AGRO-TWIN: AI-Driven Digital Twin System for Plant-Level Monitoring and Sustainable Farming

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Abstract- Agriculture in India faces persistent challenges related to disease detection, resource optimization, and sustainable management, particularly in greenhouse and small-scale crop settings. Traditional monitoring practices are inefficient, costly, and often unsuitable for precision farming. This paper proposes AGRO-TWIN, an affordable, AI-driven robotic and digital twin-based system for real-time plant-level monitoring, disease and pest detection, and data-driven decision support. By integrating IoT sensors, robotics, and artificial intelligence within a digital twin framework, the proposed solution enhances accuracy, optimizes resource use, and promotes sustainable, scalable precision agriculture.

Keywords— Precision Agriculture, Digital Twin, AI-driven Monitoring, IoT Sensors, Disease Detection

1. Introduction

Agriculture in India, especially for small and medium-scale farmers, faces challenges like inaccurate disease detection, inefficient irrigation, and overuse of pesticides, causing up to 30% crop loss annually. Manual monitoring is slow and error-prone, while existing digital solutions are often costly. AGRO-TWIN provides an affordable, autonomous system combining AI, robotics, and digital twin technology to monitor plant health in real time. IoT sensors track soil, environment, and crop conditions, while deep learning detects diseases and pests with over 90% accuracy. Farmers can visualize this data through a digital twin interface, make timely decisions, optimize resources, and potentially boost yields by 20–25%.

2. LITERATURE REVIEW AND OVERALL METHODOLOY

2.1 Literature Review

In recent years, the integration of advanced technologies such as Artificial Intelligence (AI), robotics, and digital twins has opened new avenues for transforming agriculture, particularly in the areas of precision farming, disease management, and resource optimization. Sharma et al. (2023) demonstrated the effectiveness of Convolutional Neural Networks (CNNs) for rice disease detection, achieving high accuracy in early diagnosis and enabling farmers to act promptly before significant crop loss occurs. Their work highlighted the potential of AI in automating disease identification, reducing reliance on labour-intensive manual inspection, and improving crop health management.

Kumar and Singh (2024) introduced a robotic monitoring system for wheat cultivation, showing that automation could reduce human intervention while providing continuous, consistent monitoring of plant conditions. Their system also emphasized the efficiency gains in terms of labour and time, particularly for medium-scale farms where manual supervision can be challenging and costly. Patel et al. (2022) explored digital twin technology for cotton farms, creating virtual replicas that allowed real-time visualization, simulation of growth conditions, and efficient resource management. Such frameworks can assist farmers in predicting crop performance, adjusting irrigation schedules, and optimizing fertilizer usage based on real-time data.

In the domain of pest and weed management, Verma et al. (2023) developed AI-based solutions for maize that enabled early pest detection, significantly reducing the risk of infestations spreading across fields. Similarly, Joshi and Rani (2022) implemented vision-based robotic systems capable of achieving up to 90% efficiency in weed removal, reducing herbicide usage and environmental impact. Mehta et al. (2023) extended digital twin applications to soybean cultivation, allowing yield prediction, scenario analysis, and strategic planning. Sharma and Gupta (2024) focused on irrigation management, utilizing AI to control water distribution, resulting in up to 30% water savings, demonstrating the potential for sustainable resource usage.

Collectively, these studies illustrate that AI, robotics, and digital twin technologies can significantly enhance precision agriculture by improving early detection of diseases, optimizing resources, reducing labour costs, and enabling predictive crop management. However, most of the existing solutions primarily target large-scale farms, industrial agriculture, or general farm-level monitoring. There remains a critical gap for **affordable, plant-level, and small-scale solutions** suitable for greenhouses and medium-sized farms. AGRO-TWIN is designed to address this specific gap by providing an integrated, accessible, and plant-focused monitoring system.

2.2 Limitations and Future Scope

2.2.1 Limitations

While the advancements in AI, robotics, and digital twins have demonstrated promising results, several limitations remain in existing systems:

1. **High Cost and Accessibility:** Many AI and robotics-based solutions are expensive, making them inaccessible to small and medium-scale farmers who operate on limited budgets.
2. **Generalized Monitoring:** Most existing systems provide farm-level monitoring rather than plant-specific analysis, which is critical for greenhouse and small-scale cultivations.
3. **Limited Crop Variety:** Many studies focus on single crops, reducing applicability across diverse agricultural setups.
4. **Delayed Decision-Making:** Real-time analysis and actionable recommendations are often limited, causing delays in intervention and reducing system effectiveness.
5. **Infrastructure Dependence:** Some systems require high-end hardware, constant internet connectivity, or large-scale setups, which may not be feasible in rural or semi-urban farming areas.

