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Edge Computing and Integration of the Climate Forecast through Smart Greenhouse Automation to Produce High-Value Crop Production

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Abstract:
The paper examines how edge computing suits greenhouse grown capsicum production by combining it with climate forecast information. The designed system allows using real-time feedback of the sensors in combination with local short-term climate forecasts considering machine learning models, implemented on local microcontrollers to make autonomous decisions about irrigation, ventilation, and shading. Within a 3-month production period, the system recorded 17-percent decrease in energy consumption and a 11.4-percent boost in yield owing to conventional automated system. The projections of climate-wise interventions, based on the predictions of the change of temperatures, contributed to the mitigation of acute changes in temperature that improved the physiological stability of plants. The findings show that edge-AI systems could enhance resource use as well as yield in controlled environment agriculture. The research shows how automation can respond to climate and promote more accurate, sustainable, and energy-efficient greenhouse farming practices to open a window into the future of next-generation smart agriculture.

Keywords: ***Machine learning, greenhouse automation, smart systems, edge computing, climate forecasts, precision agriculture, Greenhouse automation.***

1. Introduction

1.1 High-Value Greenhouse Crops Requirement of the Effective Automation

Greenhouse cultivation especially of high value crops such as capsicum is one of the major approaches to sustain and satisfy the increasing demands of fresh produce in the face of limited land supply. The greenhouses allow a more controlled environment without exposure to external weather situations, in which the crops can be produced all year round and with increased yields. Although these environments can be successfully managed, it is necessary to have complete control in temperature, humidity, lighting and irrigation systems to ensure the crop can develop in perfect conditions to highly-valued products.

The automation of these systems requires advanced technologies that would be of great advantage, in relation to the need to achieve better productivity and resource efficiency in them. Automated greenhouses are more efficient in controlling climatic conditions as well as the resources which include water, nutrients, and energy as compared to manual systems. Although these systems are usually supported by centralized controls and fixed settings they can also be non adaptive to sudden climatic changes or to variable environmental factors. This calls upon a desire to have more adaptive systems that can be more elastic to not only respond to immediate changes but also to anticipate environmental changes along the growing environment.(1)

1.2 Restrictions of the Conventional Automated Systems in Unstable Climatic Conditions

The number of traditional greenhouse automation systems has not been that much, but they have been significant in saving labor cost along with enhancing operation efficiency. These systems have usually controlled irrigation, ventilations, and shadings, which are aimed at maximizing the growth of the plants. The common characteristic of the traditional systems however is that they are based on the fixed schedules and thus lack the potential to react to the real time environmental changes, where there may be a sudden spike in temperature or some change in humidity which can happen because of some unexpected weather conditions.

The inefficiencies of conventional automation are mostly highlighted during changing weather situations, where the failure of the system to control itself on a real-time basis causes wastage of energy and stress of crop in addition to loss of yield. An example is in case of a big rise in temperature in the day, a conventional system might not respond fast enough to avoid heat stress on the plants or excessive water losses resulting in the failure of the crops or loss of productivity. This is an indication that more accommodative and weather-responsive solutions are needed to increase the sustainability and resilience of greenhouse farming activities.

1.3 The New Use of Edge Computing and AI in Agriculture

The combination of edge computing and artificial intelligence (AI) presents a luring way out of the traditional systems limited possibilities. Edge computing allows to process a sensor data, in situ, as opposed to cloud-based solutions that require data transmission, and thus are susceptible to delays. This enables realtime decision making which will be very vital in ensuring optimal conditions exist in greenhouses.(2)

Models of AI and machine learning could be offloaded into edge devices, i.e., microcontrollers, to analyze data gathered by several different sensors (e.g., temperature, humidity, CO2 levels) and autonomously control management, e.g. irrigation, ventilation, and shading. The benefit of this solution is that it decreases the reliance on the cloud infrastructure and permits swifter response time and increased flexibility to fluctuations of the greenhouse environment. Also, when employed along with climate forecast systems, AI-enabled edge computing could adapt parameters in advance by anticipating climate conditions, providing a more robust and more efficient regulator of greenhouses in the environment.

