International Journal of Horticultural Science and Technology (2025) Vol. 12, No. 4, pp. 1219-1228 doi.org/10.22059/ijhst.2025.376832.852

International Journal of Horticultural Science and Technology
Journal homepage: https://ijhst.ut.ac.ir

Precision Agriculture: Soil Moisture-based IoT Drip Irrigation System to Optimize Water Usage for Aglaonema in Greenhouse Environment

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ARTICLE INFO

Article history:

Received: 21 May 2024,
Received in revised form: 14 December 2024,
Accepted: 8 January 2025

Article type:

Research paper

Keywords:

Aglaonema Stardust
Drip irrigation
Greenhouse cultivation
Internet of Things
Water scarcity

ABSTRACT

This research paper explores the use of Aglaonema 'Stardust,' a variety of Chinese Evergreen known for its air-purifying properties, in addressing water scarcity challenges. It presents an IoT-based monitoring and irrigation system tailored for greenhouse environments, designed to precisely determine water requirements and optimize growth conditions. The system employs microcontrollers to collect and analyze real-time data. A 30-d drip irrigation experiment was conducted in a greenhouse using four Aglaonema plants, i.e., three integrated into the IoT system with varying soil moisture levels between 45% and 75%, and one irrigated manually. The results demonstrated that maintaining soil moisture between 55% and 65% significantly improved water efficiency, reducing water usage by approximately 2.6 times. This study highlights the potential of IoT-integrated drip irrigation to enhance horticultural productivity and sustainability, particularly for ornamental plants like Aglaonema.

Introduction

The Aglaonema plant, commonly known as 'Chinese Evergreen,' belongs to the Araceae family and is native to Southeast Asia. It is classified into pure strains, which have green leaves with dark patterns, and cross-hybrid strains, distinguished by their more vibrant and varied leaf coloration. The market value of these plants varies widely, ranging from tens of thousands (e.g., Rotundum, Butterfly, Legacy, Adelia) to tens of millions (e.g., Goliath, Golden Hope) in Indonesian Rupiah. Recognized as a popular indoor decorative plant, Aglaonema has gained attention from horticulturists and enthusiasts due to its aesthetic appeal, adaptability to low-light environments, and ability to thrive under artificial lighting and greenhouse conditions (Henny and Chen, 2001). Beyond its ornamental value, Aglaonema contributes to indoor air quality improvement by removing pollutants such as volatile organic compounds (VOCs) and formaldehyde, which are linked to various health risks (Kim et al., 2011; Song et al., 2011; Wi et al., 2020). This study focuses on Aglaonema 'Stardust,' a variety distinguished by its red and green speckled leaves resembling dust. While the benefits of Aglaonema are well documented, optimizing its cultivation requires an in-depth understanding of environmental factors influencing its growth. The plant thrives at a soil moisture level of approximately 60–80% (Akbar, 2021), as insufficient moisture can cause leaf chlorosis and wilting. The ideal air humidity ranges from 50% to 75%; levels below 50% lead to wilting, while those exceeding 75% increase susceptibility to pests. Light intensity should be maintained between 1,000 and 2,000 lux (Wijayanti et al., 2021), as excessive exposure can scorch the leaves, whereas inadequate light diminishes their vibrant coloration. Optimal temperature conditions range from 24–27 °C during the day and 18–21 °C at night, as extreme temperatures may hinder plant development (Bande et al., 2023). The precise management of water and environmental conditions is essential for Aglaonema cultivation, highlighting the broader challenges faced by the horticulture industry in efficiently utilizing water resources (Tzanakakis et al., 2020). Given the substantial water demand in plant development, effective water management is crucial for sustaining productivity (Sabzevar et al., 2021; Bwambale et al., 2022). However, the increasing scarcity of global water resources underscores the urgency of conservation initiatives. Sustainable water use strategies are imperative to ensure both horticultural viability and the responsible utilization of this finite resource. As evidence suggests, re-evaluating water consumption objectives in horticulture is necessary to enhance resource efficiency and sustainability (D'Odorico et al., 2020; Bwambale et al., 2022). Consequently, implementing efficient irrigation methods, such as drip irrigation for Aglaonema plants, can promote optimal growth while significantly improving environmental sustainability. The adoption of advanced technology, particularly the Internet of Things (IoT), in agriculture has revolutionized water management by increasing efficiency and sustainability (Kamienski et al., 2018; Kholifah et al., 2019; Yusof et al., 2019; Hanafi et al., 2021). The cultivation of plants such as Aglaonema demonstrates that IoT-enabled solutions offer an innovative approach to precisely managing water requirements. In addition to irrigation, previous studies have emphasized the role of IoT and various sensors in acquiring environmental data for improved plant monitoring (Choi and Lee, 2020; Kondratieva et al., 2021; Lee et al., 2022; Pramudita et al., 2022; Idros et al., 2023; Lee et al., 2023). The effectiveness of IoT technology is further enhanced when integrated with complementary horticultural support systems. For instance, IoT-based drip irrigation delivers water directly to plant roots, reducing water consumption by approximately 30–60%, lowering labor requirements, mitigating soil erosion, and enhancing crop quality (Arshad, 2020). Although various irrigation technologies have been developed, this study specifically examines Aglaonema, a species that has not previously been analyzed in the context of IoT-based drip irrigation, particularly in a controlled greenhouse setting. While prior research has predominantly focused on the general application of IoT technologies and drip irrigation systems for irrigation management and plant monitoring, it has not extensively investigated the precise water requirements tailored to different environmental conditions and specific plant needs.

