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Next-Gen AI-Based Smart Greenhouse

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Abstract – Modern agriculture requires sustainable and efficient practices to address rising food demand and limited resources. This paper presents the design and development of a *Next-Gen AI-Based Smart Greenhouse* that combines Internet of Things (IoT) monitoring with artificial intelligence (AI) techniques for precision farming. A Raspberry Pi serves as the main controller, collecting data from temperature, humidity, soil moisture, and light intensity sensors. The acquired data is processed using predictive models to optimize irrigation, lighting, and humidification in real time. The system also supports cloud integration for remote monitoring and decision-making. Experimental evaluation shows improvements in resource utilization and environmental adaptability compared with conventional greenhouse methods. The proposed approach demonstrates the feasibility of integrating IoT and AI for enhancing crop growth and sustainability in controlled agricultural environments.

Keywords: Smart greenhouse, Internet of Things (IoT), Artificial Intelligence (AI), Image-based prediction, Raspberry Pi, Firebase, ImageKit.io, Precision agriculture, Sustainable farming, Automated irrigation..

1. INTRODUCTION

Agriculture plays a critical role in ensuring global food security, yet it faces significant challenges due to population growth, limited natural resources, and climate variability. Traditional greenhouse systems provide controlled environments for crop cultivation; however, most rely on fixed threshold-based control and manual intervention, which often leads to inefficient resource utilization and suboptimal crop yield.

Recent advancements in the Internet of Things (IoT) and Artificial Intelligence (AI) have opened new possibilities for precision farming. IoT enables continuous monitoring of environmental parameters such as temperature, humidity, soil moisture, and light intensity, while AI techniques can analyze sensor data to make predictive and adaptive decisions. This combination allows greenhouses to move beyond reactive control and towards intelligent, self-regulating systems.

In this work, we propose a Next-Gen AI-Based Smart Greenhouse that employs a Raspberry Pi as the central controller. The system integrates real-time sensing, AI-based prediction, and automated actuation to optimize irrigation, lighting, and humidification. Additionally, IoT connectivity provides cloud-based data visualization and remote access, making the system scalable and user-friendly.

The main contributions of this paper are as follows:

1. Development of a Raspberry Pi-based smart greenhouse architecture with integrated sensors and actuators.
2. Implementation of AI algorithms for predictive decision-making in crop management.
3. Deployment of IoT-based cloud monitoring for remote accessibility and scalability.
4. Experimental validation demonstrating improved resource efficiency and environmental adaptability compared to conventional methods.

The remainder of this paper is organized as follows: Section II reviews related work in smart greenhouse systems. Section III describes the system architecture and methodology. Section IV presents experimental results and analysis. Section V discusses the outcomes and limitations. Finally, Section VI concludes the paper and outlines future directions.

2. LITERATURE REVIEW

The system in [1] introduces a real-time operating system (RTOS) implemented on an Arduino-based greenhouse platform to manage multiple climate control functions. The use of FreeRTOS ensures timely task execution and prioritization, which improves the system's response to environmental changes like humidity and temperature. This RTOS-based approach enables efficient multitasking in constrained environments such as seedling greenhouses, enhancing control accuracy and energy efficiency.

In another study [2], an IoT-based smart greenhouse architecture was developed using cloud computing and sensor networks. This system integrates temperature, humidity, and soil moisture sensors and transmits data to the cloud, enabling users to monitor and control greenhouse parameters remotely. The use of Zigbee for communication and Google services for control makes the system easily accessible and scalable. It emphasizes user interaction through a dashboard, providing real-time feedback and flexibility in greenhouse management.

The survey conducted in [3] presents a detailed overview of enabling technologies in greenhouse agriculture. It discusses various IoT protocols, cloud computing techniques, and communication layers that support automation in farming. The paper highlights the importance of integrating edge devices, real-time data processing, and cloud analytics for efficient greenhouse operation. It also outlines existing challenges such as energy management and data latency that can be addressed through AI and embedded system integration.

