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Precision floriculture in controlled environments: Integration of IoT, sensor analytics and intelligent automation

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Abstract

Floriculture is considered to be among the most high-tech aspects of horticulture with the production of ornamental plants and cut flowers being undertaken in high-value, closely-monitored environmental conditions. Floriculture may leverage precision horticulture technologies as a result of rising consumer demands for high-quality flowers, increasing shortages of labor, limited resources, climate change, and sustainable development in agriculture. In this survey paper, we consider the components employed in precision floriculture where IoT, sensor networks, AI, ML, data analytics, robotics and automation are applied to maximize output in terms of crop production, with the best quality flowers, minimal resources used and hopefully maximum profit. Controlled Environment Agriculture (including greenhouses, polyhouses, plant factories, vertical farming systems, etc.) is considered as an excellent candidate for the application of these technologies due to monitoring and environmental control potential. IoT-enabled sensors gather data continuously that provide information in real time on temperature, humidity, light intensity, CO₂ concentration, moisture of substrate, nutrient conditions, and plant physiological activities. Sensor analytics apply these massive datasets to actionable information, enabling predictive decision support management. Intelligent automation also offers wireless irrigation control, fertigation, climate control, lighting control, disease detection and harvesting automation. New developments in cloud computing, edge computing, wireless communication technology, digital twins, computer vision, and robotics are enhancing the digitization of the flower industry. Studies show that IoT-enabled greenhouse management could considerably enhance water-use efficiency and decrease energy consumption, uniformity of crops, and marketable flower production. Here, the concepts, technologies, applications, benefits, limitations, challenges, and future perspectives of precision floriculture in controlled environment (CE) with a focus on IoT integration, sensor analytics and intelligent automation are reviewed.

Keywords: Precision floriculture, controlled environment agriculture, IoT, smart greenhouse, sensor analytics, artificial intelligence, automation

1. Introduction

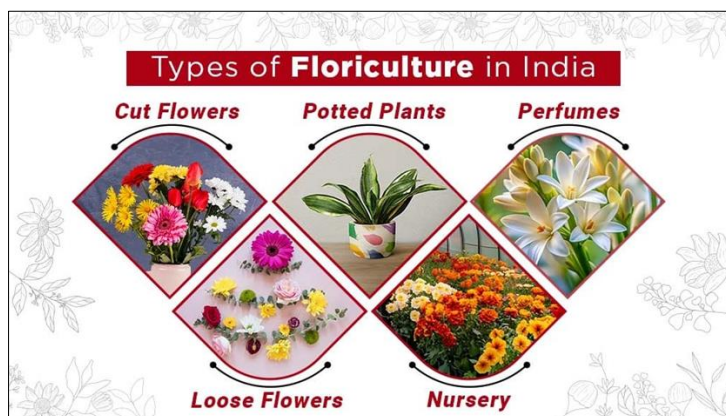
Floriculture is one of the fastest developing sectors of horticulture involving the production of flowering and foliage plants for use as cut flowers, potted plants or for landscape gardens. With increasing urbanization, income levels, lifestyles, and global trade in flowers, the consumption of flowers including rose, gerbera, carnation, chrysanthemum, orchid, lily, anthurium has increased substantially across the globe. As flower crops are very vulnerable to environmental influences, environmental conditions, including temperature, humidity, light intensity, carbon dioxide concentration, irrigation, and nutrient supply, need to be tightly controlled. Even small changes from the optimum can have unfortunate effects on quality of flowers, length of stems, colour, vase life and value in market. In the past, floriculture production has been a manual monitoring-based and grower-experience-dependent process that could not always respond promptly to dynamic changes of crop and environment (Wani *et al.*, 2023; Ingole *et al.*, 2025) [52, 22].

Adoption of controlled environment production systems, such as greenhouses and polyhouses, has allowed the growers to manipulate the crop growing environment more effectively and lead to higher productivity (Slathia *et al.*, 2018; Kumar, 2024) [47, 28]. Yet, traditional greenhouse management is still based on expectation of observations and manual interventions, causing underutilization of resources and overexploitation of the microclimate. The Development of Precision Agriculture in floriculture has revolutionized the industry by incorporating technology

like Internet of Things (IoT) devices, environmental sensors, wireless communication networks, cloud computing, artificial intelligence (AI), machine learning, and automated control systems (Lea-Cox *et al.*, 2013; Mahmud *et al.*, 2023; Srivani *et al.*, 2022; Kumar *et al.*, 2026) [30, 34, 50, 27]. Monitoring systems, controlled by these technologies, allow for monitoring of crop and environmental parameters, analyzing data in real-time, performing intelligent decision support for irrigation, fertigation, climate control, and disease management. This

paradigm innovation, dubbed Floriculture 4.0, facilitates higher productivity, better flower quality, sustainable use of water, fertilizers, energy and labor, and improved overall environmental and economic returns when integrated in flower production system (Attar *et al.*, 2024; Ahmad *et al.*, 2026; Singh *et al.*, 2025) [5, 3, 46].

Types of Floriculture in India



Source: <https://tractorkarvan.com/blog/what-is-floriculture>

2. Concept of Precision Floriculture

Precision floriculture is the use of modern technology including IoT, sensors, artificial intelligence, big data, control systems etc. to monitor, analyze and control flower production at a very high level of detail. By facilitating in-situ observation of environmental and crop conditions, it promotes data-based decision making and the detailed management of irrigation, fertigation, climate, and crop health. The objectives of precision floriculture is to improve flower quality and yield, the economic return, the use of water, fertilizers, energy, and labor, mitigate environmental impacts, sustainability, improve crop health monitoring and real-time decision support for effective and sustainable flower production (Wheeler *et al.*, 2018; Saini and Yadav, 2025) [53, 44].