This study aimed to address this gap by evaluating an IoT-driven irrigation system designed to optimize water use for Aglaonema cultivation in controlled environments. It focused on water conservation through the precise quantification of water requirements necessary for optimal plant growth and development, advancing beyond fundamental research on sensor positioning and basic irrigation automation. The research was conducted in a greenhouse, providing a controlled environment that regulated essential variables for plant growth, such as air temperature, humidity, and light intensity, within Indonesia's tropical climate, thereby promoting optimal plant development. To achieve this, a soil moisture-driven drip irrigation system was proposed within the greenhouse setting to enhance control over variables critical for the optimal growth of Aglaonema plants. Additionally, the study aimed to determine the optimal irrigation strategy and the necessary water volume within 24 hours to maintain soil moisture levels between 45% and 75%, ensuring optimal soil conditions while promoting water conservation and sustaining ideal growth conditions. Previous research introduced the concept of a high-precision smart irrigation system for agriculture. This IoT-based solution optimized irrigation water distribution and utilization by collecting data on natural water cycles and specific plant growth information. The project, piloted in Italy, Spain, and Brazil, investigated several irrigation techniques, including center pivot and drip irrigation. The process involved collecting data from multiple sensors, making decisions using various methodologies, and adapting irrigation based on crop conditions. The study demonstrated significant potential for improving irrigation efficiency, thereby enhancing water conservation and agricultural practices (Kamienski et al., 2018).

Another study presented an innovative technique for precise irrigation aimed at improving water use efficiency in agriculture. It demonstrated a system for real-time monitoring of soil moisture and pH utilizing IoT technology, with data relayed by NodeMCU ESP8266. A key feature of this system was its energy efficiency, achieved through the use of solar panels. The results highlighted the system's effectiveness in automating irrigation based on soil moisture levels, thereby improving water efficiency in agriculture. This strategy demonstrated the potential for intelligent agricultural solutions, leveraging IoT for sustainable resource management (Kholifah et al., 2019). A different study focused on developing an IoT-based intelligent irrigation system to enhance agricultural productivity. The methodology utilized sensors to evaluate soil moisture, temperature, and environmental variables, including ambient temperature and humidity. These sensors were integrated with a CC3200 microcontroller for data processing. The system enabled real-time monitoring of soil and environmental variables through a web interface, allowing for remote access and management. The study’s findings demonstrated the system’s effectiveness in tracking vital agricultural data, facilitating more precise and efficient irrigation techniques. This approach underscored the potential of IoT technologies to enhance agricultural productivity and resource management (Yusof et al., 2019). Another study investigated the significance of efficient drip irrigation systems in agriculture, emphasizing their role in water conservation and enhanced productivity. It analyzed various components and design concepts of drip irrigation systems, highlighting advantages such as water conservation, labor efficiency, and consistent water distribution. The evaluation underscored the importance of proper system installation, management, and maintenance, emphasizing the need for regular upkeep and the rectification of issues such as obstructions and leaks. The study reinforced the usefulness of drip irrigation systems in improving agricultural practices and sustainability (Arshad, 2020).

