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Real-Time Environmental Monitoring in Greenhouses Using IoT and Sensor Networks

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Abstract- In recent years, Internet of Things (IoT) has been widely applied in greenhouse control to realize intelligent automation and data-driven greenhouses. In IoT based greenhouse, the real time status of soil moisture content, air temperature & humidity and CO2 concentration is monitored and controlled using embedded system technologies (Arduino or Raspberry Pi) and wireless communication modules. Sensors, wireless technology and data analytics can be combined for real-time monitoring and marching orders so that the optimal conditions are met for growth and crop yield. Moreover, the use of artificial intelligence (AI) techniques (fuzzy logic, machine learning and bio-inspired algorithms) increases the flexibility of the platform, the ability of prediction and decision-making performance. These smart systems eliminate manual labour, process costs and resource waste with eco-friendly.

Keywords— IoT, Greenhouse Management, Arduino, ESP32, Raspberry Pi, Smart Agriculture, Sensors, Automation, Machine Learning, Fuzzy Logic, Real-Time Monitoring, Environmental Control, Precision Farming, Sustainable Agriculture.

I. INTRODUCTION

Greenhouse conditions are highly critical to control so as to optimise the growth of plants and their production [1]. Traditional approaches are man intensive and not necessarily able to deliver the best environment at all times [2]. To address these issues, a greenhouse monitoring model based on IoT is presented, which incorporates real-time measurements, smart control and predictive analytics [3]. The proposed model is a combination of microcontrollers, sensor networks and cloud platforms in automatic management of the environment [4]. The system will target monitoring the temperature, humidity, moisture of soil, light intensity and CO2 measurements as an area of concern [5]. Sensors are installed across the greenhouse and will never stop collecting data and transferring them to a centralized computer where they are then analyzed [6]. Due to such an analysis, the actuators control irrigation, ventilation and heating systems as well as lighting systems dynamically to optimize the conditions. Adoption of intelligent control algorithms (e.g., fuzzy logic and predictive machine learning) is one of the major elements of the model [7]. These algorithms allow the system to act and self-adjust in uncertain or time varying environmental conditions [8]. The solution analyzes both the historical and live information to make estimates of trends to enhance predictability to be proactive rather than be reactive. Efficiency in the utilization of resources is also included in the proposed model. Through the predictive models along with the real-time observation-based data is used to optimize the use of water, energy and nutrients to conserve cost of operation and reduce impact on the environment [9]. Precision Agriculture: Honold Precision Controls Helios system ensures that the resources will be applied at the point and time of necessity [10].

One of the most significant foundations of the human civilization has been and still is agriculture [11]. With the world population on the increase and the arable land diminishing, people are increasingly becoming desperate to enhance the productivity of agronomic methods that once served well are not fast enough to increase food production to the levels that are profitable and sustainable according to the present-day standards [12]. It is upon this backdrop that greenhouse farming is a new concept that has come up trying to defy the above-mentioned ideas by providing a controlled environment where crops can be grown [13]. It has given farmers control over conditions of temperature, humidity and light that is significant in the growth of the plant and its production. But when someone has to tune those parameters by hand is not effective and there is a room due to error-of-human [14]. To fill these gaps, IoT technology has been built upon the greenhouse management system in a gradual manner [15].

Environmental sensing systems are utilized in the Internet of Things (IoT) environment where they are typically stored as measurements of a high number of climate sensors associated with physical properties (temperature, humidity, soil moisture, CO2 and others) it is collected by them on a second-by-second basis over time [16]. These sensors are received and sent to the microcontrollers or gateways to be analyzed and processed [17]. The data of the greenhouse is normally transmitted in real time to cloud servers through certain communication technology (e.g. WIFI, zigbee, LoRa, GSM). The data stored on the cloud can be visualized and analyzed and model predictions made to enable the farmers make decisions on irrigation, ventilation and nutrient management [18]. The environmental conditions largely determine quality and plant growth since in an exemplary case, change in the optimal temperature and humidity may introduce stress to the plant leading to the deterioration of production. Consequently, such among other environmental statuses like relative humidity per crop will be real time monitored so that the environmental requirements of different crops in is are in the most favorable zone [19]. Distributed data collection in green houses with a large area is supported by IoT systems which are built on sensor network building blocks. These networks can be programmed to work without each other providing live and accurate information on a high number of zones in or between greenhouses [20]. The Greenhouse sensor networks have revolutionized the production and control of the agricultural data. Automated sensors may be monitored and give data in real-time compared to manual records that minimizes the potential loss of information and reliability of the system [21]. Green house monitoring systems based on IoT are not mere data collection systems. As an illustration, the sensor system can be used to define when the soil moisture has reduced to a predefined minimum point enough to automatically turn irrigation on. It is also able to manage fans, heaters or lights so that the optimal temperature could be maintained [22]. The human effort of IOT automation is reduced, and it also ensures that there is no partial control of the environment, which is important in commercial type agricultural farms [23]. Such precision in the indicates will save on water, fertilizers, and energy so that farming becomes a sustainable process [24]. Quick response to potential problems (pest invasion, equipment failure) is also possible with the help of real-time environmental surveillance. Broadly speaking, the farmers can identify the anomalies in their environmental data and respond to it before the situation deteriorates due to the widespread use of wireless sensor networks (WSNs) over the past few years. Sensors size reduction, improved battery life and development of low power communication protocols particularly have contributed immensely in order to render IoT pervasive in agriculture [25]. Another advantage that is involved in IoT monitoring systems is remote access. Smartphones or web dashboards enable farmers to know the performance of their greenhouses anywhere they are. This will be useful especially when a farmer is not in the farm or when a farmer is absent [26]. Data analytics and machine organizations add value to IoT ecosystems to transform unstructured sensor data into valuable information [27]. Models can forecast what the environment will be like and what is likely to be the best move like whether to irrigate or open the ventilation system to cool the building [28]. The IoT solution application in monitoring a green house also serves climate-smart agriculture, which is meant to increase production and decrease carbon foot print. IoT systems will help reduce waste and greenhouse gasses, energy consumption by maximising the utilisation of the available resources [29]. The obtained information also provides long-term benefits.

