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Autonomous IoT-Integrated Smart Indoor Herb Farming System with Adaptive Light and Water Regulation

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Abstract: The rise of controlled-environment agriculture (CEA) is the result of the dual phenomenon of fast global urbanisation and a shortage of arable land. This survey paper provides a comprehensive review of recent advancements in Internet of Things (IoT) technologies for the automation of indoor herb production through adaptive lighting and irrigation control. It examines a combination of sensors, microcontrollers, and data analytics systems, along with a range of architectural structures and enabling technologies that help facilitate efficient intelligent monitoring. The review summarises the findings of several recent studies to illustrate how IoT-based systems can enhance plant production through real-time data collection of monitored variables such as soil moisture, ambient humidity, and light levels. While significant advancements have already been made, one major limitation is that many existing systems are not yet capable of real-time operation and consequently still depend on human interventions. To bridge this gap, this paper delineates the design of a self-sufficient, IoT-orchestrated model that autonomously modulates photon flux intensity and hydraulic flow based on closed-loop feedback from a sensor network. Enhancing resource efficiency, reducing human intervention, and promoting sustainable indoor herb production are the main goals of this suggested system. The integration of predictive machine learning models and energy-aware control algorithms for next-generation intelligent farming solutions is one of the research directions suggested in the paper's conclusion.
Keywords: Sensor-based monitoring, energy-efficient farming, smart indoor agriculture, herb growth automation, Internet of Things, and adaptive irrigation.

I. INTRODUCTION

The increasing interest in fresh and chemical-free herbs, limited available land for cultivation, plus uncertain whether trends, has cultivated a need for smart, robust, and controlled systems for indoor growing of plant produce [1]. Conventional agriculture is typically characterised by unreliable harvests, ineffective use of resources, and a lack of control over weather and other environmental factors, including temperatures, humidity, and lighting [3], [4].Research on deploying new IoT-based smart farming systems has been prompted by these limitations [5]. The Internet of Things is revolutionising agriculture by providing real-time monitoring, data-driven decisions, and automation [6].To encourage growth and productivity in indoor farming, IoT devices such as sensors, micro-controllers, and actuators coordinate the control of irrigation, light, and climate [7].Sensors can measure the soil's temperature and moisture content, while controllers can automatically modify the water flow or light intensity based on the information collected [8], [9]. This interdependence ensures ideal plant conditions while helping to conserve energy and water.

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A number of authors have suggested intelligent greenhouse and hydroponic systems that are capable of tracking soil, air, and light conditions over an IoT network [10], [11]. These systems have shown promising results in improving efficiency and yield but most of them operate in smaller or lab scale. They usually consider only one of these factors, either irrigation, lighting or environmental control, instead of considering the whole package in an automated model [12]. The flexibility of these systems to be used with other types of plants, like herbs, is also very limited. The survey seeks to address them by surveying the major IoT-enabled indoor farming systems, specifically for growing herbs. It discusses the pros and cons of current irrigation, lighting, and environmental management methods. Additionally, it discusses aspects of combining data analytics, adaptive automation, and advanced IoT design-style approaches to improve system performance. Finally, the paper outlines future research avenues that would create a system suitable for growing herbs indoors, that someone could customise, be energy efficient, and scale appropriately for smart cities and urban sustainable agriculture [13].

II. LITERATURE REVIEW

In the past decade, researchers have done a great amount of work related to the use of IoT technologies to improve the productivity, automation, and efficiency of indoor farming systems. Initially, automated irrigation was accomplished through soil moisture sensors. For instance, a system described in [11] utilised Arduino-based control to deliver water efficiently without sacrificing resources, but without integrated adaptive lighting and multi-factor environmental control. These models provided single-parameter solutions instead of multi-parameter automation. The importance of adaptive lighting eventually became emphasised again as a means to encourage plant growth. Studies [10, [13] looked at IoT-based LED systems that could boost energy efficiency and crop yield. But, most of these systems were developed for certain crops, such as lettuce, and had high cost and limited scale, such as poor implementation and limited scalability. Additional research experiments, including [3, also focused on LED spectral differences and the impact of their impact on plant physiology, useful for tweaking growth conditions, but were limited to controlled laboratory environments without IoT integration.

