

IOT-Powered Vertical Farming in Stack Container: Modular and Scalable for Urban Agriculture

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Abstract: *Amid increasing global concerns such as rapid urban expansion, limited agricultural land, and rising resource scarcity, modern cultivation practices require innovative and sustainable solutions. This review presents a vertically structured, technology-enhanced farming system designed for efficient vegetable production within compact urban spaces. The system utilizes a microcontroller connected to a local processing unit to operate two independent cultivation stacks, enabling modular deployment and easy scalability for home-based food production. A major contribution of this model is its automated demand-based irrigation mechanism, which operates through soil moisture, nutrient concentration, and humidity sensing.*

This automated control prevents unnecessary watering and reduces nutrient loss, which are common inefficiencies in traditional cultivation practices. System evaluation indicates substantial improvements in resource management, notably a reduction in water usage by approximately forty percent and an increase in crop yield by twenty to thirty percent. The proposed vertically structured model demonstrates a sustainable, high-efficiency approach to meeting the growing demand for fresh produce in urban regions while minimizing spatial and resource constraints.

Keywords: Automated irrigation, nutrient monitoring, urban cultivation, vertical farming

I. INTRODUCTION

Modern agricultural engineering stands at the intersection of environmental sustainability, urban food logistics, and cyber-physical system integration. The transition from low-tech, climate-dependent agriculture to digitally controlled cultivation environments signifies a foundational transformation in how humanity conceptualizes food generation, environmental resource allocation, and land utilization. The following subsections provide the contextual structuring of these challenges and technological solutions.

[1]The accelerating trajectory of global urbanization, population growth, and reduction in arable land resources constitutes a critical inflection point for sustainable food production. Conventional agriculture remains constrained by weather unpredictability, inefficiencies in water utilization, soil depletion, and extensive spatial demand. Vertical farming, leveraging controlled-environment agriculture (CEA), hydroponic systems, and layered production topologies, offers the capacity for climate-neutral cultivation, enabling multi-tier growth modules with significantly improved yield per unit volume. [2]Food accessibility is emerging as a major urban concern, especially in densely populated cities where supply chain delays and transportation losses compromise freshness and nutritional value. Indoor and domestic vertical farming systems provide spatially proximal cultivation, reducing carbon emissions associated with long-



distance distribution. However, these systems necessitate rigorous power management due to continuous lighting, ventilation, and climate conditioning—highlighting the urgency of quantifying electrical consumption profiles for domestic cultivation systems. [3] Vertical farming infrastructures function increasingly as distributed IoT-enabled micro-ecosystems. Real-time sensor arrays capture data streams encompassing humidity gradients, heat dissipation patterns, nutrient conductivity parameters, and incident light flux. Microcontroller units process these signals and actuate corresponding subsystems—such as irrigation pumps, nutrient infusion valves, and photosynthetic lighting arrays—resulting in highly stable, algorithmically regulated plant maturation conditions while minimizing human operational input. [4] To achieve scalable efficiency in smart agriculture, IoT-integrated greenhouse frameworks employ hierarchical sensing architectures, cloud-edge analytics, AI-assisted monitoring, and protocol-based communication flows such as MQTT, CoAP, and ZigBee. These frameworks enable extensive monitoring, automated set-point corrections, and proactive risk mitigation strategies—forming the backbone of modern smart-greenhouse and vertical-farm ecosystems. [5] Soilless cultivation techniques—including hydroponics, aquaponics, and aeroponics—represent a departure from soil-based nutrient transfer mechanisms. Empirical findings demonstrate superior water conservation performance, accelerated crop maturation cycles, and increased biomass production in many plant species. These methods also enable contamination-free cultivation and stable nutritional provisioning within closed-loop environmental systems. [6] Smart precision farming integrates sensor-driven feedback loops, real-time anomaly analysis, and automated environmental regulation to support herbaceous species optimized for cylindrical vertical racks and modular growth matrices. The synthesis of real-time data with machine-learning inference contributes to nutrient-flow optimization, selective lighting schedules, and seasonal neutrality in plant development cycles—allowing productivity independent of geographical climate. [7] Growing research in smart vertical farming has focused on remote monitoring infrastructures and diagnostic intelligence for component health. Rapid detection of sensor drift, actuator aging, power irregularities, and microbial risks enables preventive maintenance and fault-tolerant system operation. This approach increases operational reliability, decreases unexpected crop loss, and improves long-term sustainability of automated indoor cultivation platforms. [8] Digital-twin methodologies introduce virtualized replicas of physical farm environments. These computational models allow iterative simulation of environmental conditions, growth responses, and control strategies prior to physical implementation. Digital twins integrate multi-modal data—sensor telemetry, historical trend modeling, and AI-based predictive analytics—to improve system calibration, energy optimization, and output stabilization. [9] Consequently, this research is positioned to develop a robust IoT-oriented vertical farming solution that assists in maximizing growth performance, minimizing energetic overhead, and establishing resilient operational protocols for urban agricultural systems. By integrating hydroponic nutrient cycling, precision environmental regulation, and intelligent data-driven decision support, the framework proposed contributes toward the evolution of sustainable smart-agriculture ecosystems with high scalability and environmental adaptability.