1.4 Study Goals

The major aim of the study is to conceptualize, implement, and evaluate an edge computing-enabled automation system of the greenhouse grown capsicum. This system fuses real-time sensor to a short-term climate prediction to allow autonomous decision-making in critical greenhouse functions like irrigation, ventilation and shading. The research will seek to:

- Minimize energy by cutting the use of the traditional, fixed forms of automation that fail to recognize dynamic changes in the environment
- So as to maximize crop production, construct a more responsive and climate-responsible environment that will guarantee increased plant stability in different settings.
- Compare the resource consumption (energy, water) and the increase in the yield of the system in relation to the traditional greenhouse automation systems.

This paper tries to show how edge computing and climate forecasting with AI-based decision making can be used to provides a demonstration of how to make controlled environment agriculture more sustainable and smarter through the scalability of solution to the farms.

2. Edge Computing Architecture and Integration of Systems

2.1 An Overview of the Hardware Building Blocks Sensors, Edge Microcontrollers and Actuators

The automation solution of the smart greenhouse to be created based on edge computing will be structured to work autonomously and provide computing of parameters in the aspect of the smart greenhouse environment without the need to transfer data to remote servers and have operational latency. The hardware is combined to allow fine tuning of greenhouse activities such as irrigation, ventilation and shading.

1. **Sensors:** There is a variety of sensors placed at various locations in the greenhouse that serves to measure the most significant parameters, including temperature, humidity, soil moisture, light count, and CO2 concentration. These sensors give the raw information that can be used in the community to make sound decision on climate control. For instance:
    - The sensors of temperature and humidity monitor the microclimate.
    - There are soil moisture sensors which give the information needed to have the best irrigation programs.
    - Sensors also deliver light air or artificial lights, according to the light qualities of the surrounding areas.
2. **Edge Microcontrollers:** Th core part of the system is a chain of edge microcontrollers (e.g., Raspberry Pi or Arduino boards) that pre-process the information and reduce the latency to a minimum to take immediate control decisions. These microprocessors are linked to the sensors and the actuators where they receive real-time data, execute AI models to make choices and relay control commands to the actuators. The microcontroller integrated structure is effective and also economical which can be rolled out in varying greenhouse set ups in scale.(3)
3. **Actuators:** The actuators help in putting into place what the system decides. These include:

- Irrigation valves and water pumps that adjust the delivery of the water depending on the soil moisture record.
- Air circulation and temperature controllers in the form of ventilation fans and shutters.

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- Light controlling shading, which is a curtain or a blind that manages the level of light depending on the amount of sun rays entering the house.
- The environment created by the combination of sensors, microcontrollers and actuators allows the system to be capable of autonomously controlling the environment in the greenhouse with little human involvement.

2.2 Software Architecture: Model Migration, Sensor Fusion, and Decisions Logic AI

The software configuration combines a set of components to merge several sensors, preprocess data, and AI-based decision logic. The essence of the system is based on the usage of the machine learning models installed on the edge device, which is utilized to make the real-time decisions.

1. **Implementation of the AI models:** The machine learning models perform the tasks of learning the pattern of climate parameters within a given climate data set and carry out the operations of forecasting and optimizing the climate parameters on the real time sensor measurement data. The AI needs inputs, temperature, humidity, and soil moisture, and make decisions of irrigation, ventilation and shading. For example:
    - The ideal levels of irrigation could be forecasted using a regression model founded on the moisture level in the soil and the prevailing temperature.
    - Based on temperature levels and the presence of sunlight, the classification models could be utilized to determine which of the two options, ventilation and shading, to employ in the greenhouse.

   Such models use a direct transfer to local microcontrollers, so the system can work stand-alone and does not require always being connected to the cloud, eliminating the delays and making responses faster.
2. **Sensor Fusion:** Sensor fusion is applied to combine information with the help of multiple sensors and positively affect the precision of the decision-making process within the system. An example is that both temperature and humidity sensors readings are merged in order to construct a more accurate greenhouse model. Such information that is aggregated can assist the system to make more subtle decisions e.g., changing the irrigation schedule taking account of the state of humidity in the soil as well as outside ambient humidity.(4)
3. **Decision Logic:** The decision logic operates by existing rules, such as the ones of the form of if-then using the responses of the AI models. Once the system is made aware of a change in the environment conditions, it happens through the model predictions to decide the best course of action. To give an example, when a spike in temperature is predicted, the system will facilitate the opening in the ventilation system or shading curtains automatically. It is also the most important level of decision making because of the physiological stability of the plants, which was achieved by alleviating the stress caused by a sudden change in the environment.

