal imaging detects the anomalies of the canopy temperature caused by water stress or disease.

The adoption of machine learning models facilitates the automatic analysis of images, detecting pest infestations or nutrient deficiencies prior to the appearance of visual signs. The monitoring based on UAV is commonly used today to conduct orchard canopy analysis, flower counting and yield prediction, having transformed horticultural management at the research and commercial levels.

Variable-Rate Technologies: Variable-Rate Technologies (VRT) provide the capability to apply the agricultural inputs (water, fertilizers, and pesticides) precisely to the need of the land on a field-by-field basis or according to within-field variability. Integrating geospatial data with sensor and imaging data, these systems dynamically modify rate of application to maximize resource utilization (Saleem *et al.*, 2023) ^[31]. In precision fertigation, soil moisture sensor and canopy temperature feedback are used by variable-rate irrigation systems to adjust the timing and amount of water

applied. Likewise, variable-rate sprayers use ultrasonic or LiDAR sensors to measure canopy density, enabling a differential pesticide application which reduces chemical sage by up to 40% (Zude-Sasse *et al.*, 2021) ^[46].

In greenhouse production, automated fertigation system with nutrient-solution sensor connected to EC/pH controller is able to provide optimal growing environment for crops in a real-time manner (Sulaiman *et al.*, 2025) ^[39]. The use of VRT has been associated with more uniform crops, less nutrient leaching, better fruit quality, especially for high value crops (e.g. apple, strawberry, and tomato).

Decision-Support Systems (DSS): Decision-Support Systems (DSS) combine different data streams (sensor outputs, weather forecasts, satellite imagery, and field history) to provide farmers with data-driven advice, helping them improve the sustainability of their operations and/or maximize yields. These systems use AI models, crop simulation software, and predictive algorithms to provide advice for irrigation scheduling, nutrient management, and pest control (Supriya *et al.*, 2024) ^[40].

Today, DSS platforms including CropSyst, AquaCrop, Irrimodel, FruitLook, are increasingly cloud-based and can be accessed through mobile devices. Developed dashboards are user-friendly and visualize field conditions and notify growers when they are at risk (Jones *et al.*, 2017) ^[16]. The combination of DSS with IoT devices creates real-time feedback loops, in which data collected in the field are immediately processed and management actions adapt in real time.

AI-based DSS systems increase not only the accuracy of decisions but also enable predictive management, which means the possibility of intervening ahead of time, before the crop experiences severe stress (Mishra and Mishra, 2024) ^[23].

Automation and Robotics: Automation and robotics are changing horticultural production at a rapid pace by solving labour constraints and enabling greater precision of operations. Autonomous vehicles, robotic harvesters, and drone sprayers are now in use on fruit orchards, vineyards, and protected culture (Fontani *et al.*, 2025) ^[9].

Fruit-picking robots utilizing computer vision and machine learning algorithms can detect ripe fruits, remove weeds, or carry out selective pruning with little supervision from humans (Zhou *et al.*, 2022) ^[45]. In crops like tomato, strawberry and citrus, robotic harvesters have shown high picking accuracy and fruit damage was less than that caused by ground laborers (Xiao *et al.*, 2023) ^[43].

Table 1: Key components of precision horticulture systems and their applications

Component	Function	Key Tools/Technologies	Applications in Horticulture	Key References
Sensors	Monitor soil, plant, and climate parameters	IoT sensors, WSN, LPWAN	Soil moisture, nutrient management, irrigation scheduling	Getahun <i>et al.</i> , 2024 ^[12] ; Chappell <i>et al.</i> , 2013 ^[5]
Geospatial Tools	Map spatial variability	GIS, GPS	Orchard zoning, site-specific input management	Longchamps <i>et al.</i> , 2022 ^[18] ; Singh, 2022 ^[32]
Imaging Systems	Remote crop monitoring	UAVs, multispectral & thermal cameras	Disease detection, canopy mapping, yield estimation	Di Gennaro <i>et al.</i> , 2022 ^[7] ; Sadka <i>et al.</i> , 2023 ^[29]
Variable-Rate Tech.	Optimize input use	VRT controllers, EC/pH sensors	Precision fertigation, pesticide optimization	Saleem <i>et al.</i> , 2023 ^[31] ; Zude-Sasse <i>et al.</i> , 2021 ^[46]
Decision Support Systems	Data-driven recommendations	AI models, cloud DSS, CropSyst	Irrigation, nutrient, and pest management	Jones <i>et al.</i> , 2017; Mishra & Mishra, 2024 ^[23]
Automation & Robotics	Mechanized operations	Drones, cobots, robotic harvesters	Harvesting, pruning, irrigation automation	Zhou <i>et al.</i> , 2022 ^[45] ; Fontani <i>et al.</i> , 2025 ^[9]