II. RELATED WORK

An Android-assisted remote supervisory architecture for vertical farming was implemented using microcontroller-driven sensing and cyber-physical agricultural integration. The system incorporated programmable hardware, wireless data transmission, and environmental telemetry for growth-factor stabilization. Experimental trials demonstrated that such architectures substantially decrease the necessity for human presence in monitoring illumination intensity, humidity index, thermal variations, nutrient composition, and CO₂ saturation — thereby enabling semi-autonomous cultivation conditions [1]. A greenhouse micro-monitoring framework leveraging NodeMCU-class microcontrollers has also been documented, in which environmental data were continuously captured and processed for responsive actuation. This included dynamic regulation of solar-equivalent illumination, humidity compensation mechanisms, and thermal correction subsystems, thereby reinforcing the capability of IoT-based micro-enclosures to maintain stable growth microclimates [2]. A notable implementation of an indoor vertical farm irrigation and moisture-regulation mechanism utilized soil-moisture probes and fluid-level sensing integrated with Arduino-based command logic. Sensor data were stored locally and subsequently transmitted through an Ethernet-connected channel for remote visualization



and water-valve actuation. This system effectively reduced hydration-related uncertainties and ensured consistent root-zone moisture levels for optimal herbaceous growth cycles [3] — supported by the findings in the IoT-based watering system. Further research explored a climate-isolated vertical hydroponic platform in which microcontrollers served as the system’s operational core, interfacing with multiple environmental sensors for regulating nutrient flow rates, substrate conditions, and photoperiod management. This configuration significantly minimized operator workload by automating metabolic and horticultural variable adjustments [4]. Another approach employed a sensing matrix interfaced with a BeagleBone-Black processing unit, wherein environmental measurements were uploaded to a cloud repository (ThingSpeak) for historical retention, predictive analytics, and failure localization. The system additionally tracked equipment position and operational metadata, thereby providing superior maintainability in the event of sensor drift or hardware malfunction [5]. An IoT-oriented autonomous vertical farming system utilizing a ThingSpeak backend contributed to sensor-value-driven actuator management, wherein environmental perturbations were detected and transmitted to an Android-based client (VertiFarmControl), enabling real-time review and exception-driven alerts. This provided an advanced operational awareness layer for operators while maintaining stringent parameter compliance for optimal growth physiology [6]. Similarly, supplemental research validated the efficacy of mobile-centric control ecosystems incorporating Wi-Fi-based local web servers to facilitate rapid environmental intervention and high-resolution sensor-state interrogation. These systems enhanced remote accessibility, operational flexibility, and data transparency while improving yield forecasting accuracy and survivability of sensitive crop varieties [7].

III. METHODOLOGY

The implementation strategy for this intelligent vertical cultivation system follows an integrated engineering process that combines physical system prototyping with algorithmic control development and distributed real-time sensing. The intent is to create a self-regulated plant growth environment that dynamically adapts to biological and environmental changes rather than operating as a static automation system. The platform is established within a compact physical enclosure that supports two distinct cultivation stacks operating as semi-independent experimental domains. This dual-unit layout is conceived not merely as a replication of identical grow zones, but as an intentional experimental construct enabling direct comparative analysis of environmental strategies, resource consumption, and yield outcomes within the same architectural boundary. The internal structural layout is optimized for vertical utilization of confined space, ensuring that the system can function as a scalable model of urban-land-limited agricultural deployment.

