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Crop AI: A Crop-Database-Driven Smart Greenhouse Irrigation System for Drought-Prone Regions

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Abstract: Agriculture in drought-prone regions is increasingly challenged by water scarcity, irregular rainfall patterns, and inefficient irrigation practices. Conventional methods such as manual watering, flooding, and timer-based systems often fail to account for crop-specific growth stages and real-time soil moisture conditions. This paper presents *Crop AI*, a low-cost Internet of Things (IoT)-enabled smart greenhouse irrigation system that integrates soil moisture sensing, water-level monitoring, an ESP8266 microcontroller, and a crop growth-stage database. The system retrieves the required moisture threshold based on the selected crop and its growth stage, compares it with real-time sensor data, and activates irrigation only when necessary. The proposed architecture is designed specifically for small-scale greenhouse farmers operating in drought-prone and resource-constrained environments. This study outlines the system architecture, database design, control workflow, component-level cost, indicative performance comparison, as well as its advantages, limitations, and future scope. The findings indicate that crop-stage-aware irrigation has the potential to reduce unnecessary water consumption and promote sustainable precision agriculture, particularly when further validated through extended field trials.

Keywords: *IoT, Smart Irrigation, Precision Agriculture, ESP8266, Soil Moisture Sensor, Crop Database, Greenhouse Automation, Water-Use Efficiency.*

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I. INTRODUCTION

Water is a critical input in agricultural production; however, it remains one of the most stressed resources, particularly in drought-prone regions. In areas characterized by uncertain rainfall and limited groundwater availability, irrigation decisions have a direct impact on crop survival, productivity, input costs, and overall farm income. Conventional irrigation practices are often based on farmer judgment, fixed schedules, or simple timer-based mechanisms. Such approaches lack responsiveness to actual field conditions and may result in water being applied even when soil moisture is sufficient, or insufficient water being supplied during critical crop growth stages. Consequently, both over-irrigation and under-irrigation emerge as common operational challenges.

The Food and Agriculture Organization states that crop water requirements vary depending on crop type, climatic conditions, growth stage, soil characteristics, and management practices (Allen et al., 1998). This variability implies that irrigation systems relying solely on fixed time intervals or a single moisture threshold are inadequate for efficient water management. Recent IoT-based irrigation systems have enhanced monitoring and control through the integration of sensors, microcontrollers, cloud platforms, and mobile dashboards (Muthuramalingam et al., 2024; Morchid et al., 2024). However, many of these systems primarily emphasize automation and real-time control, with limited incorporation of crop growth-stage-specific decision-making.

This study proposes *Crop AI*, a crop-database-driven smart greenhouse irrigation system that integrates real-time soil moisture sensing with crop-specific growth-stage thresholds stored in a structured database. Rather than applying a uniform irrigation rule throughout the crop lifecycle, the proposed system dynamically adjusts decision thresholds based on the biological requirements of the crop at each stage of development. The design emphasizes affordability and simplicity, utilizing components such as the ESP8266 microcontroller, capacitive soil moisture sensors, water-level sensing modules, relay-based pump control, and a mobile-friendly monitoring interface.

➢ *The Major Objectives of the Study are:*

- To design a low-cost IoT-based irrigation framework suitable for small greenhouse farmers in drought-prone regions.

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- To integrate a crop-specific growth-stage database that stores moisture thresholds for different phases of plant development.
- To automate irrigation decisions by comparing real-time soil moisture with stage-wise crop requirements.
- To provide a simple architecture that supports remote monitoring and future expansion through weather and predictive analytics.
- To evaluate the proposed system conceptually in terms of water savings, cost, reliability, scalability, and limitations.

II. RELATED WORK / REVIEW OF LITERATURE

Smart irrigation has emerged as a significant area of research within precision agriculture due to its potential to enhance resource conservation, enable automation, and support data-driven decision-making. Early irrigation scheduling approaches primarily focused on estimating crop evapotranspiration and applying crop coefficients. The FAO-56 methodology proposed by Allen et al. (1998) provides a standardized framework for determining crop water requirements, emphasizing the role of crop coefficients, climatic conditions, soil moisture levels, and crop growth stages. This foundational work highlights that crop-stage sensitivity is a critical factor in effective irrigation planning.