Further research explored an IoT-based technology designed to enhance agricultural irrigation efficiency. The system utilized pH and soil moisture sensors to collect real-time data, which was analyzed in a cloud environment using microcontrollers. A key feature of this system was a mobile application that enabled farmers to manage and control irrigation, focusing on soil moisture and water pH levels. The results indicated that systems utilizing sensor data and WiFi-enabled microcontrollers could efficiently manage crop irrigation, demonstrating their potential to improve water conservation and agricultural practices (Balasooriya et al., 2020). Additionally, another study presented a comprehensive IoT solution for greenhouse agriculture. The system employed multiple sensors to assess and control environmental factors, including soil moisture, air temperature, and humidity, ensuring optimal growing conditions. A key component was the integration of soil moisture sensors into a drip irrigation system, which autonomously regulated water use based on real-time soil conditions. The results highlighted the system’s effectiveness in reducing water consumption and enhancing crop yield, demonstrating the potential of IoT in promoting sustainable agricultural practices (Kodali et al., 2016).

Furthermore, in 2022, a study presented a system for chili aquaponics farming that utilized IoT technology for monitoring and control. The device employed sensors to evaluate characteristics such as pH level, water level, temperature, and humidity, which were essential for optimal plant growth. The information collected by these sensors was transmitted to a smartphone application, enabling real-time monitoring and control. The study demonstrated that the system effectively maintained key growth parameters within ideal thresholds, with an average sensor accuracy of 96.29%. This finding illustrated the system's effectiveness in maintaining optimal conditions for aquaponics cultivation, highlighting its potential to enhance agricultural efficiency and productivity (Pramudita et al., 2022). In 2023, a report outlined the development of an advanced irrigation system that utilized Internet of Things (IoT) technologies. This system integrated ESP32 microcontrollers with several sensors for measuring soil moisture, temperature, air humidity, and water flow. A key feature of the system was its ability to automate irrigation based on real-time soil conditions, thereby improving water efficiency. The research demonstrated the system's effectiveness in irrigation management, emphasizing its ability to enhance water conservation and agricultural productivity in smart farming (Pereira et al., 2023). The development of IoT-based smart irrigation systems had been a significant trend in agricultural research over the past decade, as evidenced by numerous studies. These advancements revolutionized irrigation and monitoring, underscoring the growing importance of technology in agriculture. Most studies illustrated systems that utilized sensors to measure soil moisture, temperature, and environmental variables, with data processed using microcontrollers and cloud platforms. Notable advancements in specific research included automation based on real-time soil conditions, energy efficiency through solar panels, and remote monitoring and control interfaces. In contrast to previous studies that primarily focused on implementing IoT systems for irrigation automation and monitoring, this research aimed to determine the most efficient water usage for Aglaonema, ensuring optimal growth conditions by regulating ideal soil moisture, air temperature, humidity, and light intensity. The study was conducted in a greenhouse to provide a controlled environment, enabling precise regulation of conditions tailored to Aglaonema's needs.

Material and methods

This research proposed an IoT-based monitoring and irrigation system specifically designed for Aglaonema plants within a greenhouse setting. The system employed an Arduino microcontroller to regulate the drip irrigation operation, while a Raspberry Pi functioned as the interface linking the Arduino to the database server. The research was conducted in several stages, as depicted in Figure 1, encompassing hardware construction, software development, system integration, data collection, and data analysis.