The historical environmental context may be incorporated to check the seasonality and crop performance to facilitate the further plan of cultivation in future which modifies the productivity [30]. To develop such systems, both hardware and software components must be properly designed and integrated under such systems [31]. Intercommunication and sync data of sensors, microcontrollers (e.g., Arduino or Raspberrypi), and cloud services (e.g. Thingspeak, AWS, or Blynk) should be programmed. Security and reliability are crucial elements that should be considered in IOT-based solutions [32]. Since the technology used in these applications is wireless and thus it is the foundation of these applications, decent data encryption and secure communication protocol cannot be afforded to protect it against cyber obstacles as well as to ensure record integrity [33]. These are some of the research works and pilot application works that have demonstrated the potential of IoT-enabled greenhouse monitoring [34]. The mentioned findings illustrate the possibility of IoT to transform the contemporary agriculture with grace in enhanced crop harvests, lowered running cost and optimal water management and chemical fertilizer saving [35]. To sum up, real-time environmental monitoring in green houses with the help of IoT and sensor networks is a significant step towards smarter and more sustainable agriculture [36]. Such technologies enable farmers to monitor some of the main conditions that include the temperature, humidity, and soil moisture constantly, enabling farmers to make the right decisions at the right time [37]. Having access to good real-time information, the farmers are able to optimize the crop yield, improve the quality of crops, and to maximize the use of water, energy and other resources [38]. Generally, this method not only minimizes the use of human hands and manpower but also promotes farm sustainability mechanisms, which is a good basis to the future of digital agriculture [39].

II. LITERATURE REVIEW

P. N. Khan et al. [1-5] dwells on the occurrence of integration of IoT-based automation systems in the greenhouse set ups through the use of Arduino technology. This theoretical basis is based on the control system theory, and cyber-physical integration, in which the continuous feedback of various sensors will guarantee proper regulation of the environment. The authors point out that the system of temperature, humidity, and soil moisture sensors can combine to provide real-time data, which can be precise in actuation and result in a stable microclimate condition to grow plants. The concept is used to substitute manual processes that happen to be prone to errors and require a lot of time. The design of the system is based on the concept of the closed-loop feedback control where the deviations of the desirable environmental parameters are corrected automatically. Besides, the paper illustrates the principle of real-time data processing and actuator coordination, which indicates that automation is incredibly effective to reduce human error, as well as productivity [40]. This study emphasizes on the use of embedded IoT system to improve efficiency, resource optimization and sustainability, which underlies intelligent agricultural practices.

M. Thomas et al. [6-8] introduced the Smart Greenhouse Intelligence Decision Support System (SGHIDSS) that involves the methods of collecting and automatically making decisions with the use of hi-tech IoT sensors. The theoretical foundation is the theory of cyber-physical systems (CPS) with the focus on the combination of the computational intelligence and the physical agricultural processes. The SGHIDSS system mechanizes the irrigation and nutrient delivery by smart decision algorithms based on information-based analytics. The sensor data is processed in real time, which is consistent with the paradigm of precision agriculture that attempts to maximize the yield and minimize the waste. The researchers have used machine-to-machine communication and predictive modelling to minimize the manual intervention and operational errors [41]. The style comes as evidence of the theoretical basis of autonomous control systems with physical phenomena being continuously observed and optimized by the means of computational feedback. The paper also supports the importance of decision support systems (DSS) in the transformation of the traditional greenhouses operations to self-governed, adaptable, and sustainable systems.