Muthuramalingam et al. (2024) proposed an IoT-based smart irrigation system designed to monitor soil moisture and automate irrigation processes. Their work demonstrates the practical benefits of integrating sensors and automated control mechanisms to reduce manual intervention and improve water-use efficiency. However, a key limitation of such systems is their reliance on fixed moisture thresholds, which do not account for the varying water requirements across different stages of crop growth.

Similarly, Morchid et al. (2024) developed an IoT-based smart irrigation management system incorporating embedded systems, telemetry data, cloud computing, communication protocols, and sensor networks. Their approach emphasizes the importance of real-time data acquisition and cloud-based processing for enhancing agricultural water management and security. Despite its technological robustness, the system’s multi-layered architecture may introduce increased complexity and implementation challenges, particularly for small-scale farmers.

Kaur et al. (2024) presented a hybrid smart irrigation system that integrates IoT sensors with machine learning techniques. Their prototype monitored multiple environmental parameters, including soil moisture, rainfall status, wind speed, water level, temperature, and humidity, to improve irrigation decision-making. While the study highlights the advantages of multi-sensor integration for more adaptive and While multi-sensor integration enhances the precision of irrigation systems, the use of numerous sensors can increase installation costs and maintenance requirements, thereby limiting suitability for low-cost greenhouse applications.

Gupta et al. (2025) emphasized the role of IoT-enabled smart agriculture through automated control mechanisms and sensor-based monitoring, highlighting the importance of real-time data in improving both water and energy efficiency. Similarly, Khupse et al. (2025) developed an IoT-based irrigation system integrating soil moisture, pH, and NPK sensors to enable comprehensive soil condition monitoring. Although such systems contribute significantly to precision agriculture, their implementation may not be economically feasible for small-scale farmers who require simpler and more affordable solutions.

Balamurali et al. (2025) explored a solar-powered IoT irrigation system combined with rainfall prediction, demonstrating the potential of integrating renewable energy sources with environmental forecasting. This approach is particularly relevant for promoting sustainable agriculture in remote and off-grid regions. However, the incorporation of solar infrastructure and predictive modules introduces additional cost and system complexity. Furthermore, recent studies indicate that IoT- and cloud-based irrigation systems can significantly reduce water consumption compared to conventional manual methods (Morchid et al., 2026).

Overall, the reviewed literature confirms that IoT-based irrigation systems substantially enhance monitoring, automation, and resource management. At the same time, it highlights a critical gap in the availability of affordable solutions that integrate real-time soil moisture sensing with crop growth-stage-specific decision frameworks. The proposed *Crop AI* system addresses this gap by combining sensor-based automation with crop-specific biological intelligence, enabling irrigation decisions that are not only data-driven but also aligned with the physiological requirements of crops.

Table 1 Summary of Key Literature and Research Gap.

Study	Contribution	Gap / Relevance to Crop AI
Allen et al. (1998)	Explains crop evapotranspiration and crop coefficients for water requirement estimation.	Confirms the need for crop-stage sensitivity; not an IoT automation model.
Muthuramalingam et al. (2024)	Automates irrigation using soil moisture sensing.	Limited focus on growth-stage threshold variation.
Morchid et al. (2024)	Uses IoT, cloud, telemetry and sensors for smart irrigation.	Strong cloud model but comparatively complex for small farmers.
Kaur et al. (2024)	Uses IoT sensors and machine learning for hybrid irrigation.	Multi-sensor model may increase cost and maintenance.

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Gupta et al. (2025)	Supports automated control for water and energy efficiency.	Requires broader sensor and processing support.
Khupse et al. (2025)	Integrates moisture, pH and NPK monitoring for precision agriculture.	Useful but less feasible for very low-cost deployment.
Balamurali et al. (2025)	Combines solar energy, IoT and rainfall prediction.	Sustainable but needs additional infrastructure.