Automated irrigation systems with soil sensors and weather models can dynamically adapt watering schedules, enabling precision water management and reducing the potential for human error. Additionally, the advancement of collaborative robots (cobots), which operate in close proximity to human workers, is opening new frontiers in greenhouse operations for tasks such as grafting and sorting.

Core digital technologies in precision horticulture

- **Remote Sensing and GIS Applications:** Remote sensing (satellite, aerial, UAV) and GIS allow for the mapping of crop condition, canopy size/density, biomass, vigour and stress (nutrient, water, disease). For example, multispectral NDVI imagery can distinguish areas of low vigour for precision intervention. In horticulture, orchards canopy analysis, vineyards stress detection, and mapping of variability within management zones is important (Cisse, 2024) ^[6].
- **Internet of Things (IoT) and Sensor Networks:** IoT systems consist of sensors (soil moisture/temperature, leaf wetness, microclimate, nutrient sensors) that transmit data in real-time. These enable accurate irrigation/fertigation decisions, microclimatic management (mainly in protected horticulture), and early detection of anomalies. A recent paper presents the “Internet of Everything (IoE)” in farming considering that sensor networks unify several subdomains for an enhanced data capture (Singh and Sharma, 2025) ^[33].
- **Drones and Unmanned Aerial Vehicles (UAVs):** UAVs are also gaining popularity in fruit and vegetable production for capturing high-quality images, real-time surveillance, and selective spraying. They offer some additional flexibility compared to satellites (temporal/spatial) and allow applications such as crop scouting and monitoring irrigation. For instance an article mentions: "drones are at the heart of precision agriculture outfitted with thermal imaging to detect areas of over and under-watering. In horticulture their application in orchard for canopy health, pest/disease detection and even robotic spraying is expanding (Virk, 2023) ^[42].
- **Artificial Intelligence (AI) and Machine Learning**

- (ML): AI/ML allow the processing of large volumes of sensor, imagery, and weather data to provide insights such as: predictive analytics (e.g., yield forecasting), early detection of disease/pest, and variable-rate recommendations. A bibliometric review even commented: "With IoT technologies and artificial intelligence, agricultural inputs can be monitored and applied in real-time customized manner, increasing productivity and sustainability" (Poenaru *et al.*, 2025) ^[27].
- **Robotics and Automation:** Robotics and automation in horticulture are being applied to such tasks as smart irrigation (automated watering schedules), robotic harvesting (fruit picking), pruning robots, and autonomously driven ground vehicles. Robots seem to be the answer to the challenge of increasingly scant and costly labour. The above-mentioned bibliometric review also points out robotics and automation as “the latest technological developments in the area” within Agriculture 4.0 (Poenaru *et al.*, 2025) ^[27].
 - **Blockchain and Cloud Computing:** Cloud computing allows data to be stored, processed, analyzed, visualized through dashboards and connected for digital horticulture. Blockchain revolutionizes supply chains with traceability, transparency and secure data. The review also says: “The transparency and traceability from farm to consumer is enhanced by blockchain in the horticultural supply chain, it has been used to monitor produce during harvesting, packing, transportation, and retail (Adewusi *et al.*, 2023 ^[2]; Vignesh *et al.*, 2025) ^[41]. Cloud platforms also enable decision-support systems and integration of real-time data streams.

Smart Crop Management Applications
Precision Irrigation and Fertigation: Precision irrigation combines sensor (soil moisture, leaf wetness, canopy temperature) and weather information to apply water only where and when it is needed; fertigation means nutrients are applied through the irrigation system at variable rates. IoT and sensor data allow for such integration. For example, articles on digital horticulture emphasize the significance of precision irrigation for efficient use of resources (Singh *et al.*, 2024) ^[34].