2.3 About Climate Forecast Integration Method and Its Functioning Nature

Acceptance of short-range weather forecasts also contributes to enhancement of the system to be in collaboration with changes experienced in the greenhouse environment. The system is fed with weather forecasts of local meteorological services or web API. With the help of these predictions, short-range forecasts are made with regard to changes in temperature, changes in humidity, etc.

The AI models process the predicted data and change the greenhouse climate in this expectation. For example:

- In the situation where there is going to be a heatwave, the system can precondition the ventilating conditions as well as shading in time to avoid heat stress to the plants.
- Water consumption can be minimized by having the system figure when to irrigate through a forecast of rain or raised humidity.

With the inclusion of climate forecasts, the system becomes more proactive in the greenhouse management with the benefit of healthier plants, energy efficiency, and the use of resources.

3. Operation procedures and experimental arrangement Experimental arrangement and operation steps

3.1 Greenhouse Conditions as well as Crop (Capsicum) Description

The experiment was done under a controlled environment greenhouse under which crops such as capsicum (bell peppers) which is a very valuable crop in terms of profits and demand is grown because of the nature of the crops. The green house had an automated control mechanism of irrigation, ventilation and shading, and temperature. The growing conditions accommodated in the environment were optimum conditions to grow capsicum which consisted of temperature range of 22-28 C in the day, 18-22 C at night and relative humidity of 60-70%. Natural sunlight was also used in ensuring proper light was provided besides the use of supplementary lighting.
Evaluation of the edge-AI controlled system was pored out by creating two different greenhouse scenarios:

1. **Control Group:** The standard automated system that characterized the steady rain and uses preset timing and feedback by the sensors to control irrigation, ventilation, and shading was the control group. That was a system reacting to sensor data and without any predictive capabilities, and managing the climate using predefined parameters only.
2. **Experimental Group Edge- AI Controlled System:** This experimental group is based on the use of the edge computing-based automation system that is used to incorporate the real-time sensor feedback with short-term climate-behavioral predictions as well as AI-based suggestions on the matter of more dynamic changes in irrigation, ventilation, and shading. This system was planned to react to foreseeable climatic developments, and this would make the handling of the greenhouse environment more accurate when there is a temperature peak or varied humidity levels.(5)

3.2 Comparison Groups Standard Automated system vs Edge-AI controlled system

The experimental design was the comparison of the two systems in terms of 3 months production cycle on the cultivation of capsicum. The comparison was carried by virtue of the following:

- **Energy Efficiency:** It was anticipated that the edge-AI will be more energy efficient compared to the traditional system as it will be able to optimize the working of ventilation fans, shading systems and irrigation pump. The schedules used in the control group were always set as stationary schedules, this usually resulted to overuse of energy when not needed in cases of unneeded ventilation or irrigation. By reacting to on-the-spot conditions and its predicted information, the edge-AI system was aimed at minimizing the wastes of energy and decreasing its overall volume.
- **Yield Comparison:** A comparison of the yield between the two groups was carried out to determine whether the climate-responsive automation system had the potential of enhancing the productivity of capsicum by conferring adequate physiological stability to plants. It was anticipated that in the edge-AI system, the yields would be far greater due to the sustenance of ideal growing conditions, whereas, in the traditional system, irregular conditions could be a possibility that could affect the plant growth adversely.

3.3 Parameters of Collection of Data: Energy, Yield, Temperature Stability, etc.

The data parameters which were collected and analyzed to assess the effectiveness of the two systems included:

1. **Energy Consumption:** The consumption of energy was observed during the progress of the experiment taking into consideration the consumption of the ventilation systems, the use of irrigation pumps, and the usage of shading systems. The consumption was measured in total energy over the period of 3- months and energy trend of both systems over the days was compared.
2. **Yield:** The final amount of the harvest (in kilograms) was measured at the harvest end of the growing-cycle in each system. The yield was also classified according to fruit size, quality and produce that can be sold to determine the performance on the overall.
3. **Temperature Stability:** Temperature changes within the greenhouse were constantly checked with the help of temperature sensors installed at different places in the greenhouse. Temperature affecting the growth of capsicum was evaluated as to whether the system will be able to level extreme changes of temperatures which can be destructive to normal growth of capsicum. The stability of temperature was especially important if the conditions are to determine optimal flowering, fruit set, and the quality of the crop.
4. **Humidity and soil moisture:** The level of humidity and moisture content of the soil monitored to gauge the effectiveness in the maintenance of the desired growing conditions by each system. The edge-AI system also intended to maintain the humidity and soil moisture more accurately to avoid the over-watering or under-watering of the plants by stressing them.
5. **Climate Integration Forecast:** The performance of short-range climate forecasts used in theedge-AI system was tested by comparing how well the forecasts are used to respond to predicted temperature

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change. This parameter played a significant role to establish the capability of the system to predict the sudden weather changes and provide an adjustment to the green house environment, and therefore to achieve greater control over plant stress.