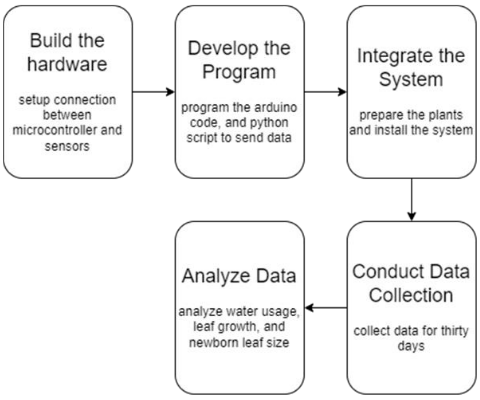

Fig. 1. Research stages of the study.

The study consisted of an experiment with four Aglaonema plants of the same species, each exposed to distinct soil moisture levels: Plant A (45-55%), Plant B (55-65%), Plant C (65-75%)—all utilizing a drip irrigation system—and Plant D, which received manual watering. The study also examined supplementary factors such as leaf count, which ranged from 11 to 17 leaves, and pot size, which had a diameter of 17 cm. This study aimed to determine the appropriate soil moisture levels and efficient irrigation water utilization for Aglaonema plants through the implementation of the proposed system, as shown in Figure 2.

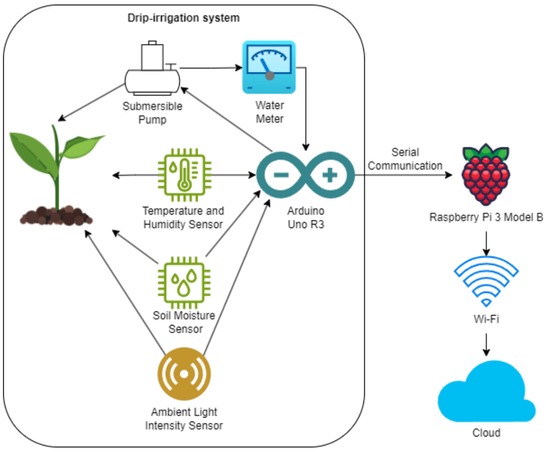

Fig. 2. System architecture design of the drip irrigation system.

Figure 2 demonstrates that in each plant configuration, an Arduino Uno R3 board serves as the microcontroller, gathering environmental data pertaining to the plant. This board is linked to multiple electrical components, with their connections illustrated in Figure 3. The HW-390 capacitive soil moisture sensor, recognized for its corrosion-resistant characteristics, measures soil moisture, thereby improving durability and reliability. The DHT22 sensor, which precisely detects humidity and air temperature (with a maximum error rate of $\pm$ 0.5 °C), is selected for its high-resolution readings, enabling the detection of slight atmospheric variations and assuring reliable real-time data collecting. The GY-302 BH1750 sensor quantifies the ambient light intensity in the vicinity of the plant. The YF-S401 water flow sensor measures water use during irrigation. Irrigation is conducted using submersible mini-water pumps, which are optimal for their effectiveness in distributing the minimal water necessary and sustaining soil moisture at desirable levels. The activation of the pump is regulated by a metal-oxide-semiconductor field-effect transistor (MOSFET), namely the IRF520 MOSFET driver module. The energy required to operate the pump is derived from a 3.7-volt battery.

All three Arduinos conveyed data to the Raspberry Pi 3 Model B board using serial transmission. This board served as the primary conduit, enabling communication between the Arduino and the database server. The BCM43438 wireless LAN module in the Raspberry Pi 3 Model B facilitated internet connectivity, allowing for data uploads to the database server. The selection of the Raspberry Pi 3 Model B board was due to its adaptability in supporting various programming languages and facilitating the integration of cloud services. Additionally, the Raspberry Pi 3 Model B enabled straightforward monitoring and troubleshooting of the data collection system through its remote access management features. Figure 4 illustrates the data collection process on the Arduino board. The drip irrigation system assessed air temperature and humidity before measuring the ambient light intensity around the plant. The system then computed the soil moisture levels. It engaged the pump when soil moisture dropped below the minimum threshold, irrigating the plant until moisture levels exceeded the maximum threshold. The measurements were subsequently broadcast to the cloud at 5-second intervals. To evaluate the efficiency and usefulness of the proposed system, we manually assessed the leaf growth of each plant. This involved measuring the length and width of each leaf, as well as documenting the number of newly emerged leaves for each plant.