Table 2: Core Digital technologies in precision horticulture and their applications

Technology	Core Functions	Major Applications in Horticulture	Key References
Remote Sensing & GIS	Spatial mapping, canopy monitoring, variability analysis	Canopy vigor mapping, orchard zoning, vineyard stress detection	Cisse, 2024 ^[6]
Internet of Things (IoT) & Sensor Networks	Real-time monitoring of soil, plant, and microclimate data	Precision irrigation/fertigation, greenhouse automation, stress detection	Singh and Sharma, 2025 ^[33]
Drones / UAVs	High-resolution imaging, crop scouting, targeted spraying	Orchard canopy health, irrigation mapping, pest detection	Virk, 2023 ^[42]
Artificial Intelligence & Machine Learning	Predictive analytics, image classification, data-driven recommendations	Yield forecasting, pest/disease diagnosis, site-specific management	Poenaru <i>et al.</i> , 2025 ^[27]
Robotics & Automation	Mechanized operations for labor-intensive tasks	Robotic fruit picking, smart irrigation, pruning, autonomous vehicles	Poenaru <i>et al.</i> , 2025 ^[27]
Blockchain & Cloud Computing	Data integration, traceability, storage, analytics	Supply chain transparency, cloud-based DSS, IoT data management	Adewusi <i>et al.</i> , 2023 ^[2] ; Vignesh <i>et al.</i> , 2025 ^[41]

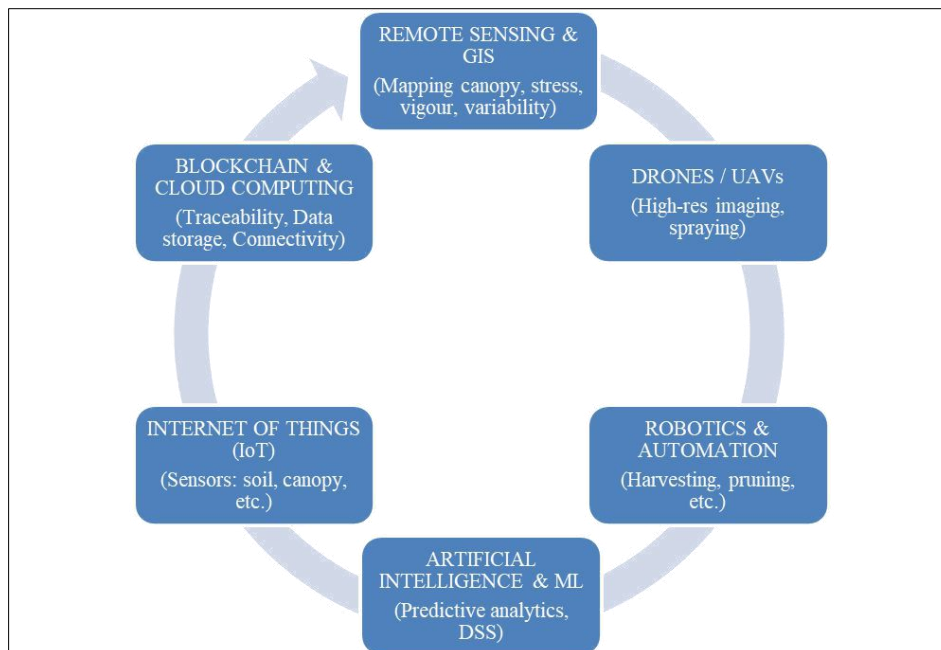
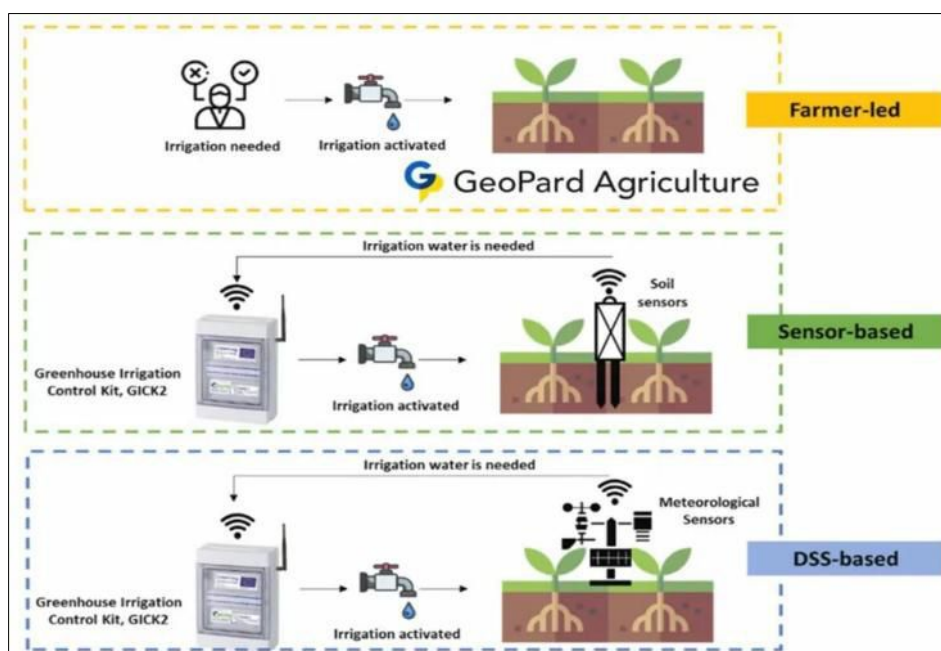