➢ *Research Gap*

Based on the reviewed literature, the following research gaps are identified:

- A significant number of existing smart irrigation systems rely on fixed soil moisture thresholds and do not adapt irrigation logic according to the varying water requirements across different crop growth stages.
- Advanced irrigation solutions that incorporate multiple sensors and machine learning techniques often involve higher costs and computational complexity, making them less suitable for small-scale and resource-constrained greenhouse farmers.
- While many systems successfully achieve automation, relatively few integrate crop-specific biological requirements into their control logic.
- There is limited emphasis on the development of centralized and easily updatable crop databases capable of storing stage-wise moisture thresholds for multiple crop types.
- Many systems are designed for large farms or experimental settings, while small greenhouse farmers require simpler and lower-cost solutions.

Crop AI is positioned as a low-cost, stage-aware, and database-driven irrigation model that attempts to bridge these gaps.

➢ *Proposed System*

Crop AI is designed using a three-layer IoT architecture consisting of an input layer, a processing layer, and an output/interface layer. The input layer is responsible for collecting field data through soil moisture and water-level sensors. The processing layer utilizes an ESP8266 microcontroller to read sensor values, establish Wi-Fi connectivity, retrieve stage-wise moisture thresholds from the database, and execute the irrigation decision logic. The output layer manages the operation of the irrigation pump and valve through a relay module and enables system monitoring via a mobile-based dashboard.