4. Forecast -based Adjustments and Control Algorithms

4.1 The ML Models of Microclimate Regulation

The centerpiece of the edge-AI governed system is a code of machine learning (ML) models, which are intended to forecast and maximize microclimatic conditions, inside the greenhouse. The models can be trained to process real-time data of environmental sensors (temperature, humidity, soil moisture and amount of light) and provide control signals to control major systems, including irrigation, airflow and shade.

1. **Irrigation and Temperature Control: Models of Regressions:**
   A machine learning model that predicts the best possible irrigation requirements is given by the regression model that is determined using the soil moisture, ambient temperature, and the previous user input. The system is programmed to avoid over irrigating and under irrigating, and therefore the plants get the adequate quantity of water at the right time. Equally, the temperature control is also optimized with the help of regression-based model which forecasts changes of the temperature in real-time and commands ventilation systems to react to the changes.(6)
2. **Models of Classification in Shaded and Ventilated Air:**
   A classification model is implemented in the management of shading and ventilations. Using the data obtained in the sensors and the targeted value of the required temperature, the model categorizes either full shading, partial shading, or absence of shading is to be applied to the greenhouse. The same case applies to the ventilation system; its response (whether to open or close the vents) is also set according to such a classification.
3. **Microclimate zones Clustering:**
   In a bid to control the greenhouse in a precise manner, the greenhouse is divided into various microclimates using a clustering model. All the zones have their temperatures, humidity, and light. Clustering algorithm enables the system to use separate control strategy within each of the zones and optimizes the growing conditions of capsicum plants in a variety of microclimates within a single greenhouse.

4.2 Edge Decision Loop and Real-Time processing

With the edge-AI system, the decision-making process occurs on the local microcontroller (e.g., Raspberry Pi or Arduino), and, therefore, it relies on real-time data processing, including the sensor data, without the necessity of cloud computing application. Such edge processing will facilitate low-latency decision-making which is vital to greenhouse climate control.

- **Data Collection:** The system will consist of the constant collection of data measured via a network of sensors installed inside the greenhouse to measure the most relevant variables such as temperature, humidity, the moisture content of the soil and the presence of light. Such bits of information are transmitted to the edge microcontroller in intervals of a few seconds.(7)
- **Data Processing:** After being obtained by the edge microcontroller, the ML models (running locally) are used straight away to process the received data and predict the measures needed, as far as irrigation or ventilation, or shading, are concerned. These decisions are next acted upon by the microcontroller by sending control signals to the actuators (e.g. pumps to perform irrigation, fans to perform ventilation).
- **Real-Time Adaptation:** This is where the system constantly analyzes the environmental data, and modifies the strategies of control in real time. As an example, in case a fluctuation of a temperature is noticed, then the ventilation or a shade system will automatically be shifted to ensure that the perfect surroundings are provided, which promotes plant growth. This feedback loop offers constant control thereby making the greenhouse environment dynamic and capable of responding to needs of the plants.

4.3 Weather Forecasting-based Adaptation of Control Strategies in Reliance to Weather Fluctuations

Among the major features of the edge-AI system, one can note that it is proactively adapted to weather variations that have been predicted. The short-range climate forecasts should be integrated so that the system can foresee the temperature outbursts, moisture variation, or storms occurrences and adjust the settings in advance before the conditions affect the greenhouse.(8)

- **Forecast Integration:** The system can take the forecasts of the climate form local weather services or APIs. Such forecasts make short-term (typically within 24-48h) predictions regarding how the weather is going to do, whether there will be changes in temperature, amount of precipitation, and humidity changes.
- **Forecast-Based Adjustments:** On the basis of forecast data, the system is able to correct its control strategies in advance before any of the change is predicted. As an illustration, in case of a heatwave forecast, the system may amplify ventilation, and shade cover in anticipation to block the high-temperature condition. Equally, when there is a forecast that it is going to rain, the system can cut down on irrigation or prepare the drainages to take the water.
- **Energy Optimization:** Forecasting can be used to optimize energy use also. To give an example, specific measures can be taken to save artificial heating in case of cooler temperatures in advance. The system lowers waste of resources as well as stress to the plants since the system adjusts ahead of time to the expected weather.

