Enhancing Watering System Efficiency of Organic Greenhouses Zonal Sensors and Solar Power Approaches in the Mekong Coastal Region

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Abstract: The need for effective irrigation has grown because of the growing demand for sustainable agriculture, especially in organic greenhouses. Traditional irrigation techniques in the Mekong Coastal Region frequently result in energy inefficiency and water waste. In order to increase irrigation efficiency and meet the demand for precision watering, this study integrates solar-powered zonal sensor systems. The goal is to create a cutting-edge system that minimizes energy use and maximizes water use. Real-time data was gathered using capacitive moisture sensors and WeMos Arduino MEGA to operate solar-powered pumps that modify water distribution according to soil moisture levels. By eliminating the need for external energy sources, the system increased water efficiency and reduced consumption by 30% when compared to traditional methods, which helped to save money and promote sustainability. This study provides a scalable model for other areas dealing with comparable issues and shows how solar-powered, sensor-based irrigation systems can revolutionize organic farming in the Mekong Coastal Region.

***Index Terms*—Greenhouses, Zonal Sensors, Watering System.**

I. INTRODUCTION[1]

The demand for sustainable agricultural practices has grown significantly in recent years, driven by the global need to enhance food security and reduce environmental impacts. Organic farming has gained prominence due to its potential for reducing the use of synthetic chemicals and promoting biodiversity. However, one of the critical challenges in organic agriculture, especially in greenhouse environments, is the efficient management of water resources. In the Mekong Coastal Region, where the agricultural sector plays a crucial role in the local economy, farmers often face water scarcity, inefficient irrigation systems, and high energy costs associated with conventional water management methods [1]. To address these issues, innovative technologies such as zonal sensor systems and solar-powered irrigation have emerged as viable solutions. These systems offer precise water delivery, improved resource efficiency, and reduced operational costs, aligning with the broader goals of sustainable agriculture [2].

Recent advancements in precision agriculture have introduced smart irrigation systems that integrate wireless sensors, data analytics, and renewable energy sources. Zonal sensors allow for real-time monitoring and control of soil moisture levels in specific greenhouse zones, thereby optimizing water usage and minimizing waste. Solar power has also become a popular energy source for irrigation, offering a sustainable alternative to grid electricity, especially in rural areas where energy infrastructure is limited. However, despite the availability of these technologies, their adoption in organic greenhouse farming remains limited due to high initial costs, technical complexities, and the lack of region-specific studies that demonstrate their effectiveness [3]. Addressing this research gap, the current study explores the integration of zonal sensor technology with solar power in organic greenhouses in the Mekong Coastal Region to enhance water-use efficiency and promote sustainable farming practices.

Existing studies on smart irrigation systems have demonstrated their potential to improve water efficiency in agricultural settings. For instance, [4] found that the use of wireless soil moisture sensors in greenhouse farming reduced water consumption by up to 40%, highlighting the role of sensor-based systems in precision irrigation. Similarly, [5] examined the impact of solar-powered irrigation systems on energy savings and found that solar energy could meet up to 80 % of irrigation energy demands in rural farming communities. However, while these studies

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provide valuable insights, they often focus on specific crops or geographic regions, and there is a lack of comprehensive research addressing the unique conditions of the Mekong Coastal Region, particularly in organic greenhouse farming.

Moreover, current research has primarily focused on either zonal sensor systems or solar power as individual technologies [6], without fully exploring their combined potential in addressing water management challenges in organic greenhouses. This gap in literature suggests that further investigation is needed to understand how these technologies can be integrated effectively to achieve optimal results. By examining the synergy between zonal sensors and solar power in a real-world agricultural setting, this study aims to fill this gap and contribute to the growing body of knowledge on sustainable farming practices.

Despite the advancements in smart irrigation technology, organic greenhouse farmers in the Mekong Coastal Region continue to struggle with inefficient water management and high energy costs. Traditional irrigation methods often lead to water wastage, while the reliance on grid electricity for powering irrigation systems increases operational expenses. The lack of research focused on the integration of zonal sensor systems with solar power in this region presents a critical gap that must be addressed to enhance the sustainability and profitability of organic farming practices. The primary objective of this study is to develop and evaluate an innovative irrigation system that combines zonal sensor technology with solar power to improve water efficiency in organic greenhouses. Specifically, the research seeks to assess the effectiveness of zonal sensors in optimizing water distribution in greenhouse zones, evaluate the energy-saving potential of solar-powered irrigation systems, and analyze the overall impact of the integrated system on water use efficiency, crop yield, and operational costs in organic greenhouses. The findings of this research are expected to have significant implications for both agricultural theory and practice. The integration of zonal sensors with solar-powered irrigation systems offers a scalable, cost-effective solution for enhancing water management in organic greenhouses, particularly in regions facing water scarcity and energy limitations. In addition to contributing to the body of knowledge on precision agriculture, the study has practical applications for farmers and policymakers seeking to promote sustainable farming practices in the Mekong Coastal Region. The results could inform future agricultural policies and encourage the wider adoption of renewable energy-based technologies in the sector.