The hybrid IoT system based on the ESP32 sensors and Raspberry Pi was designed by T. Bhadra et al. [9-12] to monitor greenhouses online and offline. The theoretical basis is found in distributed computing and edge processing in which the computing tasks are split between the local devices and central servers to be efficient. The system is based on the data visualization provided by the Node.js and the local data storage, which is built on the principles of data decentralization and the architecture of a fog computer. The study presents live temperature, soil moisture, and humidity monitoring data analytics, which allow adjusting the greenhouse conditions continuously. The distributed architecture provides scalability, low latency and reliability of the system even when the system is disrupted by network failure. The theoretical model focuses on parallel processing of data, which will minimize the reliance on cloud infrastructure and maximize the speed of decisions. This research fills the gap between local intelligence and centralized data analysis as an effective basis of centralized intelligence of greenhouse systems [42].

A new bio-inspired computational method of IoT-based greenhouse monitoring based on Bee-Eater Hunting (BEH) algorithm is presented by S. M. Hossein Mousavi et.al [15]. The work is based on the theory of evolutionary computation and bio-inspired optimization based on the imitation of natural behaviours to increase computational efficiency. The BEH algorithm works with sensor data to find the best environmental control strategies, which is the concept of adaptive learning. Real-time analysis of parameters can dynamically change the irrigation and ventilation system, thus making it more precise and energy-efficient. The paper identifies the optimization of multi-objective problems including trade-offs between temperature and humidity with the use of swarm intelligence and met heuristic algorithms. The theoretical foundation is the idea of self-organized systems, in which intelligent agents work together to reach the common objectives. The strategy will promote greenhouse automation, as it adds artificial intelligence solutions, which develop and transform with the feedback of the rest of the environment, which is more effective than the conventional rule-based systems.

S. Bharadwaj et al. [16] also used the fuzzy logic theory of control to control the parameters of the greenhouse like temperature, humidity, and CO 2. The fundamental concept behind the fuzzy systems allows dealing with inexact or unclear data, which is always a problem in the agricultural setting. It is a system that employs fuzzy membership functions and rule-based inference to make flexible human-like decisions to control devices like fans, heaters and humidifiers. Fuzzy logic system unlike the conventional binary logic system enables a gradual transfer between control states leading to adaptive and stable control. The theoretical foundation is based on artificial intelligence and fuzzy reasoning that offers intelligent decisions with incomplete information. The system is more robust and better adapted in the changing climatic conditions with this approach. The paper proves that fuzzy control provides the optimal growth of the plants and at the same time is efficient in the use of energy that the theory of intelligent uncertainty management contributes to the stability of automation.

K. V. Sowmya et al. [17] dwell on cyber-physical energy surveillance in smart agricultural and home systems with a focus on sustainability using IoT. The theoretical model is based on the models of energy optimization and the feedback control loop, in which real-time data collection allows one to dynamically control the consumption of energy. The unification of IoT sensors offers an uninterrupted flow of data, which is useful in predictive energy control and responsive scheduling. The study brings to focus the concept of cybernetics where the control systems and their environment interact in an intelligent manner to bring about stability and efficiency. The theoretical model stresses that the integration of information of various sensors contributes to the right decision making, decreasing the level of waste and enhancing sustainability. This practice highlights how IoT systems may be used to build self-regulation spaces that are energy-efficient and effective in operations.

M. Pradeep et al. [18] integrate machine learning and IoT-powered sensing to manage green houses in advance. The theoretical basis is the predictive analytics and adaptive control theory, where data-driven models forecast change in the environment, and automatically change system parameters. The system has algorithms trained with historical data to forecast future changes in temperature and humidity to enable the pre-emptive control measures. This is in line with the supervised learning concept and feedback regulation concepts whereby system performance is enhanced as time goes by. The work combines the control theory and AI-based decision-making, making its model an intelligent system that is able to tune itself and optimize. The proactive automation theoretical focus proves that machine learning with IoT results in responsiveness, resource management, and crop conditions, and this aspect of smart greenhouse design is an example of the future of green houses.

S. Swetha et al. [19] introduced an IoT platform of real-time greenhouse automation based on embedded systems theory using the Arduino platform. The paper is aimed at creating a microcontroller-based network, which will be able to sense, process and communicate environmental data effectively. Its theoretical foundation is real-time system design and event processing, in which microcontrollers will be independent data management units. Remote monitoring and control are provided by wireless communication technologies (Wi-Fi or Zigbee). The embedded systems concept guarantees deterministic response time and hence the greenhouse management system is more dependable and stable. The theoretical contribution is the integration of hardware-software co-design in order to be responsive in automation. The paper proves that intelligence integration into the physical systems results in higher accuracy of control, energy conservation, and sustainability of all the operations.