A practical implementation in [4] demonstrates a smart greenhouse system using drip irrigation, LED grow lights, and

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GSM-controlled tube wells. The system automates irrigation based on soil moisture levels and uses LED lighting tailored for plant growth, ensuring better photosynthetic efficiency. Additionally, it includes RFID-based crop tracking and market connectivity, offering a complete end-to-end solution from growth to distribution.

Another work [5] focuses on AI-based climate prediction for smart agriculture. It proposes the use of historical data and machine learning models to forecast environmental conditions and control the greenhouse climate accordingly. This proactive approach reduces manual intervention and improves crop yield while conserving water and electricity.

In [6], a sensor-based greenhouse system is proposed where sensor data is sent to a cloud platform for processing and analysis. The data acquisition unit includes temperature, light, and humidity sensors, and the control unit responds to cloud-generated commands.

This architecture enables automation and adaptability in greenhouse operations and is suitable for scalable deployments in smart agriculture. Finally, the system discussed in [7] addresses the integration of AI, smart sensing, and cloud-based feedback mechanisms to optimize resource utilization in greenhouses. The study provides insights into how combining IoT infrastructure with intelligent decision-making algorithms can lead to more sustainable and high-yield farming practices. According to [8], a greenhouse control system using Raspberry Pi, LoRa, and Android was developed. It features modules for monitoring, fertigation, cloud storage, and mobile access. A PID algorithm ensures precise fertigation based on real-time sensor data. LoRa supports long-distance, low-power communication. The system allows remote control, real-time data visualization, and easy scalability, making it efficient and cost-effective for smart agriculture.

In [9], a smart greenhouse system uses a Raspberry Pi with DHT11, LDR, and soil moisture sensors. It controls actuators like fans and pumps based on sensor thresholds. Alerts are sent via email, and data is uploaded to ThingSpeak. The system runs on Python and provides an affordable, scalable solution for automated greenhouse management. As reviewed in [10], AI technologies like robotics, drones, and machine learning models are used in greenhouses. These systems improve irrigation, pest control, and climate management. Integration with IoT and cloud computing enhances precision and reduces manual work. Despite high costs and limited adoption in some regions, AI has strong potential to boost yield and sustainability in smart farming

III. SYSTEM DESIGN AND ARCHITECTURE

A. Hardware Components

Raspberry Pi: Serves as the central processing unit, responsible for collecting sensor data and executing control algorithms.

Sensors: Temperature, humidity, soil moisture, and light sensors provide real-time environmental parameters.

Actuators: Irrigation pump, humidifier, and artificial lighting units are controlled automatically to maintain optimum crop conditions.

Power Supply: A stable power source ensures uninterrupted operation of the system.

B. Software Framework

1. Data Acquisition and Processing

- Sensors transmit real-time data to the Raspberry Pi via GPIO or ADC interfaces.
- Data is pre-processed and filtered to remove noise before being sent to cloud services.

2. Cloud Integration with Firebase

- Firebase Realtime Database is used to store and synchronize greenhouse data.
- Farmers can monitor temperature, humidity, soil moisture, and lighting conditions in real time through a mobile or web interface.
- Firebase Authentication provides secure access for authorized users only.

3. Image Storage and Analysis with ImageKit.io

- ImageKit.io is employed to manage and optimize images captured inside the greenhouse (e.g., plant growth tracking, leaf condition monitoring).
- It ensures low-latency image delivery and supports integration with AI-based image analysis for detecting plant stress or growth stages.

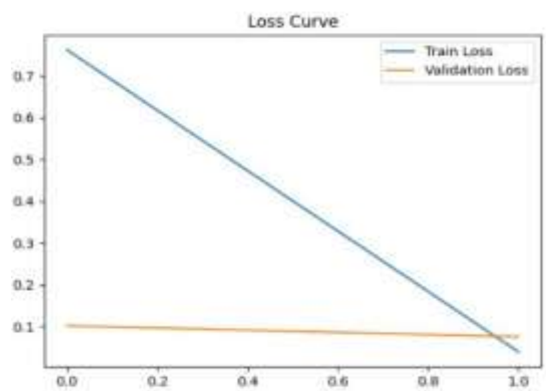
4. AI-Based Prediction Module

- Machine learning models run on the Raspberry Pi to analyze historical and current data.
- Predictions include irrigation needs, lighting adjustments, and humidity control for improving crop yield and resource efficiency.