The precision floriculture framework consists of four major components

1. Data Acquisition

Precision floriculture starts with data acquisition, where real-time information related to the environment and crops is gathered with the use of sensors, cameras, and imaging systems. Data such as temperature, humidity, light intensity, soil moisture, nutritional status, and plant health are monitored continuously to render timely and accurate information (Hosny *et al.*, 2023) [21].

2. Data Communication

Data communication is defined as the transfer of data between sensors and processing platforms over communication networks enabled with IoT, such as Wi-Fi, ZigBee, LoRaWAN, Bluetooth, cellular networks, and the like. This allows for uninterrupted and instant data flow between field devices and the management systems (Rathor *et al.*, 2024) [42].

3. Data Analytics

Processing, analyzing and interpreting the collected data using artificial intelligence (AI), machine learning (ML), and other advanced analytical tools is known as Data analytics. They

detect patterns, predict crop needs, identify anomalies and enable informed decision-making to optimize crop management (Vakhnovskiy *et al.*, 2026) [51].

4. Intelligent Action

Intelligent control is the realization of control decisions through actuators, controllers, and robotic systems in a distributed manner. From analytical results operations including irrigation, fertigation, climate control, lighting management and disease management are automated to optimize crop growth and resource use (Muhammed *et al.*, 2024) [39]. These elements together form a continuous feedback system, allowing the precision floriculture to be self-regulated and autonomous.

3. Controlled Environment Agriculture in Floriculture Greenhouses

Greenhouses are clear or translucent structures made from glass or plastic materials that let sunlight in and shield crops from extreme weather conditions. With heating, cooling, ventilation, shading, irrigation and humidity controls, greenhouses producers can provide the best possible environment for flower production. High value flowers including roses, gerberas, carnations and chrysanthemums are commonly grown in greenhouses for better yield, quality and production throughout the year (Kuhmonen and Kuhmonen, 2023; Soussi *et al.*, 2025) [26, 48].

Polyhouses

Polyhouses are a type of protected cultivation in which a polyethylene sheet is used as a cover material that modifies the outside weather to inside weather around the plants. They contribute to maintaining suitable temperature and humidity in addition to shielding the crops from rain, wind, frost and over sunny conditions. Polyhouses are cheaper to build than glass greenhouses and are widely used in commercial production of flowers for better crop growth, higher productivity and better flower quality (Bagagiolo *et al.*, 2022) [9].



Source: <https://www.protectedcultivation.com/blog/the-complete-guide-to-polyhouse-farmingeverything-you-need-to-know>

Net Houses

Net houses are enclosed structures covered with shade nets of different densities that control temperature and light intensity. They are exact shade loving display plants or nursery plants. In addition to heat stress reduction, net houses protect plants from high winds, birds as well as some insect pests, and this results in a better environment for plant growth and development (Guo *et al.*, 2023) ^[19].

Plant Factories

Plant factories are high-tech, closed systems with the environment controlled at all levels including the air. These facilities utilize artificial lighting, automated irrigation, climate control systems and nutrient management to provide optimal growing conditions, regardless of outdoor weather. Plant factories allow the production of high quality ornamental plants in all year with efficient use of resources and small environmental change (Adak *et al.*, 2022) ^[2].

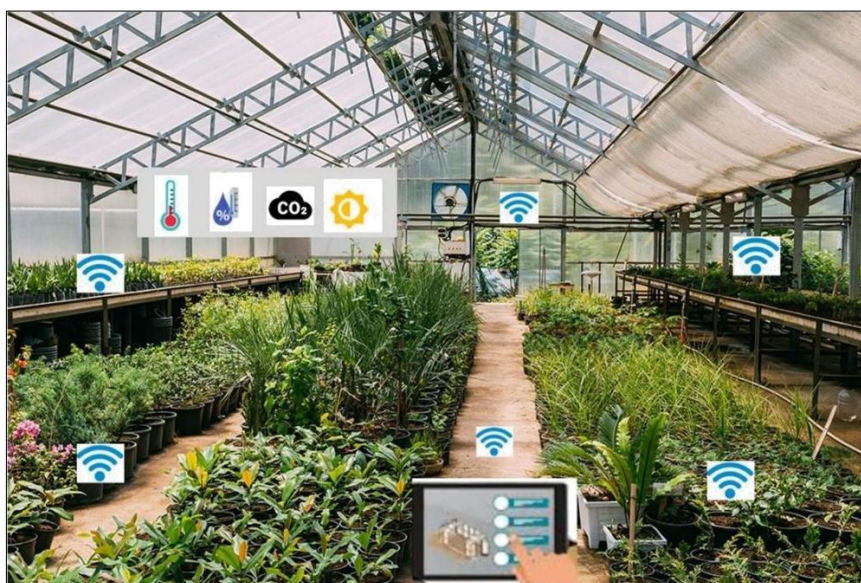
Vertical Farms

Vertical farms are innovative cultivation systems that involve growing plants in layers within a controlled-generation environment. These employ LED lights, mechanized irrigation, fertigation, climate and other controls to produce the greatest amount per square area. Vertical farming is more advantageous in urban setting where land is scarce, contributes to water,

nutrients and energy sustainable use, and provides a more stable flower quality (Yue *et al.*, 2023) ^[56]. Combined, these CEA systems create near-ideal conditions for precision floriculture in that IoT devices, sensors, AI, and automated control systems can continuously monitor, analyze, and regulate the environmental conditions. This results in enhanced yield, improved flower quality, optimized use of resources, and sustainable production (Cai and Gou, 2024) ^[11].