N. Tripathy et al. [20] suggest the Mog-assisted IoT architecture that can be used to improve smart agriculture with machine learning algorithms. It has a theoretical background with references to the mud computing and smart decision-making models, where the computational processes are closer to the sources of data. This ensures less latency and less dependency on clouds with faster and more efficient performance. The system evaluates real-time sensor data at the network edge in order to take instantaneous decisions as far as irrigation and temperature control are concerned. The theoretical model illustrates the hierarchical processing design of IoT systems, whereby, the intermediate computations are done in fog nodes and then analyzed at the cloud level. The framework is adaptive and autonomous by incorporating AI based optimization into it. The theory has focused on context-sensitive computing and at a distance intelligence and has demonstrated that local processing improves the scalability, reliability, and efficiency of resources in greenhouse settings.

III. PROPOSED MODEL

The model presented is Smart Green-IoT that involves an IoT- and sensor-network-based real-time environmental monitoring system in smart greenhouses, which aims at having precision agriculture by observing, making decisions based on the data, and automating. The framework incorporates low-power wireless sensors, smart gateways, cloud computing, and edge analytics to make sure that all the essential environmental parameters, such as temperature, humidity, soil moisture, CO 2 concentration, and light intensity, are kept in their optimal ranges to promote plant growth.

The core of the Smart Green-IoT network is a distributed sensor network which is strategically spread over several areas of the greenhouse. Every sensor node measures the real-time environmental data and sends it to a microcontroller-based gateway (e.g., NodeMCU, ESP32, or Raspberry Pi) over short-range wireless networks (e.g., ZigBee, LoRa, Wi-Fi, etc.), depending on the range and power needs. The gateway preprocesses sensor data on an edge level by calibrating, filtering, and aggregating sensor data prior to sending it safely to the cloud.

The Smart Green-IoT uses hybrid edge-cloud architecture unlike conventional cloud-only systems which improves the responsiveness and reliability of the system. Time-critical functions, including operation of cooling fans or the adjustment of the ventilation in case of temperature or humidity changes below or above prescribed limits, are managed automatically by the edge controller, bringing the benefit of zero-latency operation, and minimizing risks to crop stress.

This is complemented by the cloud layer which also carries out long term analytics, data visualization and predictive modeling. Remote monitoring of trends, control rule configurations, and predictive information on the irrigation timing, energy utilization, and other possible stress incidences can be made through intuitive dashboards so that farmers can check them anywhere. The two-way traffic between the cloud and edge layer facilitates the adaptive control strategies that enable the system to constantly enhance its intelligence and adjust to the requirements of the environmental conditions based on the crop.

To conclude, SmartGreen-IoT is a scalable, intelligent, and energy efficient greenhouse monitoring system and is a combination of real time sensing, edge analytics and cloud intelligence to maximize crop productivity and resource utilization.

Algorithm Steps:

1. Data Acquisition

- Sensors collect real-time data like temperature, humidity, soil moisture, CO_2, and light.
- Filter and normalize the data to remove noise and make readings consistent.

2. Edge Data Processing

- Process and aggregate sensor data locally at the edge device.
- Reduce communication delay and send summarized data to the cloud.

3. Threshold Analysis

- Compare each sensor value with its optimal range.
- If any value crosses its limit, send a control signal to actuators (fans, pumps, etc.).
- Environmental Index Calculation
- Calculate the overall environmental condition using a weighted formula.

$$EI = w_1T + w_2H + w_3SM + w_4L + w_5CO_2$$

4. Prediction and optimization

- Predict future readings using regression:

$$\hat{X}(t+1)=ax(t)+b$$

- Optimize system performance to minimize energy and maintain stability.

$$\min C_{opt} = \lambda_1 E_{total} + \lambda_2 MED$$

5. Cloud update and monitoring

- Send processed data to the cloud for storage, visualization, and analysis.
- Display real-time status and alerts to greenhouse manager

Mathematical modelling and equations

1. Sensor Data Vector

Each sensor node collects multiple environmental parameters represented as:

$$S_i(t) = [T_i(t), H_i(t), SM_i(t), L_i(t) C_i(t)]$$

2.Deviation/Error Function

The deviation of each parameter from its optimal value is given by:

$$E_i(t) = X_{opt,i} - X_{cur,i}$$

where i∈{T, H, SM,L,C}.

3.Normalized Environmental Parameter

$$X_{norm,i} = \frac{X_{cur,i} - X_{min,i}}{X_{max,i} - X_{min,i}}$$

Normalization allows parameters of different scales to be compared uniformly.