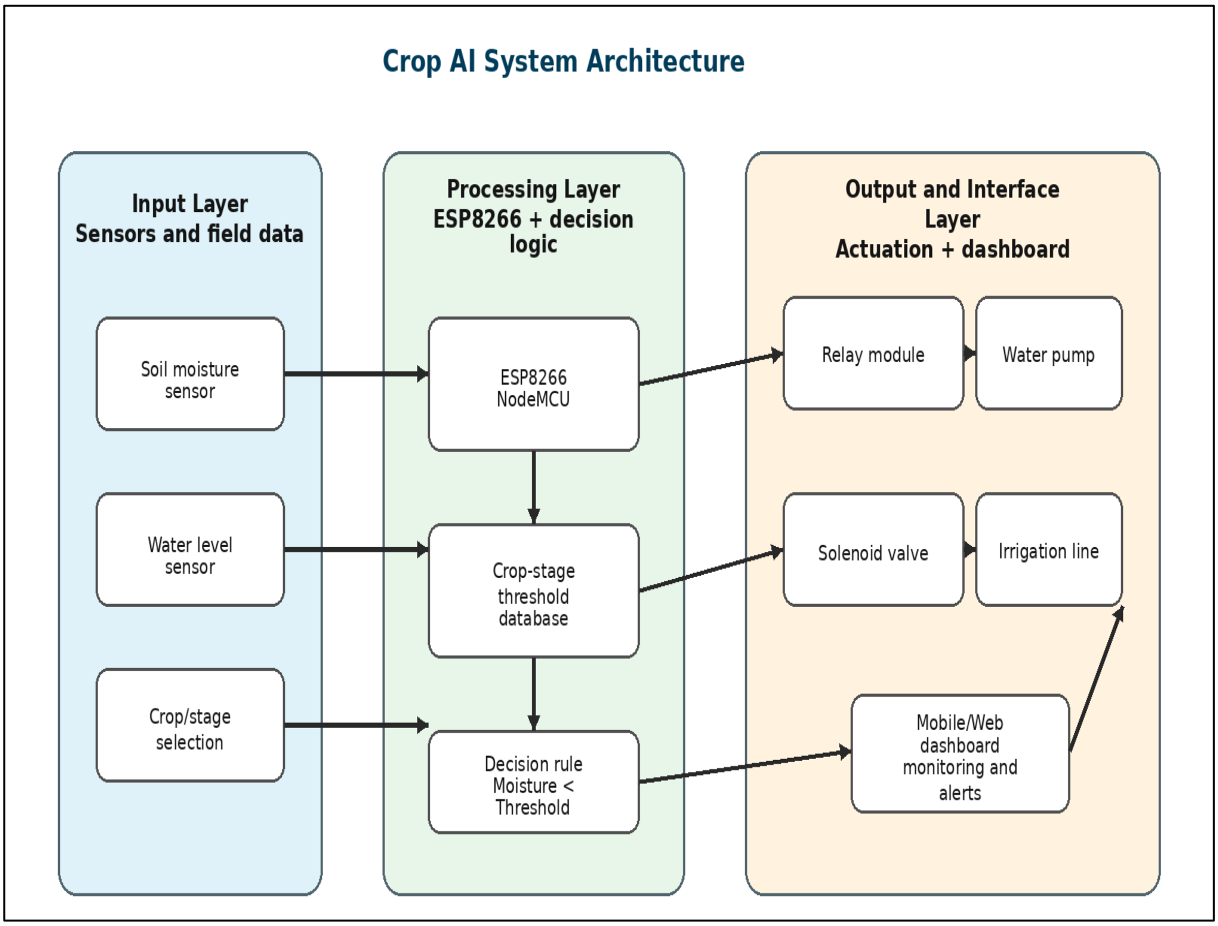

Fig 1 Proposed Crop AI System Architecture.

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- *System Components*

- ✓ Soil moisture sensor: Measures volumetric soil moisture level and provides analog input to the controller.
- ✓ Water-level sensor: Monitors the availability of water in the tank to avoid dry-run pump operation.
- ✓ ESP8266 NodeMCU: Acts as the processing and Wi-Fi communication unit for sensor reading and irrigation control.
- ✓ Relay module: Switches the pump and valve safely based on the microcontroller output.
- ✓ Pump and solenoid valve: Deliver water to the greenhouse irrigation line when irrigation is required.
- ✓ Crop database: Stores crop name, growth stage, and corresponding moisture threshold values.
- ✓ Dashboard: Displays sensor readings, irrigation status, alerts, and basic system logs.

- *Data Model and Database Design*

The crop database is the central element that differentiates Crop AI from ordinary fixed-threshold irrigation systems. It stores stage-wise moisture requirements so that irrigation decisions are linked with crop biology. A farmer may cultivate multiple crops; each crop may have multiple growth stages; and each growth stage has specific moisture threshold values. Sensor logs are stored for monitoring and later analysis.