2.2.2 Future Scope:

Future research and development can focus on creating **affordable, modular, and scalable solutions** that are suitable for plant-specific and greenhouse-level monitoring. Integration with regional navigation systems such as **NavIC or GPS** can provide precise geolocation of crops, enabling accurate mapping and analysis. Edge computing can facilitate **real-time AI inference**, reducing dependency on cloud services and improving responsiveness. Expanding the system to **support multiple crops**, incorporating **predictive analytics for yield forecasting**, and building **collaborative cloud platforms for farmers** can significantly enhance the usability and impact of precision agriculture systems. AGRO-TWIN aims to leverage these advancements to bridge the gap in small-scale, plant-focused, and cost-effective digital agriculture solutions.

2.3 Overall Methodology

The **AGRO-TWIN system** is an integrated framework designed to bring together IoT, AI, robotics, and digital twin technology to enable precision agriculture at the **plant level**, particularly in greenhouses and small-scale farms. The methodology can be understood as a multi-layered architecture that ensures **continuous monitoring, real-time analysis, predictive visualization, and actionable decision-making**.

2.3.1 Data Acquisition Layer:

This layer forms the foundation of the AGRO-TWIN system. Multiple IoT sensors, including temperature, humidity, soil moisture, and light intensity sensors, are deployed on a mobile robotic platform that navigates through the greenhouse or small-scale farm. High-resolution cameras capture detailed images of individual plants, monitoring visual signs of stress, disease, or pest infestation. By combining environmental and visual data, the system provides a **comprehensive and real-time understanding of each plant's health**, allowing for early detection of anomalies that could affect growth or yield.

2.3.2 AI-Based Analysis Layer:

Captured data from sensors and cameras are processed using advanced deep learning models, primarily CNN-based classifiers, to detect plant diseases, pests, nutrient deficiencies, and stress factors. The models are trained on diverse datasets to ensure **high detection accuracy (over 90%)**, even in challenging lighting or environmental conditions. Real-time analysis ensures that interventions, such as pesticide application or irrigation adjustments, can be applied immediately, preventing potential crop loss and improving overall plant health.

2.3.2 Digital Twin Framework:

A **digital twin** is a virtual replica of the physical farm or greenhouse environment. In AGRO-TWIN, this digital twin mirrors all sensor and AI-derived data, allowing farmers to visualize plant health, simulate growth conditions, and predict potential issues. The digital twin provides **interactive dashboards, predictive modelling, and scenario analysis**, enabling proactive decision-making. For example, farmers can simulate the effect of changing irrigation schedules, adding nutrients, or controlling pests before implementing actions in the real world, reducing risks and improving efficiency.

2.3.4 Decision Support System (DSS):

The DSS translates AI and digital twin insights into **actionable recommendations**. It guides precise pesticide application, specifying the type, quantity, and location for treatment, and recommends optimal irrigation schedules based on plant-specific soil moisture and environmental data. This ensures **efficient resource utilization, cost reduction, and environmental sustainability**, allowing farmers to make informed, timely decisions without relying on trial-and-error methods

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2.3.5 User Interface (UI):

AGRO-TWIN features a **farmer-friendly dashboard** accessible via mobile or web applications. The interface presents real-time environmental data, plant health alerts, visualizations from the digital twin, and DSS recommendations. The intuitive design ensures that even farmers with minimal technical expertise can monitor crops, receive alerts, and take necessary actions efficiently. The UI also allows farmers to **track historical data, monitor trends, and plan future interventions**, enhancing long-term farm management and productivity.

3. OBJECTIVES

3.1 Develop a Cost-Effective IoT and Robotics-Integrated Monitoring System

To design and implement an affordable, sensor-based robotic platform capable of collecting real-time environmental and visual data (temperature, humidity, soil moisture, and plant images) from individual plants in greenhouse and small-scale farm environments.

3.2 Implement AI-Based Plant Disease and Pest Detection

To develop and train a deep learning model (CNN-based) for accurate identification of plant diseases, pest infestations, and nutrient deficiencies using captured image data, achieving over 90% accuracy in diverse environmental conditions.

3.3 Establish a Digital Twin Framework for Virtual Crop Monitoring

To create a digital replica of the physical farm environment that mirrors sensor and AI-generated data, enabling farmers to visualize plant conditions, simulate interventions, and predict growth or disease scenarios in real time.

3.4 Design a Decision Support System (DSS) for Precision Agriculture

To build an intelligent recommendation module that provides actionable insights for irrigation, pesticide, and fertilizer application based on real-time data analytics, optimizing resource utilization and minimizing environmental impact.