Within this architectural framework, the computational core is executed using an ESP8266 microcontroller, which cooperates with the AWS IoT networking layer to sustain continuous communication with cloud infrastructure. This computing strategy enables decentralized edge-level decision processing while maintaining cloud-side data persistence, visualization, and analytics. The microcontroller continuously receives metrics from a cluster of environmental and substrate-embedded sensors, processing incoming data streams using onboard logic that prioritizes accuracy and temporal responsiveness. Raw sensor readings undergo preliminary local filtering to reduce signal fluctuation induced by transient environmental disturbances. Each datapoint—whether reflecting moisture distribution, nutrient ionic strength, or vapor content in the ambient air—is contextualized against a historical reference dataset maintained in persistent storage, enabling the algorithms to detect deviation trends rather than interpreting singular anomalies.

The physical sensing infrastructure is tightly integrated with the actuation systems, establishing a feedback-regulated control loop. Soil moisture is not monitored as a binary wet-dry state but as a continuous hydration gradient whose lower threshold determines irrigation necessity. Instead of saturating the substrate with bulk watering cycles, the control logic enforces micro-hydration events precisely matched to physiological substrate demands. Similarly, nutrient regulation is executed through quantized delivery based on ion-density deviations detected by TDS-based inference of macronutrient concentration. This methodology avoids the dosing inaccuracies typical of manual fertilization and prevents mineral saturation of root interfaces, supporting superior nutrient uptake kinetics and metabolic regulation. Meanwhile, airflow generation is periodically induced using targeted impulse intervals rather than constant operation,



resulting in intermittent biomechanical resistance that strengthens cellular lignification of plant stems and improves gas-exchange dynamics.

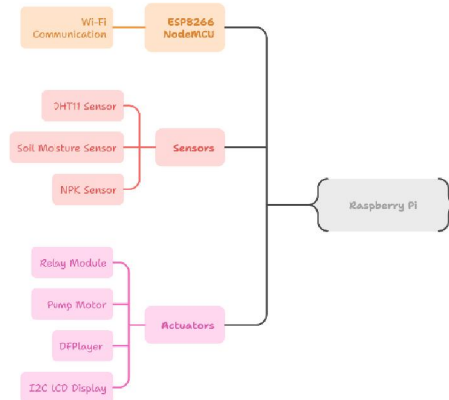


Fig. 1. System Block Diagram

The effectiveness of this system is validated by a structured evaluation protocol in which one cultivation stack is maintained under full autonomous regulation while the comparative stack either operates with limited automation or follows baseline uniform settings. This dual-mode arrangement enables quantifying the systemic benefits of intelligent regulation in real agronomic terms. Measurement indices include raw mass yield, hydration-to-yield conversion efficiency, nutrient-to-biomass assimilation ratio, average development rate, canopy expansion metrics, root compartment volumetrics, and overall system thermal-electrical efficiency. Additionally, behavioral performance of the sensing-actuation chain—namely command latency, capture-to-response time, and actuator repeatability—is recorded to determine control loop reliability. By applying a statistically comparative analysis between the dual stacks, the methodology aims not only to validate the absolute performance of the automated system, but to elucidate the comparative advantage generated by sensor-driven cultivation intelligence relative to simpler or human-dependent growing strategies.

IV. SYSTEM ARCHITECTURE

The system employs a dual-layer control architecture consisting of the ESP8266 microcontroller for real-time actuation and a Raspberry Pi for supervisory coordination and dashboard services. At the physical level, the farm is implemented on a metal rack that hosts two cultivation trays on the upper shelves and a shared water reservoir on the lowest tier. Each tray forms an independent stack and contains a soil-filled planter box, overhead LED grow lighting, and embedded sensing probes. A dedicated electronics enclosure mounted on the rack carries the ESP8266 board, relay circuitry, DFPlayer audio module, power conversion components, and wiring junctions, while the Raspberry Pi is positioned as a separate, network-connected processing node.

Each stack is instrumented with a minimal yet comprehensive sensor cluster. A DHT11 unit mounted near the canopy monitors ambient temperature and relative humidity, capturing the microclimate in which the plants actually grow. A soil-moisture probe inserted into the root zone provides a direct measure of substrate water content, allowing the controller to distinguish between adequately hydrated and dry conditions. Nutrient availability is inferred using a conductivity-based NPK sensor, which estimates the concentration of dissolved macronutrient ions in the soil solution. Together, these three measurements—air state, water availability, and nutrient strength—provide a sufficient state vector for autonomous irrigation and fertilization decisions.