Fig 1: Integration of core digital technologies in precision horticulture



Source: (GeoPard Agriculture, 2023) ^[11].

Nutrient and Soil Health Management

Contemporary horticultural practices now depend on high resolution management of nutrients and soil health to maximize production, quality, and sustainability. Among the most important technological advances are soil mapping (classical and proximal), nutrient sensors (in-field monitoring of macro and micronutrients, EC, pH, etc.) and variable rate nutrient applicators (which deliver fertilizers or amendments at spatially variable rates across a field) (Bulacio Fischer *et al.*, 2025) ^[4].

In specialty crops and small-scale horticulture systems (orchards, high-density plantings, protected cultivation), nutrient delivery precision is particularly critical because (a) minor spatial variability can produce large differences in crop performance, and (b) input costs and yield/value are high, enabling an investment in precision devices. With the aid of detailed soil maps and by using proximal sensing,

they can locate areas of nutrient deficiency or surplus, identify gradients of soil texture/structure, and apply differential rates of nutrients. Variable-rate applicators for nutrients then convert these maps into signs of input modification in real time (Sinha *et al.*, 2025) ^[35].

Sensors that monitor nutrient levels in soil solution or root-zone (as well as the advent of in-plant nutrient status) are being integrated with decision support systems to provide closely matched nutrient supply to plant demand. Recent reviews indicate that nutrient sensors and variable rate technologies contribute to the optimization of fertilizer application, the reduction of nutrient loss, and an improvement in crop yields (Reza *et al.*, 2025) ^[28]. In addition, integrating nutrient management with soil health assessment (microbial biomass, enzyme activity, soil physical/chemical attributes) makes certain that the system is not just adjusting to short-term plant needs but is also

supporting sustainable soil fertility and ecosystem services (Xing *et al.*, 2024) ^[44].

A number of studies emphasize that although the precision nutrient management is relatively well refined in broad-acre cereals, its use in horticulture is still developing and essential. For instance, a few authors state that site-specific management strategies can cut fertilizer application rates by 10-20% and increase yield in high-intensity systems (Sishodia *et al.*, 2020) ^[36]. Similarly, the review by Saiz-Rubio and Rovira-Mas (2020) ^[30] highlights how the precision data management, spatial tools and variable-rate technologies are laying the groundwork for Agriculture 5.0 such as accurate nutrient application in horticulture.

Pest and Disease Management

The timely identification of pests/diseases through imagery, sensors and AI enables focused spraying or biological treatments, that decrease the use of chemicals and enhance sustainability. For example, UAV + multispectral + AI can identify disease earlier than visible symptoms (Fuentes *et al.*, 2023) ^[10].