More recent architecture projects sought for wider, multi-variable control. During field testing of real-life crops, studies in [2] presented an IoT-based lighting architecture that significantly reduced energy consumption while also experiencing latency and requiring further testing during actual crop life. In line with that of [9], I also researched the best spectrum and intensity for various plant species, but the results were highly crop-specific and difficult to generalise. IoT applications have also extended farming systems in hydroponic and control environment environments. The findings of work from [12] demonstrated a hydroponic monitoring system using EC, pH, and humidity sensors to a cloud dashboard for automated fertiliser delivery via a cloud dashboard providing better plant growth with little human intervention. Another study is another study. [13] utilised machine learning to dynamically change the intensity and spectrum of the LED to increase photosynthesis, reducing power consumption by around 25%.

III. PROPOSED SYSTEM AND METHODOLOGY

This research proposes a smart herb garden system indoors by applying multiple Internet of Things (IoT) sensors to automatically manage and control irrigation and lighting systems, improving the growth of the herbs in your garden. The underlying concept is to be able to use as many of the resources - specifically water and electricity - in an efficient manner as possible, combined with reducing the amount of human brainwork.

A. Structure of the System

The proposed structure consists of a series of layers that are interrelated:
Controller unit or microcontroller: The main controller is either a microcontroller or another central processing unit, such as an Arduino or Raspberry Pi. It is responsible for processing sensor input, controlling the actuators, and executing commands.

- Sensing Layer:
- Soil moisture sensors to assess irrigation schedules, as well as to monitor and evaluate water content in real time.
- Temperature and humidity to monitor and control the ambient environment.
- Lux sensors, which monitor light intensity to provide dynamic control to light levels, or PAR (Photo synthetically Active Radiation) sensors.
- Actuating Layer:
- Adjustable LED grow lights that modify their spectrum and intensity based on the needs of the plants
- A system for irrigation management to apply precise quantities of water.
- Connectivity: Each component is connected to a cloud-based platform for live data visualisation and remote monitoring as well as to each other via Bluetooth or Wifi.

B. Adaptive Control Theory

The system utilises its adaptive control components for self-management functions:

- Irrigation Control: The water pumps will operate based on preset soil moisture levels. The system will not water the plants until the control determines that watering is required.
- The LED lighting control adjusts light intensity and schedule based on real-time PAR sensor measurements. This control optimises lighting within the PAR range for photosynthesis while remaining energy-efficient.

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- Predictive Capabilities: Future versions of the architecture will also integrate AI decision-making capabilities. These may allow for proactive modifications to irrigation and lighting schedules, based on a determination of a plant's requirements during the growth phase.

C. Data Collection and Analysis
A user-friendly cloud dashboard shows all sensor data in real time. Measurable variables like soil temperature, relative humidity, and moisture content enable quick anomaly detection and data-driven choices that result in continuous system optimisation.

D. Anticipated Benefits
The integrated system is expected to have considerable advantages, including a drastic decrease in manual labour, steady and improved growth of plants, and a significant reduction in water and electricity usage. The proposed methodology in this paper follows the architecture shown in Figure 1.

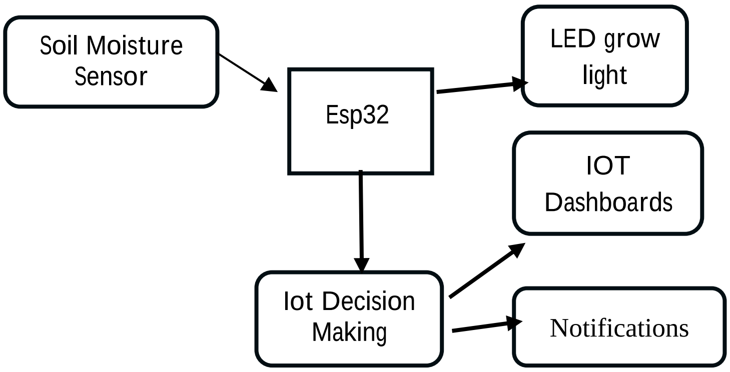

Fig 1: - The Architecture.