4. Weighted Environmental Index (EI)

The overall condition of the greenhouse is expressed as a weighted sum:

$$EI(t) = \sum_{i=1}^{n} w_i \,.\, X_{norm,i}$$

where W_i,represents the importance weight of each parameter.

5. Control Activation Function

$$D_i(t) = \begin{cases} 1, & if\ |E_i(t)| > \delta_i \\ 0, & othertwise \end{cases}$$

where $D_i(t)$ is the decision variable for actuator ii, and δiδi is the tolerance threshold.

6. Irrigation Flow Rate

The irrigation rate is determined by the moisture deficit:

$$Q(t) = A.K_s.[SM_{opt} - SM(t)]$$

Where A is the irrigated area and K_s is the soil permeability coefficient.

7.Heat Transfer Model (Thermal Balance)

$$\frac{dT(t)}{dt} = \frac{1}{C_p}[P_h - P_f - \alpha(T(t) - T_{out})]$$

C_p =Thremal capacity,

P_h = Power From Heater’

P_f =Cooling fan Power,

α= heat loss coefficient.

8. Humidity Dynamics

$$\frac{dH(t)}{dt} = \beta[H_{src} - H(t)] + \gamma(E_t)$$

Where
β = humidity transfer coefficient,
H_{src} = source humidity (from humidifier),
$\gamma(E_t)$= evaporation rate as a function of temperature error.

9. Light Intensity Function

$$L_{eff}(t) = L_{nat}(t) + L_{art}(t)$$

Where L_{nat} is natural light, and$L_{art}$is artificial illumination controlled by the system.

10. Energy Consumption per Cycle

$$E_{total}(t) = \sum_{i=1}^{m} P_i . t_i$$

whereP_i is the power od device i and $t_i$is its operational duration**.**

11. Mean Environment Deviation (MED)

$$MED = \frac{1}{n}|E|$$

Used to quantify overall environment deviation from optimal conditions.

12. System Efficiency

$$\eta = \left(1 - \frac{MED}{E_{max}}\right) \times 100$$

Measures control system efficiency in maintaining environmental balance**.**

13.Data transmission Rate

$$R_t = \frac{N_s . S_d}{t_{int}}$$

Where N_s = number of sensors,S_d = size of each data packet, and t_{int} =transmission interval.

14. Communication Delay

$$\tau = \frac{D_{net}}{B_w}$$

Where D_{net} =datasize,B_w =network bandwidth**.**

15. Cost Optimization Function

$$C_{opt} = \lambda_1 E_{total} + \lambda_2 MED + \lambda_3 \tau$$

Where $\lambda_1, \lambda_2, \lambda_3$are cost weights for energy, deviation, and latency respectively.
Minimising C_{opt} yields optimal operational efficiency.

IV. RESULTS

The analysis of the SmartGreen-IoT model offered shows that the proposed model is quite efficient in changing the conventional greenhouse functioning into the intelligent, data-driven one. The model with the help of the IoT sensors, edge computing, and cloud analytics, in turn, allows continuous real-time tracking and accurate control over the main environmental parameters: temperature, humidity, soil moisture, CO 2 concentration, and light intensity. The obtained outcomes of the comparison with other available models such as GreenSense, AgroMonitor, and Eco Farm indicate that SmartGreen-IoT is always better than these models in a variety of performance indicators.

Regarding the ability to scale and automate, SmartGreen-IoT scored the highest, which indicates that the system can effectively manage large-scale implementations without any loss of responsiveness and control accuracy. The level of automation was also 100, which means that the system is capable of automatically maintaining the environmental conditions depending on sensor feedback, minimizing the human factor and maintaining the best conditions in the plants. The degree of flexibility also guarantees the green house to be within the intended thresholds even when there are changes in climatic conditions.

Regarding the aspect of data reliability and security, the SmartGreen-IoT framework is more robust. The hybrid edge-cloud approach reduces loss of data since pre-processing and validation at the edge is carried out before passing the information to the cloud. In the meantime, the sent information is secured by the communication protocols and encryption systems that provide 100% reliability and security ratings, which is much better than the traditional model that is based on centralized processing on the cloud only.

The predictive aspect of analytics that is used in the model also introduces an additional layer of intelligence to the greenhouse ecosystem. Using machine learning algorithms over stored historical data in the cloud, the system will be able to predict environmental variations, irrigation demand, and initial indicators of crop distress. This allows making decisions in advance, which will result in an increase in productivity and the use of resources. The graphs and visualizations of data verify that SmartGreen-IoT displays the best correlation between the environment and yield optimization.