4. Internet of Things (IoT) in Precision Floriculture

The Internet of Things (IoT) forms the basis of precision floriculture by enabling communication among sensors, actuators, controllers, cloud platforms and users in the IoT environment. Standard IoT architecture includes sensing layer for acquiring the environmental and crop information, network layer for transmitting the data, processing layer for storing, analyzing, and decision making, and application layer for providing user interfaces and automated control mechanisms. IoT systems play an important role in this purpose, since they enable the monitoring of greenhouse conditions on a continuous manner, visualization of data in real-time through the cloud, and remote management through smartphones, tablets, or computers, with positive effects in the control of environment, efficiency of use of resources, and production of flowers as a whole (Pascoal *et al.*, 2024) ^[40].



Source: Hosny *et al.*, 2025

5. Sensor Technologies in Precision Floriculture

Sensors Used in Precision Floriculture and Their Functions

Sensor Type	Parameters Measured	Major Functions and Applications
Temperature Sensors	Thermistors, RTDs, DS18B20, Infrared temperature sensors	Greenhouse temperature is monitored to support disease forecasting, heating and cooling systems are controlled, flower development, flowering time, stem elongation and colour formation are optimized.
Humidity Sensors	Relative humidity (RH)	Observe humidity in the air, manage ventilation and fogging irrigation systems, diminish the occurrence of diseases, and keep flowers up to the quality standards.
Light Sensors	Light intensity, Photosynthetically Active Radiation (PAR), Spectral quality	Control supplemental lighting, shading systems, and photoperiod and enhance vegetative growth and flowering.
Carbon Dioxide (CO ₂) Sensors	CO ₂ concentration	Monitor greenhouse CO ₂ levels, operate CO ₂ enrichment equipment, increase photosynthesis and flower production.
Soil and Substrate Moisture Sensors	Capacitive sensors, Tensiometers, Time-Domain Reflectometry (TDR) sensors	Monitor water availability in media, facilitate precision irrigation scheduling, avoid over- or under-irrigation, and contribute to water conservation.
Nutrient Sensors	Electrical Conductivity (EC), pH, Nutrient concentration	To monitor the nutrient status, optimize the fertigation, diagnose nutritional disorders and enhance the efficiency of nutrient use.
Plant Physiological Sensors	Leaf temperature, Sap flow, Chlorophyll content, Plant stress indicators	Evaluate the health and physiological status of plants, identify stress situations in the early stages, follow crop development, and facilitate precision crop management.

6. Wireless Communication Technologies

Wi-Fi

Wi-Fi has become popular in precision floriculture for its high data transfer rate and access to internet. It allows fast sensor data transmission, remote monitoring and cloud management of the greenhouse. However, it may not be suitable for large-scale greenhouse production due to its comparatively lower communication range and higher power consumption (Dhanasekar, 2025) ^[15].

ZigBee

ZigBee is a low power wireless technology that has been increasingly used in greenhouse sensor networks. Its mesh networking architecture enables multiple devices to communicate with one another, without relying on a central point, and thus guaranteeing robust data transmission even if nodes are several-hop apart. This leads to ZigBee being the ideal protocol for connecting large amount of sensors in controlled environment systems (Gatkal *et al.*, 2024) ^[18].

Bluetooth Low Energy (BLE)

BLE is optimized for short the short range communication applications with very low power consumption. It is also frequently used for data transfer between nearby sensors, controllers and mobile phones. BLE is especially good for localized monitoring and control where low power consumption and ease of connectivity is important (Soussi *et al.*, 2024) ^[49].

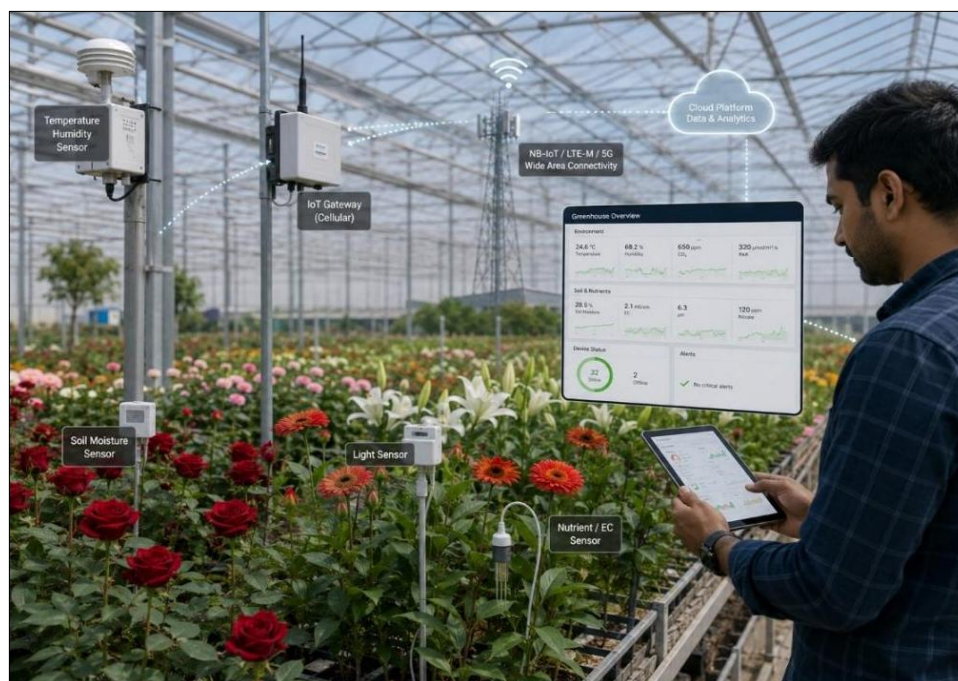
LoRaWAN

LoRaWAN (Long Range Wide Area Network) is a communication technology which allows long distance communication with low power. It is more and more used in smart greenhouse monitoring systems since it can accommodate a large number of distributed sensor nodes in vast areas with low power consumption. Therefore, it is considered to be the best choice for largescale floriculture activities that entail round-the-clock observing of the environment (Bicamumakuba *et al.*, 2025) ^[10].