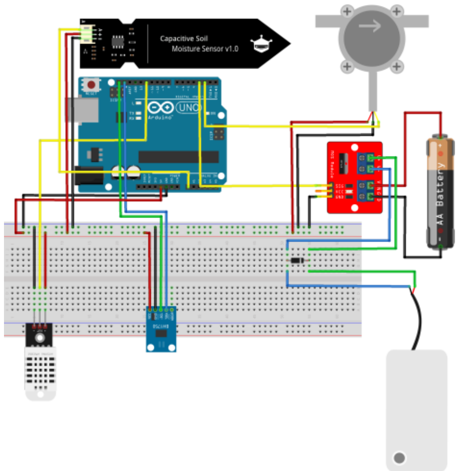

Fig. 3. Hardware design of the drip irrigation system.

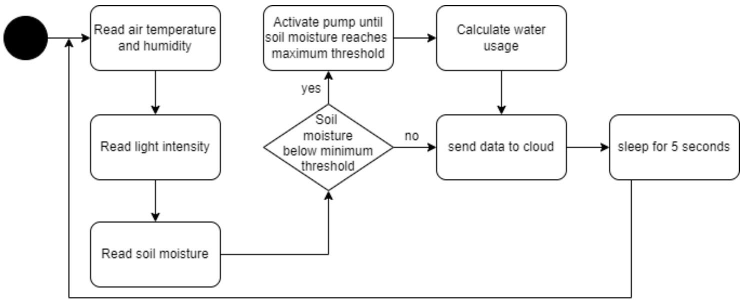

Fig. 4. Data collection flow of the drip irrigation system.

Results

Figure 5 illustrated the implementation of the system. Figures 5a-c depicted each plant utilizing the system's implementation, while Figure 5d illustrated the plant receiving manual irrigation. The experiment was conducted in a greenhouse setting, maintaining a stable air temperature of 29.7°C, air humidity of 71.66%, and ambient light intensity of 1143.56 lux during daytime hours. The system gathered data over a 30-d period, with leaf measurements taken both prior to system setup and following the 30-d experimental duration.

Following the analysis of the dataset, data were collected regarding the water consumption of all four plants. Figure 6 depicted the average water use for each plant, correspondingly. Plant A required an average of 18.59 mL of water per irrigation. Over a period of 30 d, the irrigation system for Plant A was activated 43 times. This indicated that there were instances when Plant A necessitated irrigation twice to sustain the soil moisture content between 45% and 55%. As a result, Plant A used 799.32 mL of water during the 30-d period. Conversely, Plant B required an average of 23.62 mL of water for each irrigation.

Although Plant B required a greater average water supply than Plant A, its irrigation system was engaged only 13 times over the 30-d period. Thus, Plant B's overall water use during this timeframe was lower than that of Plant A. Plant B's system used a total of 307.03 mL of water over 30 d. Additionally, Plant C required an average of 82.34 mL of water per irrigation. This elevated average was necessary to consistently sustain soil moisture levels between 65% and 75%. Similar to Plant B, the irrigation system for Plant C was engaged only 10 times during the 30-d period. Nevertheless, due to its higher average water demand, Plant C's overall water consumption exceeded that of Plants A and B, using 823.44 mL of water over the 30 d. Finally, Plant D received manual irrigation bi-daily with 50 mL of water, resulting in an aggregate consumption of approximately 750 mL over the 30-d period.

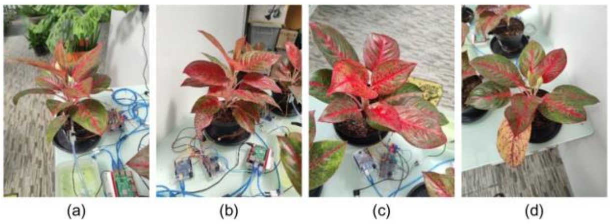

Fig. 5. (**a**) Plant A; (**b**) Plant B; (**c**) Plant C; and (**d**) Plant D.