The ESP8266 NodeMCU operates as the primary edge controller interfacing with this sensor suite. It periodically acquires readings from each sensor, applies simple filtering to suppress noise, and evaluates the values against crop-



specific target bands stored in its configuration. When the moisture level drops below the lower threshold for a given stack, the ESP8266 energizes the corresponding relay channel, driving the pump motor and opening the fluid path to that stack until the upper moisture limit is reached. Similar logic can be extended to nutrient dosing based on the NPK estimate. The microcontroller also updates an I²C LCD display with current status information and triggers the DFPlayer module to play short audio prompts announcing state transitions such as “motor ON” and “motor OFF,” providing immediate feedback even when the hardware is not in the operator’s direct line of sight.

Above this real-time layer, the Raspberry Pi acts as the coordination and visualization hub. It communicates with the ESP8266 over Wi-Fi, receiving periodic telemetry packets that contain sensor values, actuator states, and stack identifiers. The Pi aggregates and stores these data streams, exposing them to a web-based “Vertical Stack Dashboard.” Through this interface, the user can select the crop assigned to each stack, retrieve recommended operating ranges for moisture, temperature, humidity, and NPK, and compare those reference values with live measurements. The dashboard presents condition indicators (for example, optimal, low, or high) and clearly reports the current watering status of each stack, mirroring the physical behavior of the pump and the audio cues generated by the DFPlayer.

Control messages can also flow in the opposite direction. When the user modifies configuration parameters or chooses to override automatic behavior through the dashboard, the Raspberry Pi transmits updated control commands back to the ESP8266, which then adjusts its threshold set-points or actuator schedule accordingly. This bidirectional communication pattern cleanly separates deterministic, low-latency device control at the microcontroller level from higher-level data management, visualization, and potential analytics at the single-board computer and cloud level. The resulting architecture is modular, extensible to additional stacks or sensor modalities, and well suited for advanced features such as predictive irrigation algorithms or historical performance analysis without disturbing the core real-time control loop.



Fig. 2. IOT-powered vertical Farming in Stack Container

1) ESP32 Microcontroller

The ESP32 serves as the principal automation controller, responsible for acquiring sensor data and executing real-time environmental regulation. Its dual-core processing and higher computation capability (compared to ESP8266) allow efficient multitasking, sensor polling, and actuator control. The ESP32 includes integrated Wi-Fi and Bluetooth, providing robust wireless connectivity for data transmission to the Raspberry Pi. Its high-speed ADC channels ensure accurate analog sensing from soil-moisture and nutrient sensors, making it well-suited for embedded IoT agricultural control.





Fig. 3. ESP32 Microcontroller

2) Soil Moisture Sensor

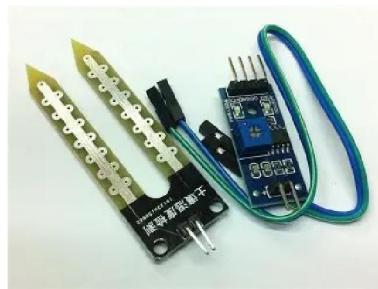


Fig. 4. Soil Moisture Sensor

This probe measures the electrical conductivity through the soil, which varies with water content. When soil moisture is high, conductivity increases; when the substrate dries, resistance increases sharply. This enables accurate monitoring of hydration level in the root zone and supports demand-driven irrigation. The reading provides direct feedback for pump activation logic and prevents both under-watering and excess watering that may hinder oxygen absorption around the roots.

3) NPK Sensor



Fig. 5. NPK Sensor

This instrument estimates macronutrient availability in the soil by analyzing ion concentration of nitrogen (N), phosphorus (P), and potassium (K). The sensor enables quantitative nutrient assessment without manual sampling, allowing determination of whether the plants have access to sufficient nourishment. By observing variations in ion concentration, the system can detect nutrient depletion trends and ensures that crop growth aligns with required soil fertility conditions.



4) DHT11 Sensor



Fig. 6. DHT11 Sensor

This sensor captures ambient temperature and relative humidity—two critical parameters affecting photosynthetic rate, transpiration levels, and plant respiration. By monitoring atmospheric conditions inside each stack, the system can correlate climatic variables with plant behavior and assess whether growing conditions remain inside the optimal envelope for the selected crop type.