Cellular IoT: Cellular-based IoT solutions such as NB-IoT, LTE-M, G enable wide-area network coverage and real-time data reporting. This allows users to connect their greenhouse systems and cloud platforms for remote monitoring and management from virtually anywhere. Cellular IoT is especially useful for large-scale commercial floriculture producers that need dependable connectivity and access to real-time production information around the clock (Rafi *et al.*, 2025) ^[41]. These communication technologies, on the other hand, are at the core of IoT-based precision floriculture system, and help facilitate seamless data communication among sensors, controllers, cloud platforms, and users, enabling real-time system monitoring, automated decisions, and intelligent greenhouse management.

Sensor Analytics in Precision Floriculture: The large volume of data produced by sensors in precision floriculture demands sophisticated analysis methods to transform raw measurements into useful and actionable information. Sensor analytics allows farmers to track the performance of their crops and the interaction with the environment, catch up with the current situations, glimpse into the future, and best manage their crops. According to the analysis objectives, sensor analytics may be divided into descriptive, diagnostic, predictive and prescriptive analytics (Miller *et al.*, 2025; Meena *et al.*, 2025) ^[38, 37]. Descriptive analytics is concerned with “what is happening” in the production system, and it can be served with aggregation of historical and current data through environmental dashboards, reports or visualizations. It delivers real-time information on greenhouse environment and crop development. Diagnostic analytics answers “why it happened” by determining the causes of events like flower quality drop, nutrient imbalance, or disease occurrence. This enables cultivators the ability to analyze what influences affect their crop performance and how to act on them (Sadik *et al.*, 2026) ^[43].

Predictive analytics answers "what is going to happen" by employing AI and ML methods to examine past and current data. This enables proactive crop management, including disease prediction, flowering prediction, yield prediction and prediction of environmental variations.



Prescriptive analytics has one more layer of complexity as it tells you "what should be done" by the results of your analytics. It also generates recommendations for irrigation scheduling, fertigation management, climate control strategies, and other operational measures for accurate and automated greenhouse management. As a result, these analyses can contribute to better decisions, higher resource-use efficiency, and intelligence floriculture production systems (Delfani *et al.*, 2024) [14].

8. Artificial Intelligence and Machine Learning Applications

Disease Detection

Computer vision enabled precision floriculture, which analyzes flowers and leaves to identify and diagnose diseases of the plants visually, it's used for automated detection. State-of-the-art image processing technology in conjunction with artificial intelligence and deep learning-based algorithms for disease identification enables detection of powdery mildew, botrytis, and viruses among others with very high accuracy. Such systems also can detect subtle symptoms before they turn visually severe, allowing them to catch the disease early and prevent further damage to the crops. When combined with environmental data derived from sensors, imaging-based greenhouse systems can remotely monitor crop condition and provide early disease detection along with coordinated decision support for enhanced management of crop health and flower quality.

Growth Prediction

Precision floriculture employs a growing number of predictive crop growth and production models derived from machine learning. Using these models, based on historical data and data from sensors in real time, it is possible to predict flowering date, stem length, biomass accumulation and a potential yield of marketable products. These predictions help producers maximize production schedules, enhance resource utilization, harvesting operation planning and market demands satisfaction in terms of accuracy and profitability (Jabed and Murad, 2024) [23].

Climate Optimization

Artificial Intelligence (AI) and machine learning (ML) algorithms are extensively applied for climate control in precision floriculture. By constantly processing environmental and crop information, such systems can establish temperature set-points, humidity levels, ventilation schedules and CO₂ enrichment in a way to optimize growing conditions. This smart climate control promotes photosynthesis, healthy plants, flower quality and quantity and resource-use efficiency with less energy in controlled environment production (Vakhnovskyi, 2026) [51].

Resource Optimization

Machine learning is important in resource management optimization in precision floriculture. On the basis of environmental, soil and crop information, the machine learning algorithms enable precision irrigation by watering according to crop water requirements, precision nutrient management by providing precise fertigation recommendations and energy conservation through the management of greenhouse systems (e.g. lighting, heating, cooling and ventilation). Such abilities increase the efficiency of resource use and decrease the cost of operation, also making the flower production systems more sustainable (Del-Coco *et al.*, 2026).

9. Intelligent Automation in Floriculture

Automated Irrigation Systems

Precision floriculture applications of smart irrigation system employ soil moisture sensor and environmental information to estimate actual crop water demand. Since moisture and climate are constantly monitored, water is applied only when needed and in the right amount. This strategy leads to a decrease in water use, an improvement in flower quality and an increase in water use efficiency (WUE), as compared to the traditional irrigation. Irrigation based on sensor technology contributes to preventing overwatering and water stress and therefore in enhancing plant growth, efficiency in resource use as well as in reducing water consumption in closed environment production systems (Evans and Sadler, 2008) [16].