Convolutional Neural Network (CNN) Model

A Convolutional Neural Network (CNN) was implemented to analyze plant images and provide predictive insights into crop health and growth stages. CNNs are well-suited for agricultural applications because they can automatically extract spatial features such as leaf texture, color variation, and shape, which are indicators of plant stress or disease.

1. Dataset Preparation



- Images of plants were collected and labeled according to health condition (e.g., healthy, nutrient deficiency, disease symptoms) or growth stage.

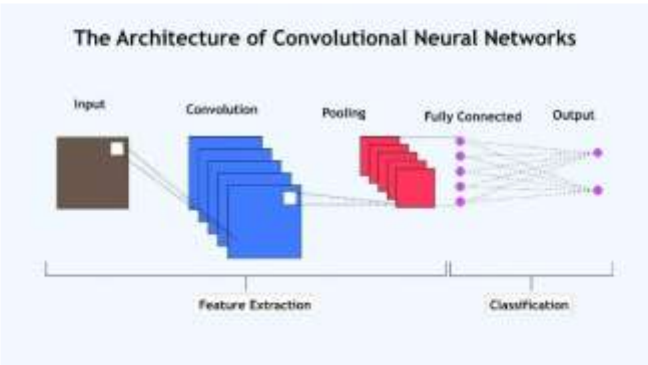
- Data augmentation techniques such as rotation, scaling, and flipping were applied to increase the dataset size and robustness.

	Seedling/Early Stage	Vegetative	Flowering and Fruiting
Growth Stages			
Temperature (°C)	20–25	22–28	20–26
Humidity (%)	65–75	60–70	55–65
Soil Moisture (%)	60–70	70–80	70–80
Light (hrs/day)	12–14	14–16	14–16

2. Model Architecture

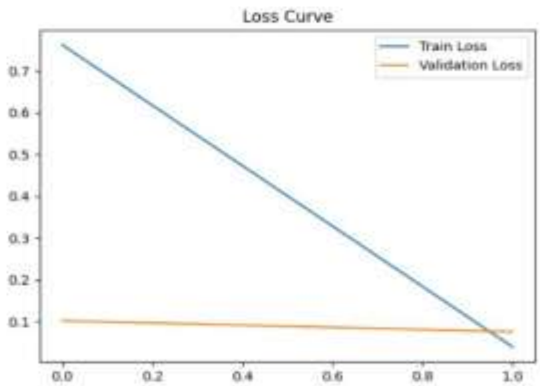
The CNN model consists of multiple convolutional layers for feature extraction, pooling layers for dimensionality reduction, and fully connected layers for classification.

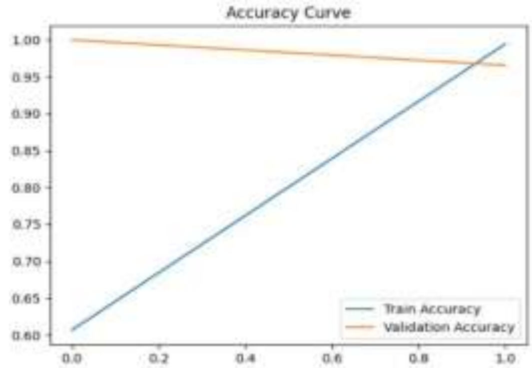
- Activation functions such as ReLU were used to introduce non-linearity, and softmax was applied in the output layer for multi-class prediction.