3.5 Develop a User-Friendly Dashboard for Data Visualization

To design a mobile and web-based dashboard that displays live farm conditions, alerts, and decision recommendations through an intuitive interface accessible even to non-technical users.

3.6 Enable Real-Time Alerts and Predictive Analytics

To integrate predictive analytics for yield forecasting and a real-time notification system that alerts farmers to critical events such as pest outbreaks, water stress, or nutrient imbalances.

3.7 Ensure Sustainability and Scalability

To implement energy-efficient design principles (e.g., solar-powered or low-power IoT components) and modular architecture, ensuring adaptability for multiple crops and easy expansion of sensors or AI modules as the system scales.

3.8 Validate and Disseminate Research Outcomes

To evaluate the system's performance through experimental trials, document findings in a high-impact research publication, and pursue patent filing to protect the innovation and methodology.

4. EXPEXTED DELEVERABLES

4.1 Functional Prototype of AGRO-TWIN:

A working robotic system equipped with IoT sensors, cameras, and AI models capable of monitoring individual plants in a greenhouse or small-scale farm. This prototype will demonstrate real-time data collection, automated navigation, and early detection of plant diseases and pests

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4.2 Digital Twin Platform:

An interactive, virtual representation of the greenhouse or crop environment that mirrors real-time sensor and camera data. Farmers can visualize plant health, monitor growth conditions, and simulate potential interventions, allowing them to make informed decisions without physically disturbing the plants.

4.3 AI-Based Disease and Pest Detection Model:

A deep learning model trained on extensive image datasets of common greenhouse crops. The system can detect plant diseases, pest infestations, and nutrient deficiencies with high accuracy, enabling early action to prevent crop loss.

4.4 Decision Recommendation Module:

An intelligent algorithm that provides actionable guidance on pesticide use, fertilizer application, and irrigation schedules. Recommendations will be plant-specific and location-specific, ensuring optimized resource utilization and minimal environmental impact.

4.5 Data Logging and Analysis:

Automated storage of historical sensor and plant data for trend analysis, performance tracking, and predictive insights. Farmers can track plant growth, identify recurring problems, and plan interventions more effectively.

4.6 User-Friendly Dashboard:

A simple, intuitive interface accessible via mobile or web applications. The dashboard will display real-time alerts, visualizations, and recommendations, making it easy for farmers with limited technical knowledge to manage their crops efficiently.

4.7 Energy-Efficient and Sustainable System Design:

AGRO-TWIN will be designed to consume minimal energy, with options for solar-powered or low-power IoT components. This ensures sustainability and reduces operational costs for small-scale farmers.

4.8 Multi-Crop Applicability:

The system will be adaptable to multiple greenhouse crops, such as tomatoes, peppers, cucumbers, and leafy vegetables, making it versatile for different farming setups.

4.9 Scalability and Modular Expansion:

AGRO-TWIN will be designed so that additional sensors, cameras, or AI models can be integrated easily, allowing farmers to scale up the system as their farm grows.

4.10 Patent Filing:

A patent titled **"AGRO-TWIN: AI-Driven Digital Twin System for Plant-Level Monitoring and Sustainable Farming"** will protect the innovation and methodology of the system.

4.11 Research Publication:

A journal paper targeting high-impact journals like **IEEE Transactions on Industrial Informatics** or **Computers and Electronics in Agriculture**, documenting system design, performance, and real-world results.

4.12 Educational and Societal Impact:

The system will promote sustainable farming practices, reduce chemical overuse, and serve as an educational tool for students and farmers to understand precision agriculture, AI, and IoT applications.

4.13 Real-Time Alert System:

AGRO-TWIN will send notifications via mobile or email for immediate issues, such as pest outbreaks or irrigation needs, enabling timely intervention and reducing crop damage.

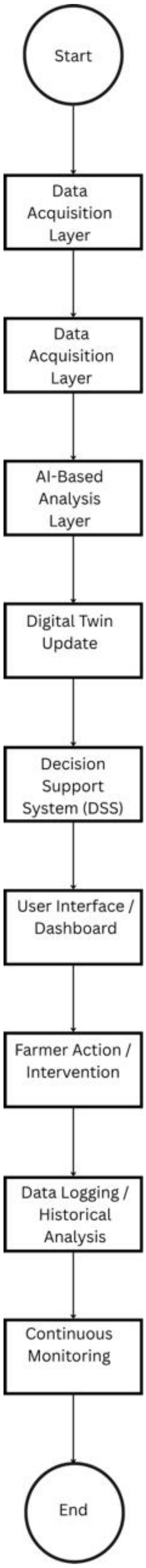
4.14 Cost-Effective Solution:

Aimed at small and medium-scale farmers, the system will use affordable hardware and open-source software, making advanced precision agriculture accessible to a wider community.