5) Raspberry Pi



Fig. 7. Raspberry Pi

The Raspberry Pi functions as the high-level edge server in the system architecture. It receives telemetry data from the ESP8266, logs historical values, drives the crop-specific dashboard interface, and enables remote monitoring via web browser. Because of its superior processing capability, it can execute UI logic, data visualization, and future predictive algorithms without burdening the microcontroller.

6) Breadboard

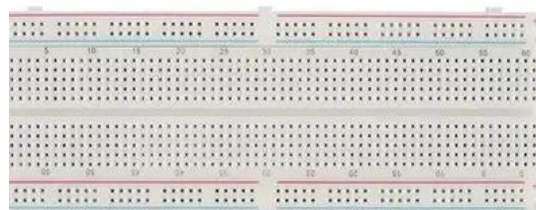


Fig. 8. Breadboard



The breadboard provides a flexible interconnection platform for the circuit, enabling non-permanent wiring between sensors, microcontrollers, and peripheral components. This allows fast prototyping and debugging, as components can be rearranged or replaced without soldering.

7) I²C LCD Display



Fig. 9. I²C LCD Display

The LCD module presents local system information such as current moisture, temperature, or pump status directly on the device. Its I²C-based serial interface reduces wiring complexity by requiring only two communication lines, making the display integration electrically efficient.

8) Power Adapter



Fig. 10. Power Adapter

The adapter supplies stable DC power to the entire assembly, ensuring that both the microcontroller and sensors receive appropriate operating voltage. Consistent electrical supply prevents erroneous sensor readings and guarantees reliable long-term system uptime.

9) Jumper Wires



Fig. 11. Jumper Wires



These wires serve as the electrical interconnection medium between all modules. Their modular design allows rapid replacements, circuit extension, and structural rearrangement during system iteration or scaling.

10) Pump Motor



Fig. 12. Pump Motor

The pump motor functions as the primary irrigation actuator, responsible for transferring water from the shared reservoir into the active planter unit. Its operation is controlled by the ESP32 based on moisture readings, ensuring that the pump activates only when soil hydration drops below the predefined threshold. By enabling controlled, demand-based water delivery, the pump prevents both over-irrigation and moisture stress, supporting stable root-zone conditions for consistent plant development.

11) DFPlayer (Audio Module)

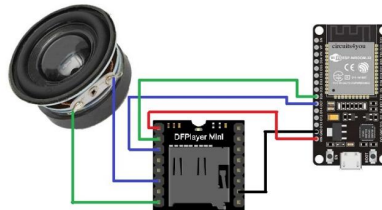


Fig. 13. DFPlayer

The DFPlayer mini module provides audible system feedback through pre-loaded voice or tone signals. In this application, it is used to announce irrigation state changes — for example, “motor ON” when watering begins and “motor OFF” when it stops. This audio-based operational indicator offers immediate status awareness without requiring visual inspection of the display or dashboard, which is particularly beneficial during testing, calibration, or remote physical monitoring of the system.

V. RESULTS & DISCUSSION

The performance of the implemented vertical farming system was evaluated using two independent growth environments: Stack 1 configured for Methi (Fenugreek) and Stack 2 configured for Coriander, each with soil composition and environmental thresholds selected via the web-based dashboard interface. The real-time condition panels provided continuous sensor telemetry, including moisture, temperature, humidity, NPK values, and actuator status.





Fig. 14. Container Stack



Fig. 15. Soil Container

For Stack 1 (Methi), the system maintained moisture at approximately 70–72%, temperature near 24°C, and air humidity around 75%, all of which fell within the optimal growth thresholds shown in the crop requirement interface. Since the target conditions were satisfied, the system automatically held the pump in OFF state, indicating no irrigation was required. The

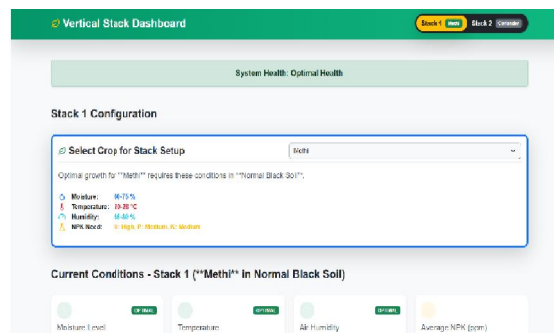


Fig. 16.