Automated Fertigation

Automated fertigation systems are designed to provide water and nutrients to the crop-specific requirements maintaining the best conditions for the growth and development of the plants. The subsystems that monitor nutrient levels and regulate fertilizer delivery in real time include nutrient sensors, mixing units, injection pumps, and control software. Automated delivery of nutrients in the proper amounts at the right time through fertigation leads to enhanced nutrient use efficiency, decreased fertilizer loss, reduced environmental pollution and increased flower yield and quality in closed environment production system (Kwakye and Kadyampakeni, 2023) ^[29].

Automated Climate Control: Heating, cooling, ventilating, shading, and humidifying processes are all involved in the automated control of climate, and these processes are important for the precision floriculture application since they enable maintaining the growing environment at a desired level (optimal condition). The controllers based on sophisticated methodologies, *e.g.*, rule-based, fuzzy logic, Model Predictive Control (MPC) and reinforcement learning, analyze the current environmental data and manipulate greenhouse environment accordingly to the needs of crops. Under stable microclimate condition, intelligent climate control systems can promote plant

growth, flowering quality and yield, reduce environmental stress, and save energy, which results in improving the effectiveness and sustainability of controlled environment flower production (Shamshiri *et al.*, 2018) ^[45].

Automated Lighting Systems

Automated LED lighting systems have been employed extensively in precision floriculture and are combined with environmental monitoring, IoT technology and AI-based control models to enhance light conditions for flower crops. These devices allow for absolute control of the photoperiod, application of supplemental light under periods of low natural sunlight, and adjustment of light spectra based on crop ontogeny and flowering needs. By providing the right intensity, duration and quality of light, LED lighting accelerates photosynthesis, enhances uniform growth, improves flowering and flower quality, and enables production throughout the year. Moreover, the LED technology has high energy efficiency property and lower running cost than traditional lighting systems that facilitate to a sustainable and profitable production in floriculture (Azizi *et al.*, 2024) ^[8].

10. Robotics in Precision Floriculture

Table 1: Robotic Technologies Used in Precision Floriculture and Their Functions

Robotic Technology	Major Applications	Key Functions/Capabilities
Harvesting Robots	Rose, chrysanthemum, and gerbera harvesting	Flowers are detected automatically, the maturity of the harvest is evaluated, precision cutting is performed, labor requirements are reduced and harvesting efficiency and uniformity are enhanced.
Grading and Sorting Robots	Post-harvest flower grading and sorting	Apply machine vision systems to measure flower size, color, stem length and other quality factors to achieve consistent grading, uniform quality standards and speed up processing.
Mobile Greenhouse Robots	Greenhouse monitoring and crop management	Conduct environmental sampling, pesticide or nutrient application, data acquisition, disease identification, and regular surveillance activities to facilitate real-time crop management while minimizing handwork.

Function In Precision Floriculture: Robotic systems are streamlining physically demanding tasks, including harvesting, grading, monitoring, and crop protection, which has led to improved operational efficiency, heightened accuracy, reduced labor dependency, and increased overall productivity in cell production of flowers under controlled environment (Comparetti, 2023) ^[12].

11. Cloud Computing and Edge Computing

Cloud computing is an important enabler in precision floriculture in that it offers flexible and scalable infrastructure for data storage, processing and analyzing, and for supporting decisionmaking. It allows harvesting and storing large amounts of sensor data from greenhouse systems, and performing data analyses to directly support crop management. Using cloud platforms, farmers can access production environments remotely and control them with a computer, smartphone or tablet from anywhere. Furthermore, cloud computing can facilitate extensive data analytics and can be easily connected with artificial intelligence (AI) and machine learning (ML) platforms, to provide real-time decision-making, predictive analytics, and intelligence automation in governed environment flower production (Wolfert *et al.*, 2017) ^[54]. Edge computing processes data near to the source such as sensors and control within the greenhouse rather than transporting all of the data to the far cloud servers. Processing

essential data at the site local area data processing reduces the latency, allow for quicker decision making, and reduces bandwidth consumption. Consequently, control systems can react immediately to modifications in the environmental factors, leading to increased efficiency of climate control, irrigation, and other greenhouse procedures. Smart greenhouse solutions are becoming an integration point for edge, fog, and cloud computing paradigms to enable real-time data acquisition and monitoring, predictive analysis, and smart automation to improve the performance and dependability of precision floriculture solutions (Ayaz *et al.*, 2019) ^[7].

12. Digital Twin Technology

A digital twin is a real-time digital replication of a physical greenhouse system using real-time data that constantly reflects the real-world environment. It combines sensor networks, simulation models, and artificial intelligence (AI) algorithms to track, analyze, and forecast greenhouse performance. Environmental and crop data are collected by sensor networks, greenhouse processes are simulated by simulation models, and management decisions are optimized by AI algorithms through the analysis of these data. Digital twins also allow producers to test various production options, anticipate crop outcomes, maximize resource use, detect challenges in advance and increase overall productivity in precision floriculture (Awais *et al.*, 2025) ^[6].

Applications

Among other things, Digital Twins can be used in precision floriculture to make climate simulations, optimize the use of resources, perform predictive maintenance, and forecast crop growth. By leveraging digital twins by way of creating a virtual replica of the greenhouse, growers can simulate environmental conditions, assess resource-use strategies, predict equipment failures before they happen, and estimate crop growth and yield. This technology allows one to virtually test management practices and operational decisions prior to their implementation, minimizing risk, enhancing efficiency, and enabling data-driven management of the greenhouse (Kritzinger *et al.*, 2018) ^[25].

13. Applications in Major Flower Crops

Rose: Precision floriculture technology are applied in rose production to include climate management, disease surveillance, and irrigation automation. These systems contribute to keep optimal conditions, leading to an increase of stem length, flower quality, productivity, and market value (Zheng *et al.*, 2021) ^[57].