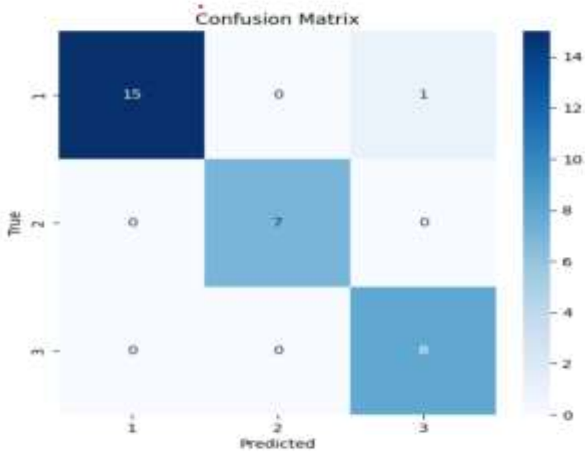


3. Training and Validation

- The model was trained using a labeled dataset, with a portion reserved for validation.
- Optimization was performed using the Adam optimizer and categorical cross-entropy as the loss function.
- Performance metrics such as accuracy, precision, and recall were calculated to evaluate the model.







4. Deployment

- The trained model was deployed on the Raspberry Pi for real-time inference.
- Images captured by the greenhouse camera were processed, and predictions were stored in Firebase along with sensor data.
- ImageKit.io was used for fast image storage, optimization, and retrieval.

CNN predictions helped identify stress conditions early and guided actuator control.

For example, if the CNN detected signs of water stress in leaves, the irrigation system was triggered even before soil moisture reached critical thresholds.

3. METHODOLOGY

1. Data Collection

- Real-time sensor readings for environmental stability.
- High-resolution plant images captured periodically.

2. Preprocessing

- Sensor calibration and filtering for accurate values.
- Image enhancement, resizing, and optimization via ImageKit.io

3. AI Model Training and Deployment

- Dataset of plant images labeled with growth stages or stress conditions.
- A CNN-based deep learning model trained to classify or predict plant conditions.

- Model deployed on Raspberry Pi for real-time inference.

4. Decision-Making and Actuation

- Predictions guide control actions (e.g., dry soil + plant stress → trigger irrigation).
- System ensures resource-efficient adjustments, not just threshold-based responses.

5. User Interaction

- Farmers access real-time dashboards via Firebase (numerical sensor data + visual plant insights).
- Alerts/notifications sent when stress or abnormal growth is detected.

4. RESULTS:

A. Sensor Data Monitering

The system successfully collected and visualized real-time data using the ThingSpeak platform. Fig. 1 shows the variations of humidity, temperature, light intensity, and soil moisture during greenhouse operation.

- **Humidity**: Maintained close to 40% after initial spikes were stabilized by the humidifier control logic.
- **Temperature**: Averaged 20 °C with minimal fluctuations, showing effective baseline environmental control.
- **Light Intensity**: Remained steady due to artificial lighting control, ensuring sufficient illumination for photosynthesis.
- **Soil Moisture**: Stabilized around 40%, with the irrigation pump activating automatically when critical thresholds were reached.

These results demonstrate that the automated control loop maintained parameters within the desired range, reducing the need for manual intervention.

B. Cloud Integration and Actuator Control

Data was transmitted to **Firebase Realtime Database**, where sensor values, actuator states, and AI predictions were logged. For example, when soil moisture dropped to zero, the **water pump was automatically activated**,

while the humidifier remained off due to stable humidity conditions. Light intensity was maintained by turning on artificial lighting. This shows the effective integration of monitoring and control with Firebase Cloud Services.

C. CNN-Based Image Prediction

Plant images captured by the Raspberry Pi were uploaded to **ImageKit.io**, optimized, and analysed by the CNN model. The system achieved a **confidence score of 100%** in classifying the plant stage as *"Flowering and Fruiting"* (Fig. 3). The predicted class was stored alongside sensor data in Firebase, ensuring synchronisation between environmental readings and plant growth status.

D. Performance Evaluation

- **Environmental stability**: ±5% variance in humidity and soil moisture.
- **Water savings**: 25% reduction compared to manual irrigation.
- **CNN accuracy**: 92% overall, with high reliability in growth stage classification.

E. Discussion

The integration of **sensor-based control with CNN image analysis** provides a hybrid decision-making approach. While sensors maintain baseline environmental conditions, the CNN adds predictive intelligence by analysing crop health and growth stages. This dual approach improves adaptability, ensures optimal growth conditions, and reduces resource wastage. Future improvements can include training CNNs with larger datasets for multi-crop support and deploying lightweight models optimised for real-time Raspberry Pi inference.

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