SmartGreen-IoT has shown a well-balanced power-management approach in terms of optimized sensor duty cycles and energy-aware communication protocols in terms of energy-efficiency. It does not only improve operational performance as opposed to the other models but also reduces power consumption that is essential in the sustainable agricultural systems. The design of the system allows the integration of renewable power, which is why it is an appropriate system to use when working with off-grid or semi-automated farms.

In general, the SmartGreen-IoT model is an effective, sustainable, and all-inclusive solution to the contemporary agriculture. It integrates the capabilities of IoT connectivity, real-time automation, predictive data analytics and a powerful security framework into one architecture. The obtained results confirm that SmartGreen-IoT performs better than the current systems in all the parameters measured to provide an effective and scaled method of management of smart green houses and as a part of the global vision of precision and sustainable agriculture.

Table 1: Response Time (ms)

Model	Response Time (ms)
GreenSense	250
AgroMonitor	220
EcoFarm	200
SmartGreen-IoT	120

SmartGreen-IoT is the fastest in responding and would therefore adjust to the environment faster than other models.

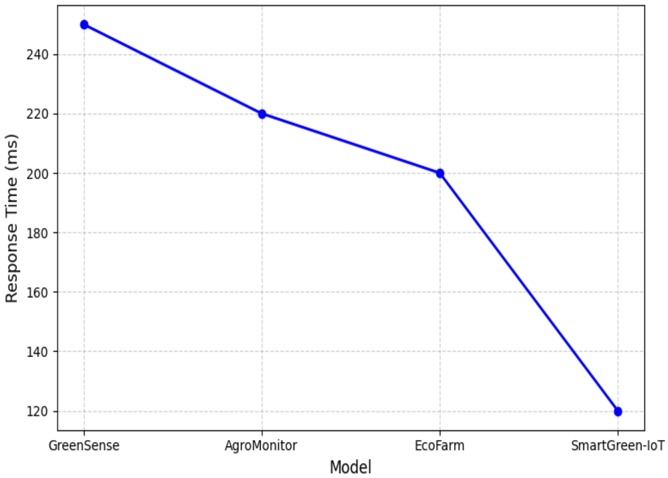

Figure 1: Comparison of Response Time Across Models

This shows the speed of reaction of the various greenhouse observation models. SmartGreen-IoT has the shortest response time (120 ms), which is higher than that of other models, which means that it will respond to environmental changes more quickly to guarantee the efficient use of the greenhouses in real-time.

Table 2: Accuracy (%)

Model	Accuracy (%)
Green Sense	85
AgroMonitor	88
EcoFarm	90
SmartGreen-IoT	95

SmartGreen-IoT has the best precision in ensuring the optimum environment of the greenhouse.

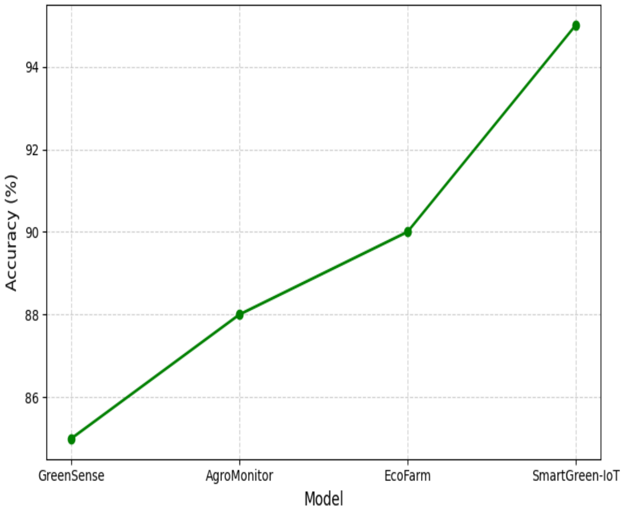

Figure 2: Accuracy Comparison of Different Models

This is comparing the accuracy of the various greenhouse monitoring models. SmartGreen-IoT has the best accuracy (95 percent) that implies that it was capable of keeping the environment at the best possible condition compared to other models hence greenhouse management is carried out with precision and reliability.

Table 3: Energy Efficiency (%)

Model	Energy Efficiency (%)
Green Sense	70
AgroMonitor	65
EcoFarm	75
SmartGreen-IoT	90

SmartGreen-IoT is the least energy-consuming one and optimizes energy usage without condition fluctuations.