Gerbera: The precision management of irrigation, nutrient, and light in a gerbera precision floriculture has been studied. The constant monitoring and automatic regulation of these parameters result in uniform growth, increased quality of flowers, and in the efficient use of resources (Maraveas, 2022) ^[36].

Carnation: The application of IoT technology allowed improvement in uniformity, early detection and management of diseases, and more precise forecasting of the yield in carnation production. Such technologies give producers the ability to make decisions in a timely manner and to increase production efficiency (Yeptho *et al.*, 2025) ^[55].

Chrysanthemum: In the chrysanthemum production, precision equipment has been extensively applied in the control of photoperiod, the management of lighting, and the prediction of flowering. With these technologies, timely flowering and uniform crop development, flower quality is maintained during the production cycle (Liu *et al.*, 2025) ^[33].

Orchid

The environment in which orchids grow must be fine-tuned to allow the plant to flourish and bloom. Precision monitoring systems are now being used to continuously monitor variables, such as temperature, humidity, light, and nutrient status, to assist in maintaining the strict environmental conditions for production of high-quality orchids (Arditti, 2009) ^[4].

14. Benefits of Precision Floriculture

Economic Benefits

The orchid growing environment needs to be adjusted to allow the plant to thrive and bloom. Precision monitoring systems are now being employed to monitor continuously parameters such as temperature, humidity, light, and nutrient status to help in maintaining the rigid environmental conditions for the production of high-quality orchids (Arditti, 2009) ^[4].

Environmental Benefits

Precision floriculture uses sensor-based irrigation water for hydroponics and cut flowers, and reduces the use of fertilizers

by more precise nutrient management. Early detection of pests and diseases reduces pesticide use, and energy use is reduced through controlled irrigation, lighting and climate. Together, these practices contribute to a reduction in greenhouse gases and foster sustainable flowers production (Garcia *et al.*, 2023) ^[17].

Social Benefits

Precision floriculture enhances the working environment by minimizing the labor-intensive activities and repetitiveness of these activities through robotization. It improves technical efficiency as crop production systems can be precisely observed and managed. Evolving information technology and advanced analytics empower growers with better decision support and enhanced real time information. These technologies are known to enhance operational efficiency, productivity and enable informed and timely management decisions (Klerkx *et al.*, 2019) ^[24].

15. Challenges and Constraints

However, precision floriculture adoption has some barriers. Development of smart greenhouse infrastructure is associated with significant initial investment, which hinders the adoption of small/medium scale growers. Expertise also is required in the areas of sensors, networking, data analytics, and automation systems for full implementation. In addition, the sensor big data generated also requires efficient storage, processing and security. Over time, sensor performance may deteriorate and sensor maintenance is absolutely necessary to keep accuracy (Mansoor *et al.*, 2025) ^[35].

Other obstacles are connectivity issues in rural areas, that could impede transmissions of data in real-time and remote monitoring. Integration can also be complicated by interoperability problems as devices from different manufacturers might rely on incompatible communication protocols. In addition, the green house system is connected to the Internet, and thus susceptible to cybersecurity attacks and privacy risks. Privacy concerns, technical complexity, interoperability, and high-investment are still blocking polarization for wide adoption of precision floriculture based technologies.

16. Future Prospects

Precision floriculture will be inspired by new digital technologies that enable more automation, intelligence, and sustainability(11). Crop prediction, disease diagnosis, and decision making will be enhanced by the evolution of Artificial Intelligence (AI) 2.0 technologies such as deep learning, generative AI, and explainable AI. Digital twin will be virtual greenhouse real-time management for growers to pre-produce, simulate and optimize production solutions. Collaborative robotic applications, for monitoring, harvesting, and crop management, will be supported by Swarm robotics, while autonomous greenhouses will be regarded as full selfregulating production facilities with limited human interaction.

The deployment of theG, and thenG, communication networks will offer high-speed and reliable connectivity for exchanging real time data and automated actions. The use of blockchain technology in cut-flower supply chain will improve traceability, transparency and quality assurance. Moreover, quantum computing can be a game changer for optimization and predictive modeling, as it can analyze intricate datasets at a very high speed. Their convergence will contribute to climate-smart floriculture development, where AI-based systems perpetually

tailor production systems according to the shifting climate conditions to cater sustainable, resilient, and high-efficient flower production systems (Abbas *et al.*, 2026) ^[1].

17. Conclusion

Precision floriculture is a disruptive technology for flower cultivation in controlled environment which combines IoT, sensor networks, artificial intelligence, data analytics, and intelligent automation. They allow to monitor continuously environmental and crop variables including temperature, humidity, light intensity, CO₂, and soil moisture, and to control irrigation, fertigation, climate, lighting, and plant health management with a high level of precision. Sensor-based data analytics transforms these complex sets of data into meaningful information for predictive and prescriptive decision making in greenhouse. The quality of flowers, harvest, efficiency of resources, and environmental sustainability are benefits of using precision technology. Smart greenhouse systems based on AI algorithms, integrated multi-sensor monitoring and distributed actuators prevalence for effective production. Nonetheless, the challenges of high investment cost, technical complexity, data management concerns, and interoperability are still the key towards maturing these visions. Recent advancements in cloud computing, edge computing, robotics, digital twins, machine learning, and wireless communication technologies are overcoming these limitations. As a whole, Floriculture 4.0 will facilitate climate-resilient, sustainable production of ornamental crops for the future global demand systems and growth.