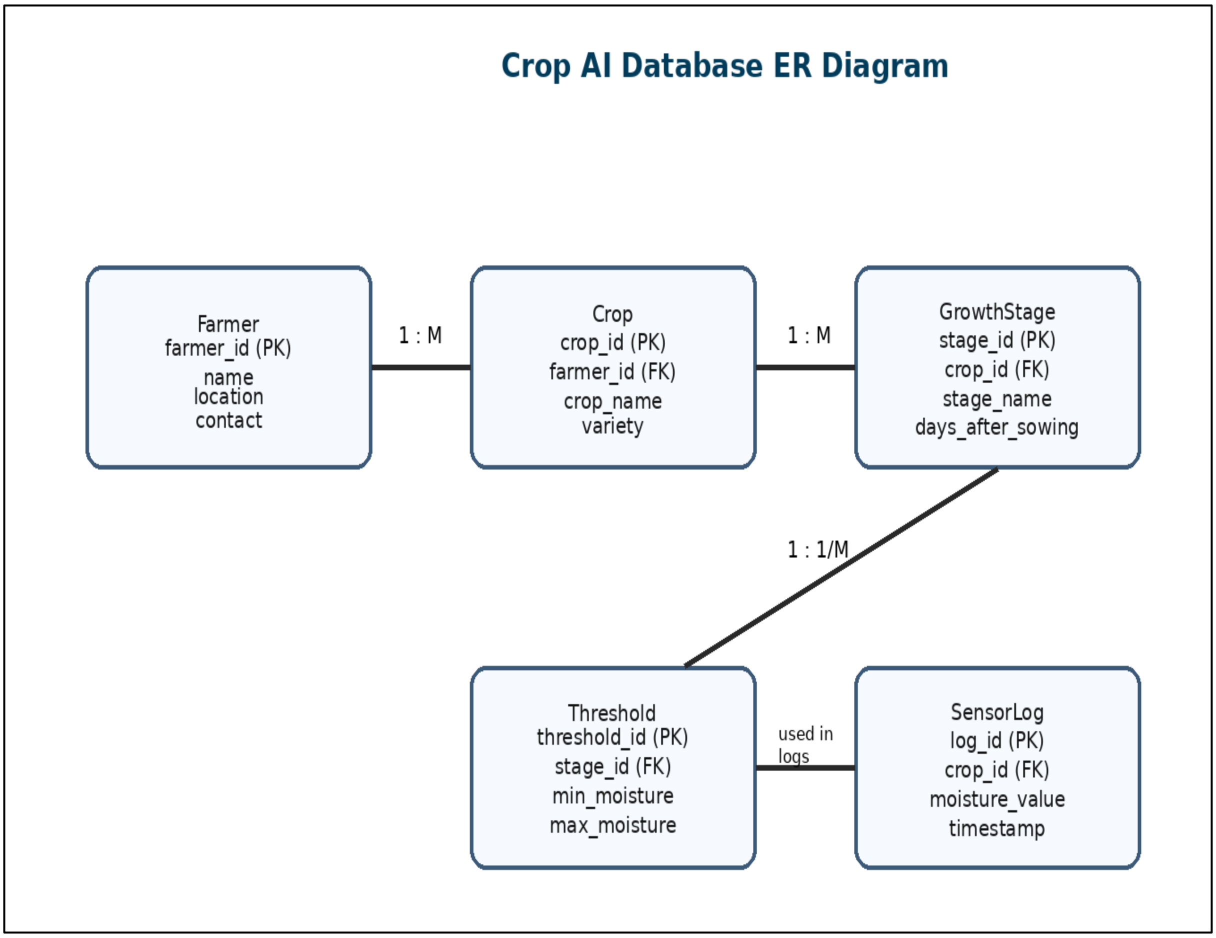

Fig 2 Entity-Relationship Model for Crop AI Database.

- *Control Logic*

The control algorithm works as a continuous feedback loop. At each cycle, the system reads the soil moisture value and compares it with the required threshold for the selected crop and growth stage. If the measured moisture is lower than the required threshold, the pump is activated. If the moisture is adequate, irrigation remains off and the reading is logged. This approach supports moisture-centric and growth-stage-aware irrigation.

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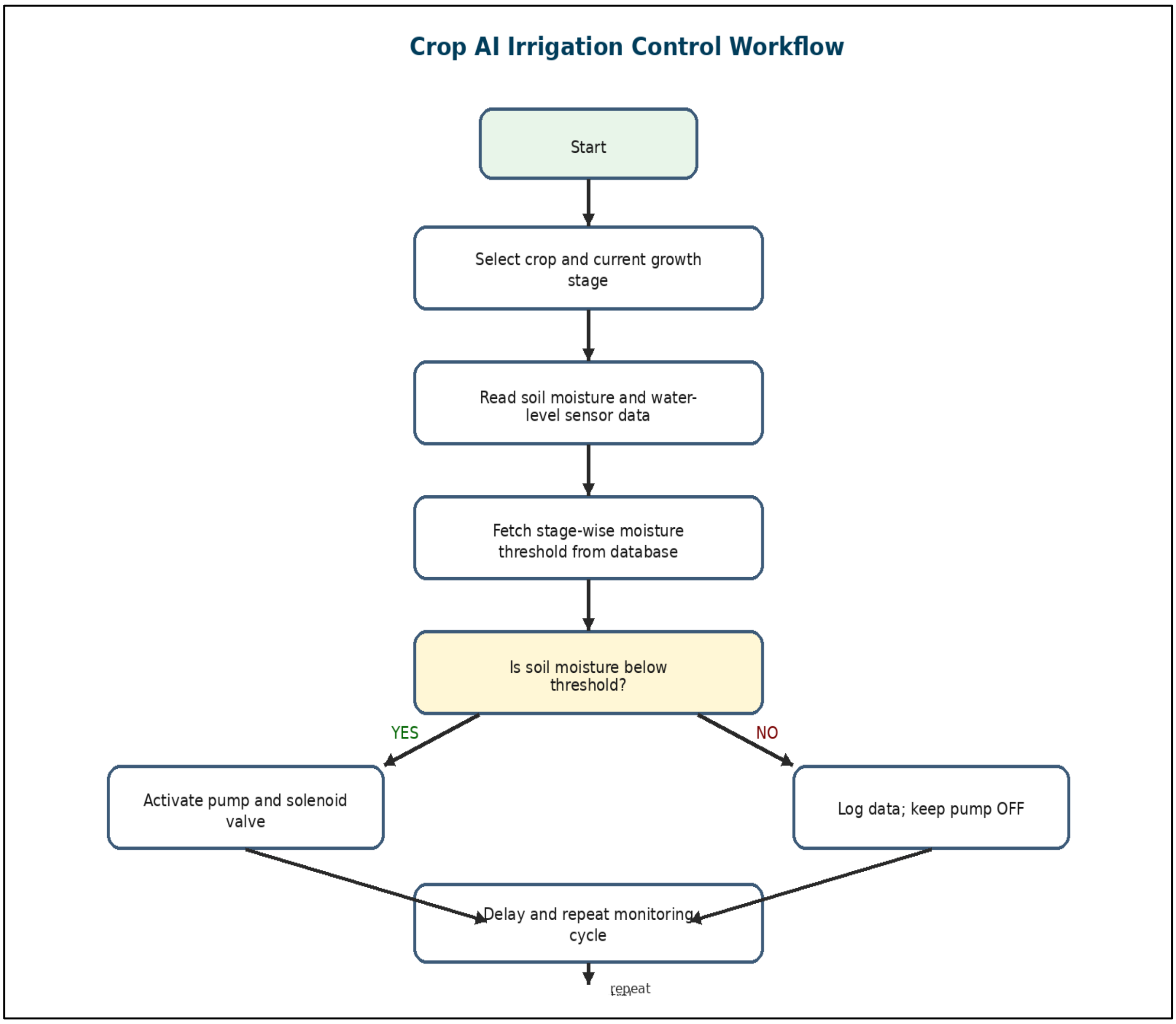