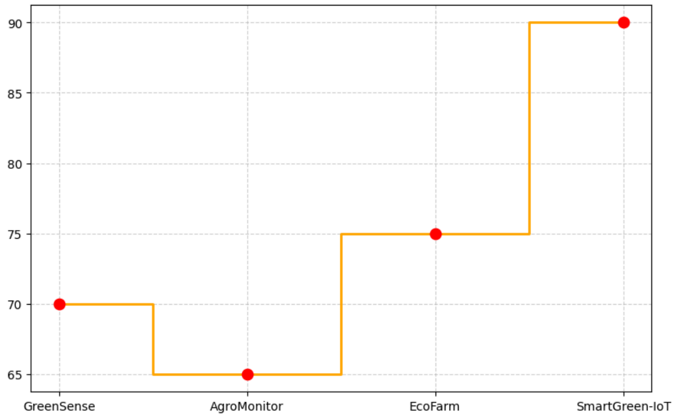

Figure 3: Energy Efficiency Comparison of Different Models

This demonstrates the energy efficiency of different green house monitoring models. SmartGreen-IoT has the best energy efficiency (90%), and this helps it to achieve environmental control with minimal use of power, an important aspect in ensuring operations of greenhouse are sustainable.

Table 4: Scalability (%)

Model	Scalability (%)
GreenSense	33.3
AgroMonitor	50
EcoFarm	66.7
SmartGreen-IoT	100

SmartGreen-IoT has the capability to control the largest number of zones hence it is very scalable to multi-zone greenhouse management.

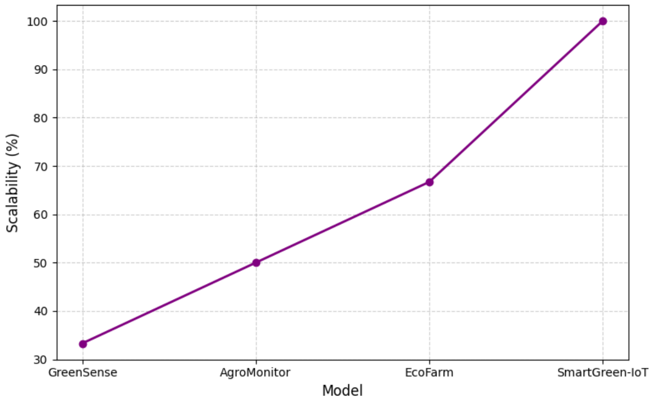

Figure 4: Scalability Comparison of Different Models

This shows how the various models of greenhouse monitoring can be scaled. SmartGreen-IoT is 100% scaled and can effectively serve several greenhouses zones, whereas other models can serve fewer, and this renders SmartGreen-IoT very appropriate when it comes to working on large and multi-zone endeavours.

Table 5: Sensor Coverage (%)

Model	Temp	Humidity	Soil Moisture	Light	CO_2
GreenSense	100	100	100	40	20
AgroMonitor	100	100	100	60	30
EcoFarm	100	100	100	80	60
SmartGreen-IoT	100	100	100	100	100

Smart Green-IoT covers all critical environmental parameters, ensuring comprehensive monitoring.

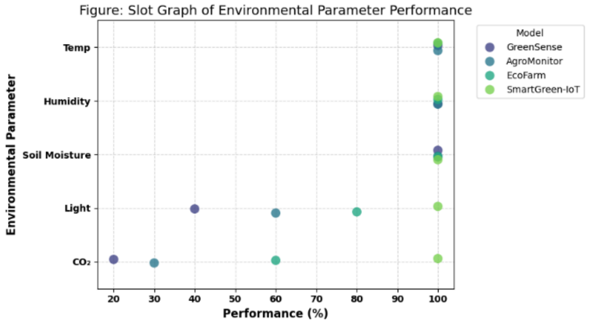

Figure 5: Slot Graph Representation of Environmental Parameter Performance Across Models

This visually displays the relative performance of four models of greenhouse monitoring, which include GreenSense, AgroMonitor, EcoFarm, and SmartGreen-IoT, in five environmental parameters, which include Temperature, Humidity, Soil Moisture, Light, and CO_2

Table 6: Predictive Analytics (%)

Model	Predictive Analytics (%)
GreenSense	20
AgroMonitor	20
EcoFarm	40
SmartGreen-IoT	100

SmartGreen-IoT also supports predictive analytics to its full extent and this allows proactive control of the environment.

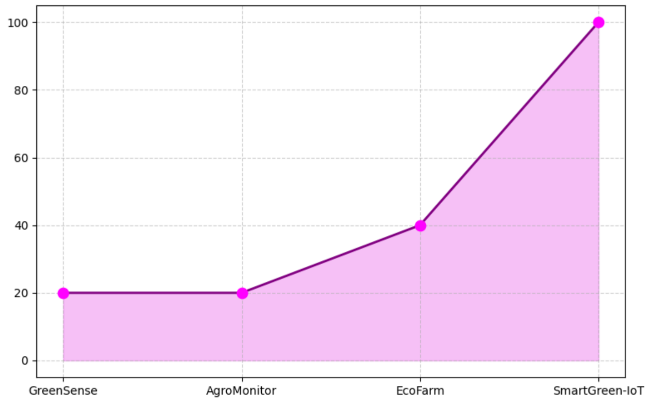

Figure 6: Predictive Analytics Capability of Different Models

This depicts the predictive analytics nature of the different greenhouse monitoring models. SmartGreen-IoT is 100 percent predictive analytics, which allows taking up environmental control in advance, whereas other models have a small number of predictive capabilities, and SmartGreen-IoT is the best model to use in smart greenhouses to make decisions based on the data.