References

1. Abbas WF, Jawad MN, Qasim HH, Majeed AH. 6G-Enabled IOT: Emerging Communication Technologies, AI Integration, and Future Research Directions. *Asian Journal of Research in Computer Science*. 2026;19:173-191.
2. Adak D, Bhattacharyya R, Barshilia HC. A state-of-the-art review on the multifunctional self-cleaning nanostructured coatings for PV panels, CSP mirrors and related solar devices. *Renewable and Sustainable Energy Reviews*. 2022;159:112145.
3. Ahmad MF, Sharma BS, Ghosh S, Khan A. Smart Floriculture for Sustainable Development: A Comprehensive Review. *Asian Research Journal of Agriculture*. 2026;19(2):172-188.
4. Arditti, J. (2009). *Micropropagation of orchids*. John Wiley & Sons.
5. Attar H, Bahy RM, Hafez M, Solyman A. Harnessing the power of IoT: a survey of Internet of Things applications in greenhouse agriculture. In: *IEEE 30th International Conference on Telecommunications (ICT)*; 2024 Jun. IEEE; 2024.
6. Awais M, Wang X, Hussain S, Aziz F, Mahmood MQ. Advancing precision agriculture through digital twins and smart farming technologies: a review. *AgriEngineering*. 2025;7(5):137.
7. Ayaz M, Ammad-Uddin M, Sharif Z, Mansour A, Aggoune EHM. Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE Access*. 2019;7:129551-129583.
8. Azizi S, Lastochkina OV, Seyed Hajizadeh H, Aliniaiefard S. Proper quality of LED light to produce high-quality ornamental plants in controlled environment agricultural systems: A review. *Greenhouse Plant Production Journal*. 2024;1(2):35-50.
9. Bagagiolo G, Matranga G, Cavallo E, Pampuro N. Greenhouse robots: Ultimate solutions to improve automation in protected cropping systems-a review. *Sustainability*. 2022;14(11):6436.
10. Bicomumakuba E, Habineza E, Reza MN, Chung SO. IoT-enabled LoRaWAN gateway for monitoring and predicting spatial environmental parameters in smart greenhouses: A review. *Precision Agriculture Science and Technology*. 2025;7(1):28-46.
11. Cai S, Gou Z. Defining the energy role of buildings as flexumers: A review of definitions, technologies, and applications. *Energy and Buildings*. 2024;303:113821.
12. Comparetti A. Plants for Environmental Protection. In: *Encyclopedia of Digital Agricultural Technologies*. Cham: Springer International Publishing; 2023. p. 984-993.
13. Del-Coco M, Leo M, Carcagnì P. Machine learning for smart irrigation in agriculture: How far along are we?. *Information*. 2024;15(6):306.
14. Delfani P, Thuraga V, Banerjee B, Chawade A. Integrative approaches in modern agriculture: IoT, ML and AI for disease forecasting amidst climate change. *Precision Agriculture*. 2024;25(5):2589-2613.
15. Dhanasekar S. A comprehensive review on current issues and advancements of Internet of Things in precision agriculture. *Computer Science Review*. 2025;55:100694.
16. Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use. *Agricultural Water Management*. 2008.
17. Garcia LD, Lozoya C, Favela-Contreras A, Giorgi E. A comparative analysis between heuristic and data-driven water management control for precision agriculture irrigation. *Sustainability*. 2023;15(14):11337.
18. Gatkhal NR, Nalawade SM, Sahni RK, Bhanage GB, Walunj AA, Kadam PB, *et al.* Review of IoT and electronics enabled smart agriculture. *International Journal of Agricultural and Biological Engineering*. 2024;17(5):1-14.
19. Guo X, Jing G, Zhu S, Feng J, Huang D. Overexpression of PpmTERF18 enhances the antioxidant capacity of peach fruit to alleviate oxidative damage. *Scientia Horticulturae*. 2023;318:112123.
20. Hosny KM, El-Hady WM, Samy FM. Technologies, Protocols, and applications of Internet of Things in greenhouse Farming: A survey of recent advances. *Information Processing in Agriculture*. 2025;12(1):91-111.
21. Hosny KM, El-Hady WM, Samy FM. *Information Processing in Agriculture*. 2023.
22. Ingole MAR, Bijewar MAL, Javalagaddi MS, Jagadeeswari VV, Sangeetha MT. *Modern Trends in Floriculture*. Chyren Publication; 2025.
23. Javed MA, Murad MAA. Crop yield prediction in agriculture: A comprehensive review of machine learning and deep learning approaches, with insights for future research and sustainability. *Heliyon*. 2024;10(24).
24. Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*. 2019;90(1):1-16.
25. Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnline*. 2018;51(11):1016-1022.
26. Kuhmonen I, Kuhmonen T. Transitions through the dynamics of adaptive cycles: Evolution of the Finnish agrifood system. *Agricultural Systems*. 2023;206:103604.