Fig 3 Crop AI Irrigation Control Workflow.

III. METHODOLOGY

The proposed methodology is structured into five sequential steps. First, the greenhouse crop is selected, and its corresponding growth stage is identified. Second, stage-specific soil moisture thresholds are defined and stored within the crop database. Third, real-time data on soil moisture and water level are continuously acquired through sensor modules. Fourth, the ESP8266 microcontroller processes the collected data and compares the current soil moisture level with the predefined threshold corresponding to the crop's growth stage. Finally, irrigation is initiated only when the measured moisture falls below the required threshold, and relevant system parameters are recorded for monitoring and analysis.

- Hardware assembly using ESP8266, capacitive moisture sensor, water-level sensor, relay module, pump, and power supply.
- Database creation containing crop, growth stage, and moisture threshold fields.
- Sensor calibration using dry soil, optimal moisture condition, and saturated soil readings.
- Decision-rule programming based on the condition: if current moisture is below threshold, activate irrigation; otherwise keep system idle.
- Dashboard preparation for remote monitoring of moisture, tank level, pump status, and irrigation history.

Table 2 Indicative Component Cost for the Prototype.

Component	Quantity	Approx. Cost (INR)	Purpose
ESP8266 NodeMCU	1	350	Controller and Wi-Fi module
Capacitive soil moisture sensor	2	300	Moisture sensing
Water-level sensor	1	150	Tank monitoring
Relay module	1	120	Pump switching
Mini water pump	1	500	Irrigation supply
Solenoid valve / tubing	1 set	850	Water distribution

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Power supply and wires	1 set	450	Power and connections
Casing and miscellaneous	1 set	630	Prototype assembly
Total	-	3,350	Approximate prototype cost

IV. RESULTS AND DISCUSSION

The proposed system is evaluated conceptually using prototype-level design parameters, component cost, and an indicative comparison with manual and fixed-threshold irrigation methods. Since extended field validation across multiple crop cycles is outside the present scope, the values reported here should be treated as prototype estimates and should be verified through controlled greenhouse trials. The comparison is consistent with prior findings that IoT-based irrigation can reduce water consumption by using real-time moisture feedback (Muthuramalingam et al., 2024; Morchid et al., 2024).

➢ *Performance Comparison*

Table 3 Indicative Comparison of Irrigation Approaches.