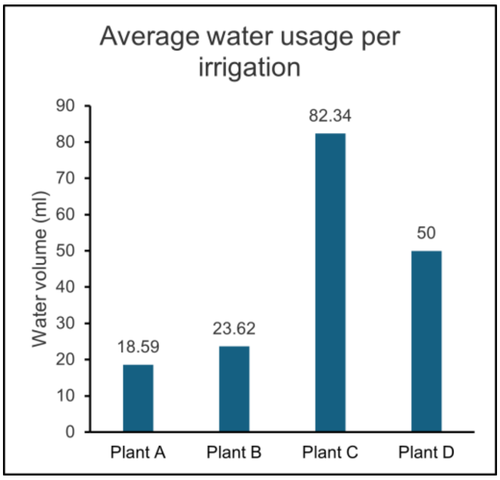

Fig. 6. Average water usage per irrigation in milliliters.

To further demonstrate the efficiency of each soil moisture level, the leaf growth of each plant was measured over a period of 30 d. Leaf growth included the measurement of both the length and width of each leaf. The growth was determined by subtracting the length and width of each leaf prior to and following the 30-d drip irrigation system implementation. Table 1 presents the leaf growth of each plant.

Table 1. Average leaf growth in length and width of each plant.

Plant	Average Leaf Growth			
	Length	Length (%)	Width	Width (%)
Plant A	0.25 cm	2%	0.11 cm	1.4%
Plant B	0.2 cm	1.43%	0.12 cm	1.44%
Plant C	0.11 cm	0.83%	0.05 cm	0.58%
Plant D	0.17 cm	1.25%	0.08 cm	0.99%

Over a period of 30 d, the mean length increase for Plants A, B, C, and D was 0.25 cm, 0.2 cm, 0.11 cm, and 0.17 cm, respectively. Their average growth in width was 0.11 cm, 0.12 cm, 0.05 cm, and 0.08 cm, respectively. Plant A exhibited the highest growth rate in length, while Plant B showed the greatest growth rate in width. In contrast, Plant C had the slowest development rate compared to Plant D. Alongside leaf growth rates, the number of newly formed leaves was also evaluated to substantiate the proposed system's effect on Aglaonema plants. Over the 30-d period, Plants A, B, C, and D produced 1, 1, 2, and 2 new leaves, respectively. Figure 7 illustrates the average length and width of new leaves for each plant. This examination of new leaf development supports the advantages of the drip irrigation technique, as evidenced by the notable enlargement of the new leaves. New sprouts emerged from the Aglaonema plants, with Plants A, B, and D, each producing exactly one new sprout.

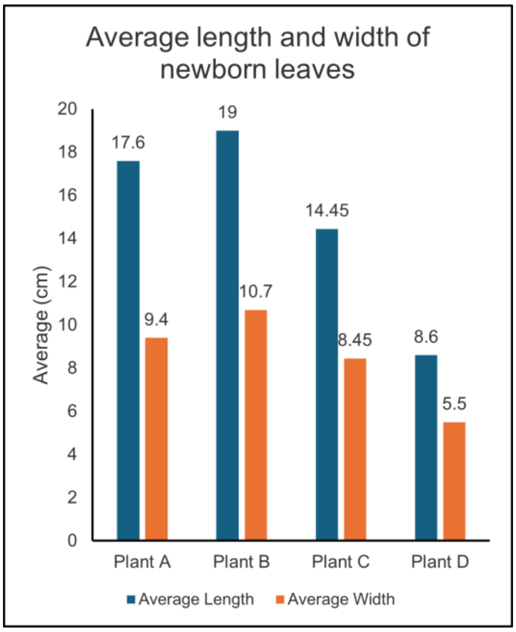

Fig. 7. Average length and width of newborn leaves in centimeters.