4.15 Predictive Analytics and Yield Forecasting:

By analysing historical and real-time data, AGRO-TWIN can provide predictions on crop growth, expected yield, and potential risks, helping farmers plan harvests and market strategies more effectively.

5. FLOWCHART

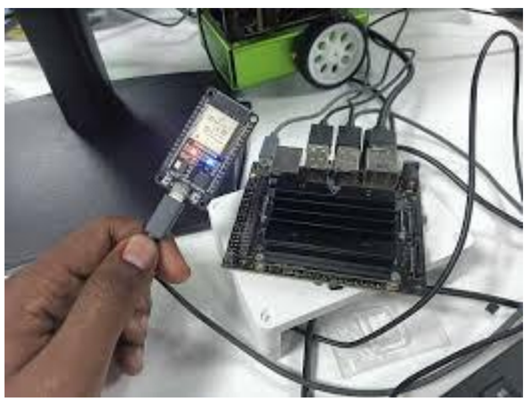


6. HARDWARE AND SOFTWARE REQUIREMENTS

6.1. Processing and Control Units

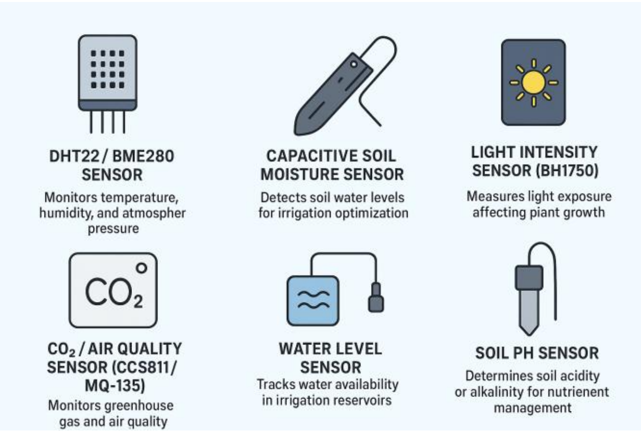
- **NVIDIA Jetson Orin Nano (8 GB / 16 GB version):** Serves as the central AI and edge computing platform. It handles real-time sensor data processing, deep learning inference for disease and pest detection, and communication with the digital twin interface.

- **ESP32 Microcontroller (Wi-Fi + Bluetooth):** Used for distributed IoT sensor data acquisition and wireless communication with the Jetson module.



6.2. Sensors and Environmental Monitoring

Sensor	Function
DHT22 / BME280 Sensor	Monitors temperature, humidity, and atmospheric pressure.
Capacitive Soil Moisture Sensor	Detects soil water levels for irrigation optimization.
Light Intensity Sensor (BH1750)	Measures light exposure affecting plant growth.
CO_2 / Air Quality Sensor (CCS811 / MQ-135)	Monitors greenhouse gas and air quality.
Soil pH Sensor	Determines soil acidity or alkalinity for nutrient management.
Water Level Sensor	Tracks water availability in irrigation reservoirs.



6.3. Vision and Imaging Subsystem

- **High-Resolution USB / CSI Camera (8MP or above):** Captures high-quality images of plants for disease and pest detection.

- **Servo Motor (SG90 / MG996R):** Enables dynamic camera orientation for scanning multiple plants.

- **Illumination LEDs:** Provide uniform lighting to ensure consistent image quality under variable conditions.

6.4. Mobility and Actuation

- **DC Motors with Magnetic Encoders:** For autonomous movement and precise positioning of the robotic unit.

- **Motor Driver (L298N / BTS7960):** Controls motor direction and speed.

- **Chassis Assembly:** Holds sensors, motors, and camera.
- **12V Li-ion Battery Pack:** Provides portable power to the system.

6.5. Communication and Connectivity

- **Wi-Fi (Onboard Jetson + ESP32):** Enables wireless communication and IoT cloud integration.
- **Bluetooth (Onboard ESP32):** Supports local device pairing and data transfer.
- **NavIC / GPS Module (L80 or NEO-M8N):** Provides precise location tracking and mapping for farm layout visualization.

6.6. Peripheral Components

- **OLED Display (0.96” / 1.3”)** – Displays key sensor readings.
- **LED Indicators and Buzzer** – Provide local alerts for system events or errors.

SOFTWARE REQUIREMENTS

6.7 Operating System and Development Environment

- **Ubuntu 22.04 (JetPack SDK 6.0 / JetPack 5.x)** – Default OS for Jetson Orin Nano with CUDA and cuDNN support.