Parameter	**Manual / Timer Irrigation**	**Fixed-Threshold IoT**	**Crop AI Proposed System**
Decision basis	Human judgment or timer	Single moisture threshold	Crop-stage threshold + real-time moisture
Relative water use	100% baseline	Approx. 78%	Approx. 65%
Crop-stage adaptability	Low	Low to moderate	High
Remote monitoring	No	Possible	Yes
Cost suitability for small farmers	Moderate	Moderate	High
Maintenance requirement	Low	Moderate	Moderate

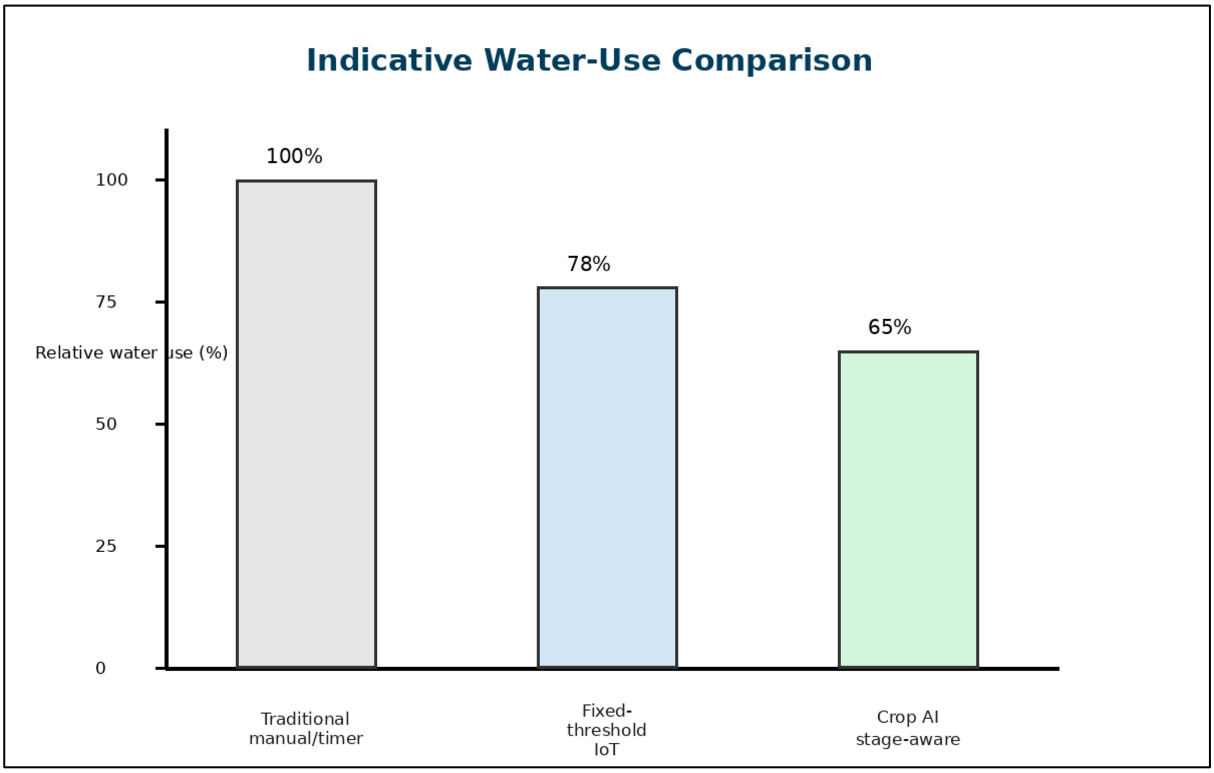

Fig 4 Indicative Water-Use Comparison.

➢ *Interpretation of Results*

The primary contribution of *Crop AI* lies not merely in automation, but in enabling adaptive irrigation. Conventional timer-based systems may operate irrespective of actual soil moisture conditions, often leading to inefficient water usage. Fixed-threshold IoT systems represent an improvement by incorporating sensor feedback; however, they typically apply a uniform moisture threshold throughout the crop lifecycle, without accounting for variations across different growth stages such as seedling, flowering, or fruiting. In contrast, *Crop AI* enhances decision accuracy by retrieving stage-specific moisture thresholds from a structured database, thereby aligning irrigation practices with the principle that crop water requirements vary across growth stages (Allen et al., 1998).