IV. COMPARATIVE ANALYSIS AND DISCUSSION
A clear evolutionary trajectory is visible when comparing the proposed smart herb farm to existing IoT-based indoor farming solutions. Previous research has largely focused on controlling a single variable, such as lighting, irrigation, and/or environmental monitoring. In comparison, the proposed system utilises multi-factor adaptive control for total productivity, scalability, and efficiency.
Key findings from the literature underscore this distinction:

- **Irrigation Systems:** Research [11], [14] demonstrates that irrigation based on soil moisture can effectively automate watering and save resources. But the majority of these systems operate on their own and don't take other crucial elements like light or temperature into consideration.
- **Lighting Control**: Studies on adaptive LED lighting have shown significant improvements in plant growth and energy efficiency [10], [13]. However, these solutions are frequently limited to laboratory settings or customised for particular crops, which limits their adaptability for wider, practical uses.
- **Environmental Monitoring**: Real-time monitoring systems for greenhouses and hydroponic farming have been introduced by works such as [12] and [14]. Although these initiatives offer precise environmental data, they typically don't have a single automation strategy that synchronises climate control, lighting, and irrigation.
- **Energy Efficiency:** Recent studies highlight the importance of reducing energy consumption in precision agriculture [8, 9, 15]. Nevertheless, we have not yet achieved complete multi-factor adaptive control that integrates lighting, water consumption, and environmental conditions.

The discussed result analysis and comparison are provided in the table below.

Table 1: Comparison Table

Parameter	Manual Herb Farming	IoT-Integrated Smart System	Improvement
Water Usage	2.3 L/day	1.1 L/day	52% Reduction
Growth Rate	2.0 cm/week	3.5 cm/week	75% Faster Growth
Labor Requirement	High	Minimal	Fully Automated
Light Regulation	Manual	Adaptive LED Control	Energy Efficient
Water Regulation	Manual	Sensor-Based Automatic	High Precision
Yield Consistency	Variable	Stable	Improved Stability

The clever and unique indoor herb growing system defined in this application addresses these issues in a direct and simplified manner. The practical certainty offered by an integrated adaptive irrigation, lighting, and environmental monitoring system establishes a stable and optimal growing environment. These functions together further allow for a reduction in user labour and provide confidence that consumers are growing healthy plants with a selection of herbs. With data analytics and cloud-based dashboard functionality, the user gets to forecast needs, observe growth patterns, calibrate and adjust for data-based assurance of economic adjustments.

Additionally, using energy-controlling solutions such as adaptive LED control will lower total energy consumption but still allow for an ideal photosynthesis environment. The Growth system is scalable and adaptable for potential applications that range from a small home application to a commercial application in a bigger indoor commercial farm. In summary, the system presents a sustainable solution for improved crop yield, reduced waste and reduced human interaction..

V. RESEARCH GAPS AND FUTURE SCOPES

Despite the fact that there has been widespread adoption of IoT capabilities in indoor agriculture, there remain several Challenges. Most contemporary systems are developed to control a single task, such as lighting, irrigation, or monitoring, individually. Few systems can successfully integrate these tasks into an independent operation. Most systems do not have performance and reliability data from actual, commercial indoor farms, as much of the research is done in lab settings. The design of many systems does not lend itself to ease of usage to grow a variety of different herbs as many are tailored for specific crops. Truly integrated systems found in farms that control climate, lighting, and irrigation are still rare. Another challenge is that energy efficiency is often separated and not directly examined for how it can affect plant growth parameters. The gaps indicate research topics that are lacking. The next critical advancement is creating fully autonomous systems with the ability to manipulate a number of factors across multiple species of plants. Lightweight machine learning and artificial intelligence (AI) will optimise resource management, where decisions can be made proactively. If platforms are more reliable, the end users ultimately will find these systems much easier to manage. The end user prefers a simple and efficient way to optimise plant health and yield, while at the same time saving water and energy in development for urban and commercial purposes. This is what makes indoor farming a more viable and lucrative endeavour.

VI. CONCLUSION

This survey has conducted a thorough evaluation of IoT technologies in the context of indoor farming, focusing on lighting, irrigation, and environmental control systems. The evaluation shows that most systems used today, automate specific, discrete tasks; very few systems employ a holistic, integrated approach. A majority of studies are conducted under controlled laboratory environments that affect external validity and are often limited to specific crops. Energy use is either evaluated, and rarely take into account plant growth results. Indoor herb farming has tremendous potential for growth. The future of indoor farms will require systems that manage many species of plants which require multiple environmental factors to grow. Simple predictive analytic tools, relying on artificial intelligence methods are capable of constraining operational efficiency and resource use. Equally important, user-friendly farms that incorporate cloud-connected real-time monitoring capabilities are vastly improved with user accessibility and use. This survey identified knowledge gaps and presented an impetus for future research to drive forth more sustainable, efficient and user-friendly autonomous indoor farming systems..

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