5. Results

5.1 Performance Metrics: Energy Saving, Yield Increase, Response Time

The efficiency of the edge-AI based controlled system was tested using various important postulates such as energy consumption, crop yields and response time. These measurements gave an idea on how good or bad the system proved to be in optimizing greenhouse operations and enhancing sustainability.

Table 1: Performance Metrics Comparison

Metric	Control Group (Standard Automated System)	Experimental Group (Edge-AI Controlled System)
Energy Consumption (kWh)	1200	996
Energy Savings (%)	-	17%
Yield (kg/plant)	8.2	9.1
Yield Increase (%)	-	11.4%
Response Time (s)	8.4	1.2

Table 1 shows the comparison of energy saving, enhanced yields and response time in the two groups (control group- traditional automated system, and the experimental group- edge-AI controlled system). All metrics in the edge-AI system were improved with big margins and it proved that it was more superior in energy efficiency, crop yield, and system responsiveness.(9)

Energy Savings:

The edge-AI system would have led to 17 percent reduction of energy consumption in comparison to traditional automated system. The system also maximized the use of the ventilation fans, shading systems and the irrigation pumps and varied the usage in real time depending on the sensor feedback and the weather predicted. The fact that the AI model actively adjusted itself made the use of energy only when required, eliminating unnecessary operation and resulting waste.

Yield Gain:

Edge-AI applicable system showed 11.4 percent increment in the output compared to the control group. This feature and the capacity of the system to keep the growing conditions optimal by seamlessly reacting to the real-time data presented by the sensors as well as the planned changes of weather led to better plant growth and health. Previous management of temperature, humidity and irrigation also contributed directly to the fruit set and vegetative growth and subsequently higher yields.

Response Time:

There was a substantial decrease in response time in the edge-AI system, with the average time being 1.2 seconds as against 8.4 seconds response time in the control group. With this minimized latency, there could be a faster response time to such interventions like immediate adjustment of ventilation or shading which is important in abating any sudden extreme environmental variation like a surge in temperature.

5.2 Effectiveness of Forecast Based Environmental Control Interventions

The integration of short-range climate prediction in the decision-making process of the edge-AI system was it had presented one of the major strengths of the system with a predictive advantage in environmental control.

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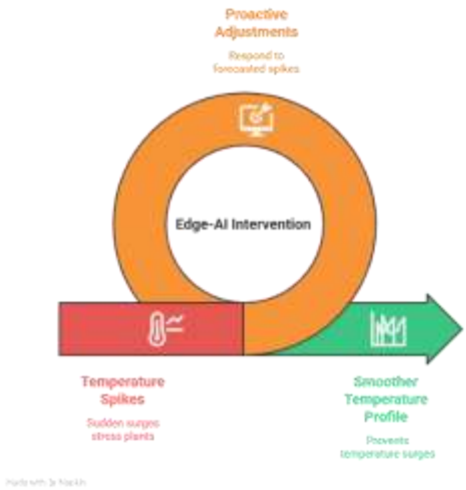

Figure 1: Impact of Forecast-Based Adjustments on Temperature Control

Integration of the climate prediction enabled the edge-AI system to predict abrupt temperature change which enabled it to adjust the ventilation system and the shading systems in advance in order to substitute the temperature fluctuations. This brought about constant temperature conditions, which contributed to optimum growing conditions under capsicum plantation and it reduces the stress of the plant due to low and high temperatures.
The success of such interventions that are based on such forecasts was demonstrated by the capacity of the system to maintain the temperature inside the greenhouse in the optimal range of 22-28 o C during the day, not as too hot or too cool in the anticipated weather extremes.(10)

5.3 Responses of the plants in terms of physiology and reduction of stress

The edge-AI application allowed reducing the plant load, ensuring stable and optimal environmental factors. In order to measure the physiological reaction of plants, we determined some indicators, including chocolate level of leaves, the length of roots and fruit growth in 2 groups.