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The indicative comparison suggests that the proposed system has the potential to reduce water usage relative to conventional manual irrigation methods. This reduction is achieved by initiating irrigation only when real-time soil moisture levels fall below the biologically appropriate threshold. Additionally, the system enhances operational transparency, as sensor readings and pump status can be monitored through a mobile-based dashboard. From an economic perspective, the approximate cost of Rs. 3,350 makes the prototype more accessible for small-scale farmers compared to advanced irrigation systems that require higher investment and complex infrastructure. multi-sensor systems that include pH, NPK, weather stations, and predictive analytics (Khupse et al., 2025; Kaur et al., 2024).

➢ *Practical Implications*

The proposed system has the potential to support small-scale greenhouse farmers in reducing water wastage, minimizing the need for continuous manual supervision, and maintaining consistent soil moisture conditions. It is particularly suitable for high-value crops such as vegetables, flowers, nursery plants, and medicinal crops cultivated under controlled environments. Furthermore, the system architecture is scalable and can be extended to support farmer cooperatives and agri-startups that manage multiple greenhouse units, enabling more efficient and coordinated irrigation practices.

V. ADVANTAGES AND LIMITATIONS

➢ *Advantages*

- Reduces unnecessary irrigation by utilizing real-time soil moisture data for decision-making.
- Enables crop-stage-specific irrigation through a database-driven approach.
- Employs low-cost and readily available hardware components, enhancing accessibility.
- Provides scope for future integration with mobile dashboards, alert systems, weather APIs, and AI-based predictive models.
- Demonstrates scalability, allowing deployment from a single greenhouse unit to multiple crop systems.

➢ *Limitations*

- Requires proper calibration of sensors to account for variations in soil type and crop conditions.
- Dependence on Wi-Fi or internet connectivity for complete monitoring and data access.
- Potential issues such as sensor drift, corrosion, or wiring faults may affect long-term reliability.
- The current system does not incorporate additional environmental and soil parameters such as temperature, humidity, rainfall, pH, or nutrient levels.
- Reported performance outcomes are indicative and require validation through extended field trials across multiple crop cycles.

➢ *Application Scope*

- Suitable for water-efficient cultivation of vegetables, flowers, medicinal plants, and nursery crops under controlled greenhouse environments.

➢ *Applications*

- Smart greenhouse irrigation in drought-prone regions.
- Educational demonstration of IoT-based precision agriculture in agricultural and engineering institutions.
- Pilot deployment by agri-startups, farmer-producer organizations, and cooperatives.
- Future integration with predictive irrigation, weather forecasting, and crop advisory systems.

VI. FUTURE SCOPE

Future developments of the proposed system may include the integration of weather forecasting models, evapotranspiration estimation techniques, and machine learning algorithms to enable predictive and adaptive irrigation. The inclusion of additional sensors—such as temperature, humidity, pH, NPK, and light intensity—can further enhance decision accuracy and system responsiveness.

Incorporating solar-powered operation can improve the system’s suitability for deployment in remote and off-grid agricultural regions. Furthermore, the architecture can be extended to open-field irrigation by integrating long-range communication technologies and deploying multiple sensor nodes for large-scale monitoring. These enhancements can contribute to the development of a more robust, scalable, and sustainable smart irrigation framework.

VII. CONCLUSION

This paper presented Crop AI, a crop-database driven smart greenhouse irrigation system for drought-prone regions. The proposed system integrates soil moisture sensing, ESP8266-based control, water-level monitoring, relay-based actuation, and a crop growth-stage database. Unlike conventional timer-based or fixed-threshold systems, Crop AI uses stage-wise moisture requirements to support biologically informed irrigation decisions. The prototype is low-cost, scalable, and suitable for small greenhouse farmers. The study concludes that crop-stage-aware IoT irrigation can improve water-use efficiency and support sustainable agriculture, provided that future field validation is conducted across crops, soil types, and climatic conditions.

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