Discussion

Plant B demonstrated the highest efficiency in water consumption among the plants, utilizing only 23.62 mL of water per irrigation, which totaled 307.03 mL over the 30-d period. This suggests that maintaining a soil moisture level between 55% and 65%, as seen with Plant B, results in reduced water consumption compared to other moisture levels and manual watering techniques. Moreover, soil moisture levels between 55% and 65% have been shown to be more effective and ideal for meeting the hydration requirements of plants. To further demonstrate the beneficial effects of each soil moisture level, the leaf growth of each plant was also evaluated. The findings revealed that Plant A exhibited the highest growth rate. However, when assessing the overall water usage over the 30-d period, Plant B demonstrated greater efficiency than the other system-implemented plants. It used 2.6 times less water than Plant A, with only a negligible difference of 0.05 cm in average leaf length growth. Despite its lower average leaf length growth, Plant B's reduced overall water consumption compared to Plant A represents a reasonable trade-off. This further substantiates the idea that effective water utilization can enhance a plant's leaf development rate. Additionally, the varying rates of water utilization influenced the development of new leaves. After the measurements, Plant B showed the greatest length and width of newly formed leaves relative to the other plants, suggesting that Plant B's water consumption positively affected both existing and newly developing leaves. In addition to the findings regarding soil moisture implications, a potential drawback of this study is the influence of uncontrollable environmental factors or variations in plant responses, which may have affected the results despite attempts to maintain consistent conditions. While air temperature, humidity, and light intensity within the greenhouse were monitored, other environmental elements, such as variations in soil composition or minor fluctuations in the microclimate surrounding individual plants, may have influenced the results.

Furthermore, Aglaonema plants may show inherent variability in their responses to soil moisture due to genetic differences or other physiological factors not considered in this experiment, potentially leading to discrepancies in growth outcomes within the sample population. Future research should focus on extending the data collection duration for a comprehensive long-term impact assessment of

Aglaonema plants, encompassing a broader range of species to assess the generalizability of the identified optimal soil moisture level. Additionally, integrating advanced sensors, such as soil temperature sensors, for more comprehensive environmental data acquisition would be beneficial. Implementing machine learning for data analysis and predictive irrigation schedules, scaling the system for diverse conditions, and enhancing energy efficiency through renewable sources are crucial steps for advancing the research. Furthermore, a thorough cost-benefit analysis for commercial scalability, comparative evaluations of alternative irrigation techniques, and a focus on soil health to examine the impact of different moisture levels on soil quality are essential for promoting sustainable and efficient farming practices.

Conclusions

This study successfully demonstrated the potential of an IoT-based monitoring and irrigation system for optimizing water usage in Aglaonema cultivation within a controlled greenhouse environment. By utilizing a soil moisture-driven drip irrigation system, this research not only optimized water consumption but also improved leaf growth and development across the plants. Among the four plants evaluated, Plant B, which was maintained at a soil moisture level of 55-65%, demonstrated the highest water-use efficiency, consuming significantly less water than the other plants, while still exhibiting commendable leaf growth. The study's findings highlight the importance of precise water management, particularly for plants with specific hydration needs, and emphasize that maintaining optimal soil moisture levels is crucial for both water conservation and plant health. While the study confirmed the efficiency of the proposed system, potential environmental variables, such as microclimate variations and genetic differences among plants, could have influenced the results. These factors underline the importance of further research that extends the data collection period, incorporates broader species variability, and employs advanced sensors and machine learning techniques for predictive irrigation. Additionally, future studies should explore the scalability of this system, its cost-effectiveness, and the impact of varying moisture levels on soil health, all of which are vital for promoting sustainable agricultural practices. Ultimately, this research offers valuable insights into the practical application of IoT technologies in precision agriculture, emphasizing the need for sustainable water use in plant cultivation. By advancing such systems, it is possible to significantly improve agricultural productivity and contribute to environmental conservation, aligning with the growing need for smart, resource-efficient farming solutions.

Author Contributions

Conceptualization, LK, R, and BS; methodology, LK and R; software, R; validation, LKarenza and R; formal analysis, LKarenza and R; investigation, LKarenza and R; resources, LKarenza, R, and BS; data curation, L Karenza and R; writing—original draft preparation, LKarenza and R; writing—review and editing, BS; visualization, R; supervision, BS; project administration, BS; funding acquisition, BS. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding

Conflict of Interest

The authors indicate no conflict of interest in this work.

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