II. METHODOLOGY

A. Area/Location

The study was conducted in organic greenhouses located within the Mekong Coastal Region, specifically in Nakhon Phanom Province, Thailand, which is known for its hot and humid tropical climate. The region experiences average temperatures ranging from 25°C to 35°C, with humidity levels typically between 70 % and 90 %. Solar radiation levels in the region are high, making it an ideal location for solar-powered systems. These environmental conditions directly influence greenhouse operations, impacting factors such as water evaporation rates and plant transpiration, which are critical to the effectiveness of the watering system.

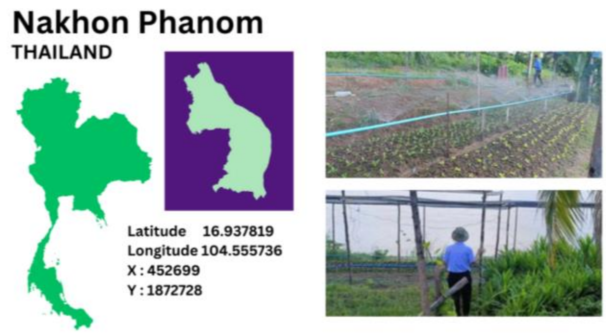

Fig. 1. Area Selection, Nakhon Phanom Thailand

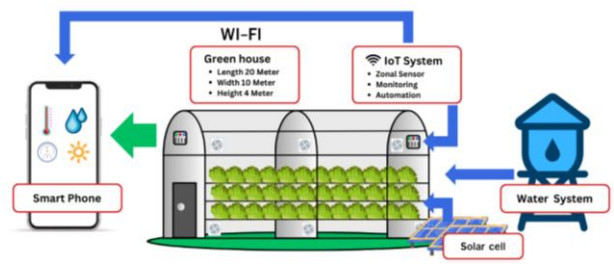

Fig. 2. Greenhouse structure and systems

B. Greenhouse Design and Setup

The organic greenhouses involved in this study were constructed using a combination of polyethylene covers and steel frames, each with a dimension of 20 meters in length, 10 meters in width, and 4 meters in height. Inside each greenhouse, distinct zones were created based on crop type and varying microclimates, including areas for leafy greens and root vegetables. The watering system was installed across these zones, with each section receiving customized irrigation based on its specific water needs. Variations in temperature and humidity within each zone were also considered, influencing water distribution strategies.

The solar power system consisted of 300-watt polycrystalline solar panels, with an efficiency rate of 18%. These were connected to a 200 Ah deep-cycle battery storage system, along with an MPPT (Maximum Power Point Tracking) charge controller to maximize energy capture. The system powered the entire irrigation network, including the control system and sensors. The solar power system was configured to operate autonomously, with the control unit automatically distributing power based on the energy demands of the sensor and watering system. This integration allowed for real-time responses to sensor data, optimizing water use based on actual environmental conditions. This study was a combination of drip irrigation and micro-sprinklers, depending on the crop type. In each zone, water was delivered either directly to the root zone via drip emitters or through micro-sprinklers for broader area coverage. Sensor feedback from each zone triggered the irrigation system when moisture levels dropped below the predefined threshold, ensuring precise water delivery. Water for the system was sourced from a rainwater harvesting tank equipped with a basic filtration system to remove particulates. Adjustments to water pressure and flow rates were made automatically based on sensor readings, ensuring optimal water distribution across all zones.

The hardware system in this research was designed with a focus on developing an efficient and autonomous environmental monitoring device for agricultural applications as shown in Fig. 3. The system prioritizes ease of use for farmers while integrating wireless connectivity and data logging capabilities. The core controller is the WeMos Arduino MEGA 2560 combined with an ESP8266 Wi-Fi module, responsible for overall system control, data display, system configuration, and environmental data storage onto an SD card. A secondary microcontroller, the WeMos D1 Mini Pro, serves as a remote sensor node that collects atmospheric temperature and humidity data from the AM2315 sensor via an I^2C interface and transmits the data wirelessly to the main controller.

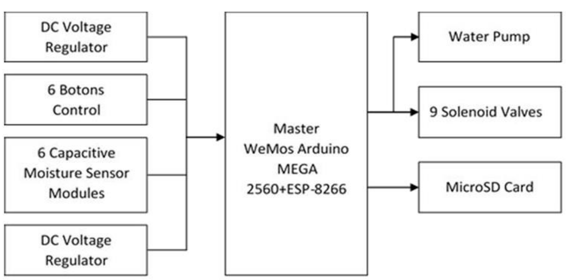

Fig.3 The greenhouse structure and systems using IoT.