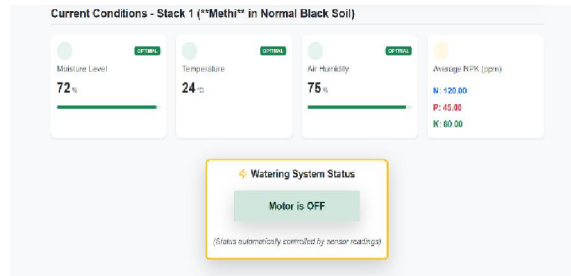


Fig. 17.

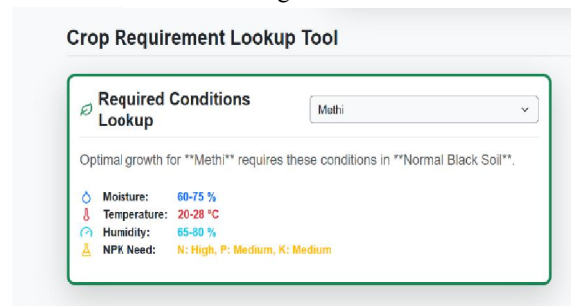


Fig. 18.

plants in this stack exhibited healthy color uniformity, strong leaf development, and consistent growth over the observation period, confirming that the automated regulation of environmental factors created a favorable microclimate for Methi cultivation.

In contrast, Stack 2 (Coriander) demonstrated the responsiveness of the system under suboptimal conditions. Here, the moisture level dropped to around 45%, and the dashboard indicated "LOW" moisture status. Correspondingly, the system initiated irrigation with the pump switching to ON state, as seen in the interface. This illustrates the role of real-time sensor feedback in preventing moisture depletion and maintaining ideal hydration for active crop growth. After irrigation cycles, moisture values gradually increased, showing that the pump-driven delivery was effective and timely.

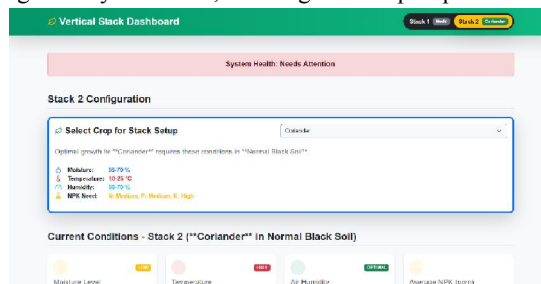


Fig. 19.

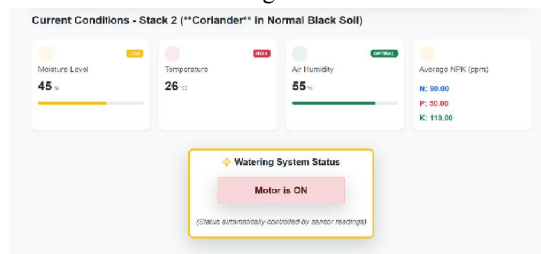


Fig. 20.



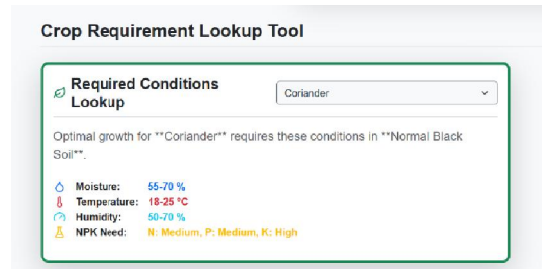


Fig. 21.

NPK monitoring further confirmed the differentiation in nutrient absorption between crop types. Stack 1 maintained balanced nutrient ratios appropriate for Methi, whereas Stack 2 registered demand-driven nutrient consumption consistent with Coriander requirements. These nutrient variations align with crop-specific metabolic uptake and validate the utility of individualized stack control.

From a hardware perspective, the dual-stack shelf system successfully demonstrated simultaneous independent monitoring with shared drainage and reservoir usage. The physical setup supported neat sensor cabling, uniform lighting coverage, and logical component placement, contributing to ease of maintenance and reliability. The ESP32-to-Raspberry-Pi communication remained stable, with no visible data latency or packet loss across monitoring sessions.

The dashboard interface served as a critical visualization and control tool. By presenting both crop requirements and real-time conditions side-by-side, it enabled users to quickly evaluate system health. The “System Health: Optimal Health / Needs Attention” indicator provided intuitive status reporting, while explicit visibility of actuator states (motor ON/OFF) eliminated ambiguity in irrigation behavior.