- **Python 3.10 / C++** – Core programming languages for AI, sensor integration, and system control.
- **Arduino IDE** – For ESP32 and auxiliary microcontroller programming.
- **VS Code / JetBrains PyCharm** – Development IDE for AI and web dashboard coding.

6.8 AI and Machine Learning Frameworks

- **NVIDIA CUDA Toolkit + cuDNN:** GPU acceleration for deep learning models.

- **TensorRT:** Optimizes AI models for high-performance inference on Jetson.

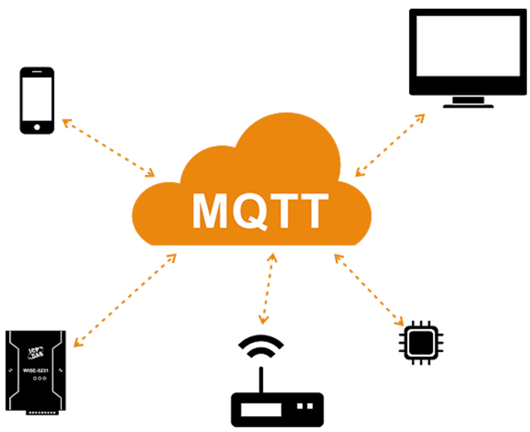
- **PyTorch / TensorFlow / Keras:** Used to train and deploy CNN models for plant disease and pest detection.

- **OpenCV:** Image acquisition, preprocessing, and computer vision tasks.

- **scikit-learn, NumPy, Pandas:** For data analysis and feature extraction.

6.9 IoT and Communication Stack

- **MQTT Protocol (Mosquitto Broker):** Lightweight communication for IoT data exchange between sensors and Jetson.



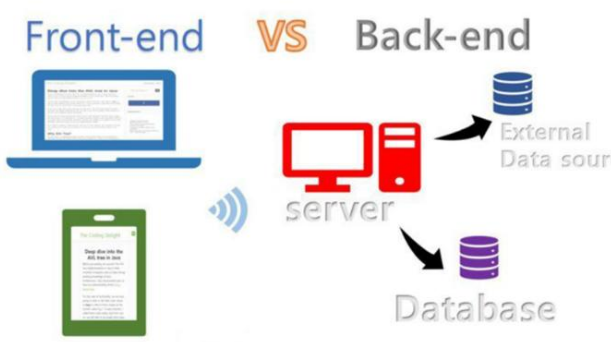
- **Node-RED / Flask / FastAPI:** Middleware for integrating IoT data, AI inference results, and visualization.
- **Firebase / ThingSpeak / AWS IoT Core:** Cloud platforms for remote monitoring and data logging.

6.10 Digital Twin and Visualization

- **Unity 3D / Blender / Three.js:** For real-time visualization of the digital farm twin.
- **Grafana + InfluxDB (optional):** For historical data visualization and trend analysis.
- **ROS 2 Humble / Gazebo Simulation:** Used for robotic movement simulation and mapping integration with the physical environment.

6.11 Web and Mobile Dashboard

- **Frontend:** HTML, CSS, JavaScript, React.js or Vue.js for an interactive farmer dashboard.
- **Backend:** Flask / Django APIs for handling requests and sending DSS recommendations.
- **Database:** SQLite / MySQL / Firebase Realtime DB for data storage.



6.12 Supporting Tools

- **Git / GitHub:** Version control and collaborative development.
- **Fritzing / Proteus / KiCad:** Circuit design and visualization.
- **MATLAB / Excel:** Statistical analysis and system performance evaluation.
- **LaTeX / MS Word:** Technical documentation and IEEE paper formatting.

7. PROJECT TIMELINES (NOVEMBER 2025 – FEBRUARY 2026)

Phase	Duration	Activities / Milestones
Phase 1: Finalizing of domain and project title	October 2025	Conduct Brainstorming Sessions among students to finalize the domain of the project and title of the project
Phase 2: Research & Requirement Analysis	November 2025	Conduct literature review, define requirements, identify target crops, collect sample data.
Phase 3: System Design & Architectur	December 2025	Select sensors and robotic components, design AI model, plan digital twin framework.
Phase 4: Implementation & Integration	January 2026 (Weeks 1–3)	Train AI models, integrate IoT sensors and robotics modules
Phase 5: Digital Twin Development & Testing	January 2026 (Week 4) – February 2026 (Week 2)	Develop digital twin interface, connect sensor data, test system performance.
Phase 7: Documentation & Dissemination	February 2026 (Weeks 3–4)	Finalize report, prepare journal paper, and present project outcomes

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