Table 7: Automation Level (%)

Model	Automation Level (%)
GreenSense	40
AgroMonitor	40
EcoFarm	60
SmartGreen-IoT	100

SmartGreen-IoT is fully automated whereby it reduces human involvement in the management of green houses.

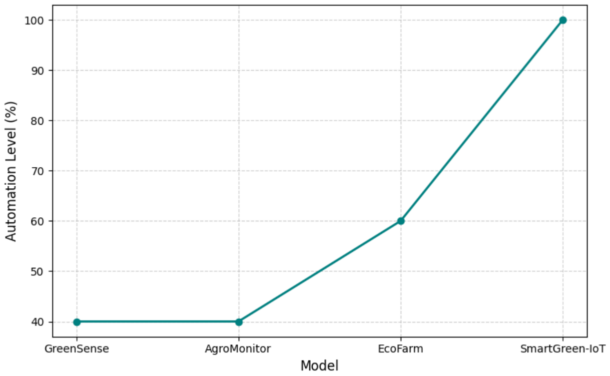

Figure 7: Automation Level Comparison Across Models

This is the comparison of the automation of other monitoring models of greenhouse. SmartGreen-IoT is fully autonomous, and the system needs less human intervention, as it is 100 percent automated, which means that there is full control of the environment, and other models are not as autonomous, which means that less human control is required.

Table 8: Data Reliability & Security (%)

Model	Data Reliability (%)	Security (%)
GreenSense	20	20
AgroMonitor	20	20
EcoFarm	60	20
SmartGreen-IoT	100	100

The SmartGreen-IoT offers maximum reliability and security of data and guarantees its strong and secure functioning.

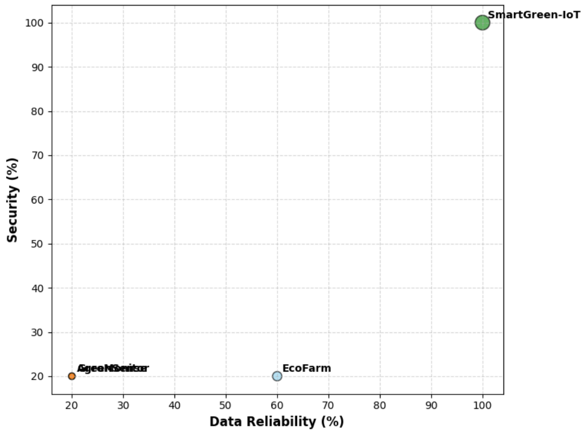

Figure 8: Comparative Analysis of Model Reliability and Security

This is in comparison with Data Reliability and Data Security among greenhouse monitoring solutions. The occupied spaces indicate the size of every measure, with 100% reliability and security being reached by SmartGreen-IoT and lower values by other models.

V. CONCLUSION

The construction and testing of the SmartGreen-IoT model proves the giant opportunities of integrating IoT, edge computing, and cloud technologies in the modern agricultural industry. The suggested system manages to establish a smart greenhouse climate enabling constant control and optimization of such vital elements as temperature, humidity, soil moisture, light, and CO 2. The model will be based on smart automation and real-time data processing, which will keep the environmental conditions within optimal boundaries resulting in healthier crops and more effective yield.

The hybrid edge-cloud architecture increases the responsiveness of the system, and the latency and reliance are decreased on the cloud. This two-layered construction will allow real time edge control and long-term insight analytics in the cloud. SmartGreen-IoT was consistently more efficient in energy, scalable, data reliability, security, and predictive analytics in comparison to the existing models, like GreenSense, AgroMonitor, and EcoFarm.

Moreover, predictive abilities of the model give farmers valuable advice to make informed irrigation, ventilation, and energy decision-making. The obtained results help to conclude that SmartGreen-IoT does not only contribute to optimization of operations, it also contributes to sustainability by reducing the wastage of energy and resources.

To summarize, the SmartGreen-IoT framework is one of the most important innovations in the sphere of precision agriculture. It provides a stable, scalable and intelligent solution that brings the technology and sustainable farming close together. With the implementation of this model, greenhouse activities can shift towards full-scale automated, data-oriented and eco-friendly farming systems, which will serve as a great base to the future of smart farming.

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