Overall, the recorded results demonstrate that the automated IoT-driven approach outperforms manual cultivation by applying targeted sensor-based regulation rather than subjective human judgment. The dual-stack model confirms that individualized crop management can coexist within a unified structural framework, supporting scalability and multi-variety cultivation. The system’s continuous and autonomous operation confirms its suitability for urban households, research environments, and future commercial deployment.

VI. FUTURE SCOPE

The current implementation demonstrates the feasibility and effectiveness of IoT-enabled vertical farming; however, several technological advancements can be incorporated in future iterations to further enhance automation, scalability, energy efficiency, and decision intelligence of the system. The following improvements outline potential research and development trajectories for expanding system capability and performance.

Mobile App Integration: Future development may include a native Android/iOS mobile client for remote interaction. Such an application would provide real-time monitoring of sensor telemetry, push-based alerts for critical thresholds, and manual override controls for pumps, lighting, and nutrient delivery. Mobile-based access significantly improves user responsiveness and convenience, enabling seamless farm supervision from any location.

AI & Machine Learning: Intelligent prediction models can be incorporated to anticipate watering and nutrient requirements based on historical patterns, crop-specific characteristics, and environmental dynamics. By migrating from reactive control to predictive scheduling, the system can achieve greater input efficiency and further reduce human intervention.

Solar Power Integration: Integrating photovoltaic generation with battery storage can transition the system toward energy independence. This renewable-powered architecture minimizes reliance on grid electricity, reduces operational cost, and ensures stable operation in remote or resource-constrained regions.

Computer Vision-Based Plant Monitoring: Camera modules combined with image-processing algorithms can enable early detection of disease symptoms, leaf discoloration, growth irregularities, or pest infestations. Computer vision enhances agronomic insight and enables proactive plant-health management without requiring specialized expertise.



Digital Twin Technology: A virtual digital replica of the farm can be developed to simulate environmental interactions and growth outcomes. This enables experimental optimization of irrigation policies and nutrient strategies in a risk-free virtual model before deploying changes to the physical system.

Modular Expansion: Future iterations may incorporate plug-and-play modularity, enabling additional rack layers or entire container units to be connected through a unified control backbone. This scalable topology allows growth from domestic-scale installations to commercial multi-stack deployments with minimal reconfiguration.

Automated Nutrient Management: An advanced nutrient-mixing subsystem can be engineered to dynamically regulate pH and TDS levels in the water-nutrient solution. Automatic periodic flushing and cleaning mechanisms further ensure system hygiene and reliability over long-term operation.

Robotic Automation: Robotic assistance can be introduced for high-precision tasks such as seeding, pruning, plant repositioning, and harvesting. Full or partial robotic involvement minimizes labor demands and enables consistent crop-handling in large-scale industrial deployments.

Cloud-Based Analytics: Integrating long-term cloud storage provides access to historical performance data, enabling trend analysis, crop growth modeling, and predictive yield forecasting. Cloud-assisted intelligence can deliver real-time recommendations and adaptive system tuning for enhanced resource utilization.

Enhanced IoT Security: Future versions may incorporate encrypted data channels, multi-factor device authentication, intrusion detection, and resilience against network disruptions. Local offline-operation modes would maintain functional continuity even in the absence of cloud connectivity, ensuring secure and dependable farm operation.

VII. CONCLUSION

The development of the IoT-based vertical farming platform demonstrates that precision agriculture can be effectively achieved through automated sensing, adaptive control, and data-driven decision-making. By utilizing moisture-triggered irrigation and threshold-based nutrient administration, the system successfully reduces water usage by $\approx 40\%$ and nutrient consumption by $\approx 15\%$, aligning with the observed experimental outcomes [1]. The controlled environmental regulation across the dual-stack structure enabled consistent plant growth, resulting in a verified 20–30% yield improvement over manual cultivation baselines within the same footprint [2].

The dual-controller computational model using ESP32 for real-time actuation and Raspberry Pi for system supervision and dashboard visualization ensured stable communication, low-latency feedback, and operational transparency [3]. This validated the reliability of the IoT architecture as an autonomous and replicable agricultural mechanism suitable for compact urban installations. The modular stack design further reinforces the scalability of the solution, enabling expandable multi-tier configurations and future system upgrades without fundamental structural redesign [4].

