

AI-based modules for vertical farming and protected cultivation of horticultural crops

The rapid advancements in Artificial Intelligence (AI) have significantly transformed traditional horticultural practices, particularly in vertical gardening and protected cultivation. As urban population increase, the demand for sustainable and space-efficient farming methods have intensified. Vertical farming and protected cultivation (like greenhouses and polyhouses) offer solutions by maximizing space and controlling environmental variables, respectively. However, achieving optimal results require precise management of resources, plant health, and environmental conditions. AI-driven systems offer a data-centric approach to address these challenges, making farming more productive, efficient, and sustainable. This article describes the role of AI modules in vertical farming and protected cultivation, examining how these technologies reduce resource usage, improve crop yields and enhance overall farming efficiency.

Vertical farming: AI's role in transforming urban farming

Vertical farming refers to the practice of growing plants in vertically stacked layers, often in urban settings with a limited space. Vertical farming systems can be established indoors within a controlled open environment, enabling the cultivation of vegetables and fruits across different agro-climatic zones as well as round the year availability. Due to urbanization, vertical farming is increasingly seen as a viable solution to urban food production coupled with safe produce and ensured supply. The integration of AI into vertical farming has revolutionized how crops are grown under intensive systems and maintained, offering more precision and control at every stage of the growth process.

Key AI modules for vertical farming

Artificial intelligence methods combine the processing of big data collected by IoT systems, the use of machine/deep learning in different vertical irrigation scenarios, as well as for yield predictions, monitoring growth and disease, and assessing sample quality.

Precision farming

Technologies like AI enables precision farming, where plants are precisely monitored through real-time data collection and analysis. AI algorithms determine the precise amount of water, nutrients, and light required for optimal growth. This level of precision minimizes resource wastage and ensures that crops receive the ideal conditions precisely for their ideal growth and development.

Data-Driven decision making

Automated growth monitoring: In vertical farming systems, crops are often grown in compact, controlled environments where traditional methods of monitoring are inefficient. AI-powered cameras and sensors installed in vertical gardens collect real-time data about plant growth. These systems utilize image recognition software to analyze plant health and development by identifying factors such as leaf colour, texture, and growth patterns. AI algorithms compare this data with predefined healthy plant models, detecting early symptoms of diseases, nutrient deficiencies, or pest infestations. For example, yellowing leaves may indicate a nitrogen deficiency, while brown spots might signify fungal infections. AI can quickly identify such issues and recommend interventions, minimizing crop losses.

Predictive crop modelling: AI-driven predictive models can simulate and optimize crop growth by analyzing large datasets, including historical data on plant performance, environmental conditions, and management practices. These models predict the ideal times for planting, pruning, and harvesting, based on specific crop requirements and current environmental conditions like light, temperature, and humidity. The goal is to maximize yields by adjusting growth schedules and managing environmental factors for individual crop. For example, leafy greens may require different light intensity than fruiting plants, and AI models can adjust light exposure accordingly.

Water and nutrient management: AI modules designed for irrigation and fertigation management are equipped with moisture sensors that monitor the water levels in the growing medium. These AI systems use machine learning

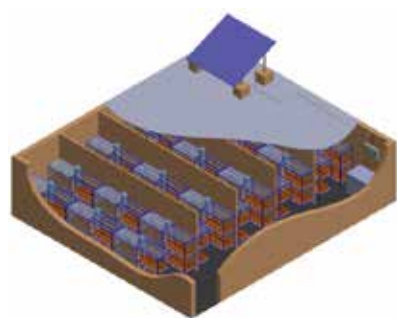
algorithms to assess plant water needs based on factors such as growth stage, temperature, humidity, and soil moisture levels. The system adapts irrigation schedules in real-time, ensuring that plants receive the optimal amount of water and nutrients, preventing both overwatering and nutrient leaching. Furthermore, AI-integrated fertigation systems deliver precise doses of nutrients, adjusting nutrient composition based on the plant's growth stage and nutrient uptake rates, thereby improving nutrient-use efficiency.

Climate control automation: Vertical farming systems are highly dependent on controlled environments to achieve consistent results, especially when growing crops year-round. AI modules automate climate control systems, managing variables like temperature, humidity, light intensity and CO₂ levels. Machine learning algorithms analyze environmental data to continuously adjust these factors, ensuring that each plant receives optimal conditions for growth. For instance, AI systems can increase light exposure during low-sunlight days or reduce humidity levels to prevent fungal outbreaks.

Automation and robotics: AI-driven automation and robotics are transforming cultural practices under protected cultivation. With capabilities like autonomous planting and harvesting, as well as intelligent sorting and packaging, AI-powered machines can perform repetitive tasks with accuracy and efficiency resulting in reduced labour costs and enhancing productivity.

Indoor vertical farming

ICAR-Indian Institute of Horticultural Research, Bengaluru designed and developed an indoor crop growing system with vertical farming approach. The plants were grown in plastic plant containers which were placed on mild steel structures. The structure was a two-tier system with 450 mm distance between these tiers for convenient crop management. Light-emitting diode (LED) lights were used as light source. Lettuce seedlings were transplanted to plastic plant containers filled with Arka Fermented Cocopeat and crop was raised with recommended nutrient (*Arka Sasya Poshak Ras*) schedule. The experimental results gave encouraging crop growth. Further, the experiment has the AI application in terms of irrigation, fertilizer application, crop protection, micro-climate data recording and photoperiod control data through temperature, relative humidity, light, chlorophyll meter sensors, etc.



Indoor crop growing system



Multitier indoor lettuce cultivation system with artificial lighting

Protected cultivation (Optimizing controlled environments)

Protected cultivation, which includes the use of greenhouses, polyhouses, and net houses, allows for controlled environmental conditions that can shield crops from external threats such as extreme weather, pests, and diseases. However, managing these environments effectively require sophisticated monitoring and control systems. AI technologies in protected cultivation optimize the use of resources and ensure that plants thrive better under controlled conditions.