27. Kumar A, Meena NK, Mazumder C, Rath P, Inamdar F, Singh A, *et al.* Application of artificial intelligence and machine learning in fruit crop management: A review. *Plant Archives*. 2026;26(1):823-830.
28. Kumar M. Role of Polyhouse Technology in Mitigating Climate Risks for Floriculture. *Shodh sari-an International Multidisciplinary Journal: International Council for Education Research and Training*. 2024;3(4):34-46.
29. Kwakye S, Kadyampakeni DM. Impact of deficit Irrigation on growth and water relations of HLB-affected citrus trees under greenhouse conditions. *Water*. 2023;15(11):2085.
30. Lea-Cox JD, Chappell M, Van Iersel MW. Wireless sensors networks for optimization of irrigation, production, and profit in ornamental production. In *International*. 2013.
31. Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant 1037 (pp. 643-649).
32. Liakos KG, Busato P, Moshou D, Pearson S, Bochtis D. Machine learning in agriculture: A review. *Sensors*. 2018;18(8):2674.
33. Liu H, Wu Y, Lu J, Gou T, Zhao S, Chen F, *et al.* Improving Growth Period Prediction of Greenhouse cut Chrysanthemum: Incorporating Precise Photo-thermal Effect and Multi-Model Ensemble Approaches. *Smart Agricultural Technology*. 2025;101685.
34. Mahmud MS, Zahid A, Das AK. Sensing and automation technologies for ornamental nursery crop production: current status and future prospects. *Sensors*. 2023;23(4):1818.
35. Mansoor S, Iqbal S, Popescu SM, Kim SL, Chung YS, Baek JH. Integration of smart sensors and IOT in precision agriculture: trends, challenges and future prospectives. *Frontiers in Plant Science*. 2025;16:1587869.
36. Maraveas C. Incorporating artificial intelligence technology in smart greenhouses: Current State of the Art. *Applied Sciences*. 2022;13(1):14.
37. Meena NK, Kumar A, Yadav V, Panigrahi S, Jaganathan T, Shekhar G, Narang ERH, Harendra. Emerging trends in precision horticulture integrating digital technologies for smart crop management. *International Journal of Advanced Biochemistry Research*. 2025;9(12):361-368.
38. Miller T, Mikiciuk G, Durlík I, Mikiciuk M, Łobodzińska A, Śnieg M. The IoT and AI in agriculture: The time is now A systematic review of smart sensing technologies. *Sensors*. 2025;25(12):3583.
39. Muhammed D, Ahvar E, Ahvar S, Trocan M, Montpetit MJ, Ehsani R. Artificial Intelligence of Things (AIoT) for smart agriculture: A review of architectures, technologies and solutions. *Journal of Network and Computer Applications*. 2024;228:103905.
40. Pascoal D, Silva N, Adão T, Lopes RD, Peres E, Morais R. A technical survey on practical applications and guidelines for IoT sensors in precision agriculture and viticulture. *Scientific Reports*. 2024;14(1):29793.
41. Rafi MSM, Behjati M, Rafsanjani AS. Reliable and cost-efficient IoT connectivity for smart agriculture: A comparative study of LPWAN, 5G, and hybrid connectivity models. In: *International Conference on Smart Computing and Informatics*; 2025 Apr; p. 389-411. Cham: Springer Nature Switzerland; 2025.
42. Rathor AS, Choudhury S, Sharma A, Nautiyal P, Shah G. Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review. *Heliyon*. 2024;10(15).
43. Sadik M, Abdelhadi E, Youssef M, Houda O, Samir E. Smart Greenhouses in the Era of IoT and AI: A Comprehensive Review of AI Applications, Spectral Sensing, Multimodal Data Fusion, and Intelligent Systems. *Agriculture*. 2026;16(7):761.
44. Saini AK, Yadav AK. A Comprehensive review on technological breakthroughs in precision agriculture: IoT and emerging data analytics. *European Journal of Agronomy*. 2025;163:127440.
45. Shamshiri R, Kalantari F, Ting KC, Thorp KR, Hameed IA, Weltzien C, *et al.* Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*. 2018;11(1):1-22.
46. Singh H, Singh T, Sood Y. Smart Floriculture: Emerging Technologies and Future Prospects. *Journal of Experimental Agriculture International*. 2025;47(2):172-181.
47. Slathia D, Nisa MU, Reshi M, Dolkar T, Hussain S. Protected cultivation of ornamentals. *Global Journal of Bio-Science and Biotechnology*. 2018;7(2):302-311.
48. Soussi A, Zero E, Ouammi A, Zejli D, Zahmoun S, Sacile R. Smart greenhouse farming: a review towards near zero energy consumption. *Discover Cities*. 2025;2(1):55.
49. Soussi A, Zero E, Sacile R, Trincherio D, Fossa M. Smart sensors and smart data for precision agriculture: a review. *Sensors*. 2024;24(8):2647.
50. Srivani P, Yamuna DCR, Niranjan A. Monitoring environment parameters of Gerbera flower cultivation in greenhouse using Internet of Things. *Indian J. Sci. Technol*. 2022;15(46):2527-2533.
51. Vakhnovskiy A. IOGRUCloud: A scalable AI-driven IoT platform for climate control in controlled environment agriculture. *arXiv preprint arXiv:2604.07586*; 2026.
52. Wani MA, Din A, Nazki IT, Rehman TU, Al-Khayri JM, Jain SM, *et al.* Navigating the future: exploring technological advancements and emerging trends in the sustainable ornamental industry. *Frontiers in Environmental Science*. 2023;11:1188643.
53. Wheeler WD, Thomas P, van Iersel M, Chappell M. Implementation of sensorbased automated irrigation in commercial floriculture production: A case study. *HortTechnology*. 2018;28(6):719-727.
54. Wolfert S, Ge L, Verdouw C, Bogaardt MJ. Big data in smart farming—a review. *Agricultural systems*. 2017;153:69-80.
55. Yeptho KH, Kreditsu R, Rahman A, Hemanta L. Supply chain of cut flowers with special reference to north-eastern region (NER): A case study. *International Journal*. 2025;9(2):269-282.
56. Yue Z, Meng L, Mu Y, Baležentis T, Shen Z. Does foreign direct investment promote environmental performance: an investigation on shadow prices of pollutants. *Journal of Cleaner Production*. 2023;387:135914.
57. Zheng Y, Fields JS, Bragg N, Caron J, Michel JC, Zaccheo P, *et al.* *Advances in horticultural soilless culture (Vol. 94)*. Burleigh Dodds Science Publishing; 2021.