Crop Growth Monitoring and Yield Estimation

Employing drones, sensors, and analytics, growers can track crop growth stages, canopy development, flowering, stress and predict yields prior to harvest useful for planning and marketing (Hocevar *et al.*, 2014) ^[15]. As remote sensing reviews highlight canopy size/density and yield estimation as major applications (Longchamps *et al.*, 2022) ^[18].

Postharvest Handling and Supply Chain Optimization

Digital technologies are not confined to the field: cold-chain surveillance, quality control, traceability through blockchain, transport modality. These can be used to reduce waste in the postharvest supply chain and open up opportunities for premium prices. For example, blockchain was applied to enhance traceability from farm to consumer (Poenu *et al.*, 2025) ^[27].

Data Analytics and Decision Support Systems (DSS)

Soil moisture data from sensor networks and weather station, and soil mapping has to be integrated, cleaned, analyzed and translated into actionable recommendations through a DSS. Big data analytics, AI models, cloud dashboards support decision-making (Mehedi *et al.*, 2024) ^[20].

Integration of Digital Platforms

Farm Management Systems can be cloud-based, which facilitate data storage, data analysis, dashboards that can be accessed via the web or mobile. Mobile applications allow farmers and advisors to access field data, alerts, and recommendations in real-time. Smart dashboards provide visualization of sensor and UAV data, and decision support. As blogs on digital horticulture mention, such platforms are instrumental for scalability and reach (Boruah *et al.*, 2024) ^[3].

Case Studies and Global Experiences

Advanced Horticultural Systems (Netherlands, Israel, USA)

These areas benefit from high levels of technology adoption, automation in controlled environments, and high-density orchards utilizing precision tools. For example, reviews

mention 15%-40% of large farms in Western Europe applying some form of precision agriculture technologies (Fuentes *et al.*, 2023) ^[10].

Indian Context and Developing country initiatives

Horticulture is a significant industry in India (such as 351.92 million tonnes fruits & vegetables in 2022-23), but it has the problems of small land-holdings, low technology adoption. The blog "Horticulture 4.0" gives Indian context. The paper "Digital horticulture: Status and future prospect" deals with Indian issues (Singh *et al.*, 2024) ^[34].

Challenges and Limitations

- Technical and financial barriers (high cost of sensors, drones, analytics systems, in particular for small-scale farmers), (Subudhi *et al.*, 2025) ^[38].
- Data privacy, interoperability issues: many systems are based on proprietary formats, minimal standardization.
- Capacity development and farmer uptake: Unawareness, lack of training, lack of trust in technologies.
- Infrastructure and policy barriers (connectivity, data management, extension services) in developing countries.
- From pilot to full farm / region.
- Data overload and management-meaningful insights needed, not just data collection.
- Small land-holdings and heterogeneous fields limit the scope for economies of scale for precision tools. For India: "in countries like India, where the majority of the farmers have small land holdings using aerial remote sensing has proven to be a challenge".

Future Prospects and Research Priorities

- Integration of "AIoT" (Artificial Intelligence of Things), Senses + AI + connectivity, more deeply integrated.
- Climate smart digital tools, Climate variability models, resilience in horticulture.
- Genomics × phenomics × digital integration for precision breeding and management (this will be particularly applicable to your work on mango rootstock/variety).
- Technologies for scaling up to smallholders: inexpensive sensors, mobile applications, pay-as-you-go models.
- Institutional and policy arrangements: open source platforms, data sharing, extension models.
- Integration across sectors, farm to fork traceability, circular systems (resource recovery), sustainability metrics.
- Studies on human-machine interface, farmer acceptability, socio-economic outcomes.

Conclusion

Precision horticulture enabled by digital technologies is a paradigm shift in crop production towards smarter and more sustainable agriculture. It improves production, fruit quality and resource-use efficiency with reduced environmental impact. While the shift from conventional systems towards data-driven ones is gaining momentum, the adoption and cost barriers remain high. The use of technologies including the IoT, AI, GIS, and automation

will be critical in this transition. To support smallholders with access to affordable digital solutions, and also the training necessary to take advantage of those solutions. Real-time management based on superior data, analytics, and decision support is required. Researchers, policymakers, and industry should collaborate to spur innovation and scale. In the end, sustainable smart horticulture will result from the integration of technology, knowledge and ecological stewardship.

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