Key AI modules

Precise environmental control: In greenhouses and polyhouses, temperature, humidity, CO₂ concentration, and light exposure must be precisely regulated to create ideal conditions for crop growth. AI-based systems equipped with sensors monitor these environmental parameters and use predictive algorithms to adjust climate control systems (heating, cooling, ventilation and lighting). By analyzing weather forecasts and real-time sensor data, AI modules can predict how external conditions will impact the greenhouse environment and adjust accordingly thus maintaining optimal growing conditions. This ensures efficient energy use while maintaining high productivity levels.

AI-driven disease and pest detection: AI-enabled computer vision systems can identify early signs of pests and diseases in crops. Using high-resolution cameras and deep learning algorithms, these systems can scan leaves and stems for abnormalities that indicate the presence of pests or diseases, such as discolouration, spots or deformation. AI models trained on thousands of images can accurately identify specific pathogens or pests, enabling early interventions that reduce the need for chemical pesticides. For instance, detecting aphid infestations early can prevent the spread of the pests without resorting to broad-spectrum pesticides.

Automated pollination with AI: In protected cultivation, where natural pollinators like bees may be absent, AI-driven robots or drones can facilitate effective pollination. These devices use computer vision and AI to detect flowers ready for pollination and mimic the action of natural pollinators. For instance, small drones equipped with soft brushes can gently transfer pollen between flowers, increasing the likelihood of fruit set in crops like tomatoes or cucumbers, which rely on precise pollination for yield.

Smart fertilization and irrigation: AI modules are also used in fertigation systems to optimize the delivery of nutrients and water. Sensors in the soil or artificial growing medium provide real-time data on nutrient levels and water content. AI algorithms analyze this data alongside environmental conditions to determine the exact amount of water and nutrients required by the plants. This ensures that each plant receives what it needs for growth without excess water or fertilizers, which can lead to wastage or nutrient runoff. This precision improves crop yields, while reducing resource consumption and minimizing the environmental impact.

Advantages of AI in vertical farming and protected cultivation

Increased resource efficiency: One of the most significant benefits of AI in these systems is resource efficiency. AI modules optimize water usage by ensuring that irrigation occurs only when plants need it, reducing water consumption by as much as 40%. Similarly, AI-driven fertigation systems ensure that plants receive the exact amount of nutrients required at specific crop growth stage, minimizing waste and improving nutrient uptake and their use efficiency.

Higher yields and better quality: By continuously adjusting environmental factors such as light, temperature, and nutrient delivery, AI systems can create optimal growth conditions for crops, leading to higher yields, productivity and improved crop quality. AI's ability to predict and prevent stress factors (such as pests, diseases, moisture deficiency and nutrient imbalances) ensures that plants remain healthy, which directly contributes to better yields.

Labour savings: Automation through AI reduces the need for manual labour, particularly in tasks like monitoring, irrigation, fertigation, and climate control. With AI handling these aspects, growers can focus on more strategic tasks, reducing operational costs and making farming more scalable. In large-scale vertical gardens or greenhouses, this can significantly lower the labour costs.

Early detection and prevention of stresses: AI's ability to process and analyze large amounts of data allows for early detection of stresses, such as diseases,

pests, or nutrient deficiencies. This early detection is critical for preventing crop loss and ensuring that interventions are applied in a timely and efficient manner. For example, detecting powdery mildew early in a greenhouse can prevent the spread of the disease, protecting yields and reducing the need for chemical fungicides.

Challenges and Future prospects

While AI technologies offer enormous potential, some challenges remain. The initial investment in AI-based plant production systems can be high, particularly for small-scale farmers. Additionally, the use of AI requires specialized knowledge to interpret the data and manage the systems effectively. Data security and privacy concerns, especially in large-scale operations, where AI systems rely on cloud computing, are also emerging challenges.

However, the future of AI application in vertical farming and protected cultivation looks promising. As the AI technology becomes more affordable and user-friendly, its adoption is likely to increase. In the coming years, advancements in AI-powered robotics, drones, and machine learning models will make these systems more autonomous and scalable. The integration of AI with other technologies like the Internet of Things (IoT) and big data analytics will further enhance precision in agriculture, allowing farmers to manage crops with unprecedented accuracy.

SUMMARY

AI-based modules are transforming vertical farming and protected cultivation technologies by making these systems more efficient, productive, and sustainable. Intention of using automated systems is to maximize the yield per unit area with least human interventions. Inputs should be delivered to plants with utmost care by using sensors. Sensors can be utilized for collecting real time data for monitoring the environmental parameters and substrate parameters for precise provision of lighting in grow light system. LED lightings have careful adjustments to different wavelengths, which is directly related to better growth and hence this is one of the most innovative inventions in the field of vertical farming. Automation helps to eliminate the levels of labour and risk of human faults for precise vertical farming. Artificial intelligence (AI) could be integrated in vertical farming for various activities like crop and substrate monitoring, pest and disease detection, spraying of nutrients and PP chemicals, harvesting, grading, sorting etc. Introgression of AI would further improve the nutrient and water-use efficiency, product quality and yield, and can help in accomplishing the goal of maximising crop production and enhanced livelihood.

For further interaction, please write to:

Dr G. Senthil Kumar (Principal Scientist), ICAR-Indian Institute of Horticultural Research, Hesaraghatta Lake, Bengaluru, Karnataka 560 089. *Corresponding author: senthilkumaran.g@icar.gov.in



Vertical farming – Leafy vegetable cultivation



Vertical farming – Flower crop cultivation



Vertical farming – Foliage cultivation



Low-cost homestead vertical garden