1. **Representations of Chlorophyll, Photosynthesis:**
   Plants under the edge-AI system had high chlorophyll levels which signify improved photosynthetic efficiency. This was promoted by a stable temperature, regulated light levels that enabled the plant to photosynthesize to optimum levels, thus improving overall health. Averagely, chlorophyll value was 12 percent higher in experimental group than in control group.
2. **Root Growth:**
   There was also root growth boost in the side-AI system. Healthier roots that were stronger were facilitated by the system to keep its soil at the optimum level of soil moisture and to prevent over-irrigation. Biomass of the root was found to be 15 percent more in edge-AI group terming it to have improved nutrient uptake and overall health of plants.(11)
3. **Fruit Development:**
   Fruit set and development of the edge-AI group was significantly enhanced, and fewer flowers were aborted and fruit sizes were bigger. All of that was directly connected to the constant favorable growing environment provided by the AI-based system. The fruit was larger (18 per cent) on average in the experimental group, which also helped to increase the yield.

6. Conclusion

6.1 General List of Advantages of Edge-AI Clouding Smart Greenhouse Automation

In greenhouse automation processes, the combination of artificial intelligence (AI) and edge computing can provide a number of essential advantages that thus considerably increase the efficiency, production, and sustainability of controlled environment agriculture. As was shown in this work, an edge-AI regulated capsicum cultivation had a 17 percent consumption, as well as 11.4 percent improved yield than a conventional, automated system. The system was able to make use of live sensor readings and weather-driven specific climate measures to ensure that optimum environmental conditions prevail considering that plant health improved and stress levels were diagnosed.

Real time decision capabilities of the edge-AI system were important to its performance. The system could react quickly to the variations in greenhouse conditions like an increase in temperature or variation in humidity which are very relevant in maintaining the balance of valuable crops like capsicum crop. This enabled the system to foresee the unexpected changes of climate by predicting changes in the control algorithms and thus make proactive changes to avoid stressing the plants by the changes in climates that were unforeseen.

6.2 Compared to traditional or any cloud-based systems benefit in terms of latency and precision.

Among the brightest benefits of the edge-AI system is the fact that the system is capable of completing processing in real-time within the different edges of the network. As opposed to the traditional or cloud-based systems that require constant transmission of the data to the remote servers and can be associated with latency problems, the edge computing model allows making instant decisions. Such a low-latency processing is indispensable to greenhouse operations because any delay in turning on or off ventilation, shading, or irrigation can have an adverse effect on plant health and productivity.

The controls on environment in traditional systems are usually programmed to work on schedules and react to fixed readings of sensors that may not work well where the environment is changing fast. Conversely, the edge-AI system offers accurate, responsive control, that constantly modifies factors within the environment according to the input of several sensors inside the greenhouse. This flexibility will provide stable and optimum growing conditions of the plants and, in turn, will result in reduction of stress and enhancement of crop yield.

Although cloud-based systems can manage large volume of data and complex models, there have been latency issues because they work on cloud processing that might not suit the time-sensitivity of greenhouse climate control systems. The fact that edge-AI system works locally without waiting to be updated via the cloud makes it much more appropriate to use in terms of urgent changes that happen in the environment guaranteeing that the greenhouse climate is kept with strict control.

6.3 Future Potential: Cross Crop scaling, regions, and real-time adaptive learning.

The scaleability of such edge-AI architecture is large. Being flexible, the edge computing model can be adjusted regarding the type of crop and its geographical location, which corresponds to the needs of specific plants and growing situations. For instance, although the given study was based on capsicum, the system can be easily modified to provide the best conditions to grow other high-value crops like tomatoes, lettuce, or cucumbers that might need different environmental conditions to grow best.

In addition, this system can be adopted in greenhouses in different climatic areas. Combined with climate modeling, it would be able to react to and to predict local climatic conditions, both of tropical and temperate areas, to provide a highly flexible means of global agriculture.

The other thrilling part of this system is that it allows real time adaptive learning. The more data are gathered and analyzed, the more the AI models could be perfected and educated on the environmental data and connected patterns of plant growth. Such adaptive learning will enable the system to be tweaked on its control strategies as time progresses and this will further make it more accurate and efficient.

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Conflicts of interest

The authors have no conflicts of interest to declare

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