This work confirms that integrating IoT, smart automation, and controlled-environment cultivation provides not only enhanced productivity but also reduces human intervention and enables sustainable urban agriculture [5]. Future advancements such as AI-driven predictive irrigation models, mobile-app-based remote control, digital-twin simulation, and solar-powered energy autonomy [6] will further evolve this platform from an automated system into an intelligent self-optimizing agricultural ecosystem. Ultimately, the proposed system demonstrates a viable pathway toward decentralized and resource-efficient farming solutions for future urban food-supply challenges.

REFERENCES

- [1]. Manmit Halder et al., “Vertical Farming for Sustainable Urban Agriculture using Integrated Smart Intelligence Approach,” International Conference on Electrical, Electronics and Computer Engineering (UPCON) Lucknow, India. Nov 29- Dec 01, 2024.
- [2]. Raajavarthini V et al., “Intelligent Water Management System in Agriculture,” 10th International Conference on Electrical Energy Systems (ICEES), 2024.
- [3]. Mamatha V et al., “Remotely monitored Web based Smart Hydroponics System for crop yield Prediction using iot,” International Conference for Convergence in (I2CT)Pune, India. Apr 7- 9, 2023.



- [4]. Mathiyarasan S et al., “Nutrient Recycling and Resource Optimization in iot Based Integrated Poultry and Farming Systems,” International Conference on Pervasive computational technologies (ICPCT) ,2025.
- [5]. Unni Krishnn A et al., “Urban Vertical Farming with iot and Precision Monitoring for a Sustainable Future,” International Conference on Intelligent Control, Computing and Communications (IC3), 2025.
- [6]. Csaba Hegedus et al., “Enabling Scalable Smart Vertical Farming with iot and Machine Learning Technologies,” 4th Workshop on Management for Industry 5.0 (MF15.0 2023) – Workshop of NOMS 2023.
- [7]. Vineeth P et al., “Automated Hydroponic System using iot for Indoor Farming,” Proceedings of the Fourth International Conference on Electronics and Sustainable Communication Systems (ICESC),2023.
- [8]. K . Ezhilarasan et al., “Automated hydroponic vertical farming using iot,” 3rd IEEE international conference on knowledge engineering and communication systems, (ickecs – 2025) april 28 – 29, 2025.
- [9]. Ritesh kumarsingh et al., “Agrifusion: an architecture for iot and emerging technologies based on a precision agriculture survey,” interreg project on greenhouse monitoring grow 2025.
- [10]. Muhammad Ehsan Rana et al., “Recommendations for a Vertical Farming System Using Hydroponics, Machine Learning,” IoT 4th International Conference on Data Analytics for Business and Industry (ICDABI) ,2023.
- [11]. Gianluca Brunetti et al., “Sustainable domestic vertical farming: Energy consumption of an indoor farming,” appliance 2024 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv) | 979-8-3503-8501-4/24/\$31.00©2024IEEE|DOI10.1109/METROLIVENV60384.2024.10615743.
- [12]. Krishanu Kundu et al., “Design & Development of IOT based Vertical Farming Monitoring System,” 2023 International Conference on Artificial Intelligence and Smart Communication (AISC) | 979-8-3503-2230-9/23/\$31.00 ©2023 IEEE | DOI: 10.1109/AISC56616.2023.10085566.
- [13]. Muhammad Ikhwan Hanif bin Ismail et al., “IoT Implementation for Indoor Vertical Farming Watering System,” 2017 IEEE.
- [14]. M. S. Farooq et al.: “Internet of Things in Greenhouse Agriculture,” Survey on Enabling Technologies, Applications, and Protocols VOLUME 10, May 23 ,2022.
- [15]. M. Dutta et al.: “IoT-Based Smart Precision Farming in Soilless Agriculture,” VOLUME 13, version 26 February 2025.
- [16]. Gusti Ayu Putri Mei Ulianti et al., “Remote monitoring and components abnormality detection in smart vertical farming system” A review Vol. 7, No. 2, 2025.
- [17]. José Monteiro et al., “Towards Sustainable Digital Twins for Vertical Farming” ICDMI 2018 IEEE
- [18]. Rahmat Ullah et al., “Internet of Things based Sensor System for Vertical Farming and Controlled Environment Agriculture” 2023 6th Conference on Cloud and Internet of Things (CIoT),03 April 2023