The system also incorporates a capacitive soil moisture sensor, which delivers analog signals directly to the microcontroller, as well as a real-time clock module (RTC DS3231) that provides accurate timekeeping for scheduled data logging and automated control operations. A 3.5-inch TFT LCD display presents real-time environmental data for user-friendly monitoring. The entire system is powered by a solar cell, ensuring energy autonomy in off-grid environments. Additionally, a solenoid valve is integrated to automate irrigation based on the detected soil moisture levels, thereby supporting precision agriculture practices.

The design process was carried out in a structured, step-by-step manner, beginning with the specification of system requirements, selection of appropriate components, and design of the communication architecture. This was followed by circuit assembly, firmware development, and preliminary testing in laboratory conditions. The final system was deployed and validated under actual field conditions. The integration of hardware, firmware, and energy management within this system demonstrates a practical and reliable solution for smart farming applications, providing a balance between technological capability and ease of implementation in real-world agricultural contexts. .

An Arduino Mega 2560 microcontroller was used to automate the entire system. The control system processed real-time data from the sensors and triggered specific actions such as starting or stopping irrigation in different zones. The algorithm programmed into the controller ensured that watering occurred only when moisture levels dropped below set thresholds, optimizing water usage based on current environmental data. The system also used time-based control for areas with a fixed irrigation schedule, allowing flexibility in managing different crop needs

Fig. 4 illustrates the configuration of the Zonal Soil Moisture Monitoring System, comprising six nodes (Node 1 to Node 6). Each node is outfitted with capacitive moisture sensors to measure soil moisture levels. The acquired signals are subsequently relayed via the analog input connection to the WeMos Arduino MEGA 2560 control board, which interfaces with the ESP8266 for processing and data storage. The microcontroller is energized by solar panels and presents real-time data on a 3.5-inch TFT LCD display. Furthermore, data is retained on a Micro SD Card for subsequent analysis. This system is engineered to autonomously monitor and assess soil moisture across several sections of the cultivation greenhouse, facilitating accurate water regulation in each zone, minimizing water wastage, and improving water management efficiency for sustainable agriculture in the Mekong River region.

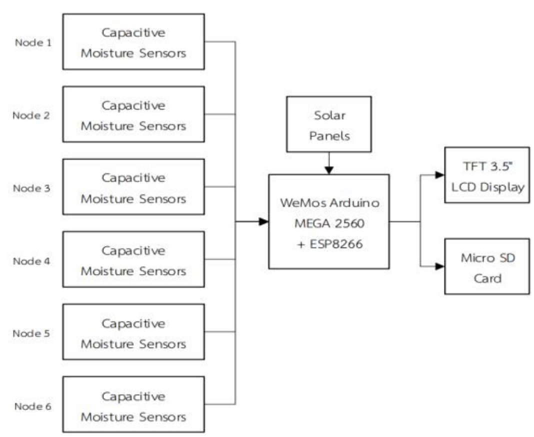

Fig. 4 System architecture of zonal soil moisture sensing and monitoring for intelligent greenhouse cultivation.

The capacitive soil moisture sensor outputs an analog voltage signal that inversely correlates with the actual soil moisture level: a higher output voltage indicates lower soil moisture (drier soil), whereas a lower output voltage reflects higher soil moisture (wetter soil). To simplify interpretation and enhance the consistency of control logic, the raw signal must be converted and inverted accordingly. The analog signal is first read from the sensor pin using the following expression:

$$RAW = 1023 - analogRead(PIN) \quad (1)$$

This transformation inverts the signal to align with the actual moisture percentage (i.e., a higher RAW value represents higher moisture). To normalize the raw values into a more intuitive percentage scale (0–100%), Equation (2) is used:

$$Value(\%) = \frac{(RAW - InMin) \times (OutMax - OutMin)}{(InMax - InMin) + OutMax} \quad (2)$$

Where InMin is the minimum input value (typically 0), InMax is the maximum input value (typically 100), OutMin is the raw analog value representing the driest condition of the soil (approximately 340), OutMax is the raw analog value representing the wettest condition of the soil (approximately 690),Value (%) is the converted output that represents the current soil moisture in percentage form. This conversion method ensures that the soil moisture readings are correctly scaled and ready for real-time decision-making in the automated irrigation system. It also enhances the consistency of data logging, monitoring, and analysis over extended deployment periods in various zones within the greenhouse. The installation of equipment inside the control cabinet was designed with an emphasis on systematization, safety, ease of use, and long-term maintenance. The cabinet functions as the central processing and control unit for both the zonal soil moisture monitoring system and the automatic irrigation system within the greenhouse. It houses the WeMos Arduino MEGA 2560 microcontroller integrated with ESP8266, which serves as the main controller, as well as a 3.5" TFT LCD screen for real-time display of environmental parameters. A Micro SD Card module is also included for logging collected sensor data. Power is supplied via solar panels, regulated through a voltage controller to ensure stable power for all electronic components within the cabinet. The internal wiring is organized according to safety standards, clearly separating low-voltage circuits from data communication lines to minimize signal interference (noise) that could affect sensor readings. Environmental protection features such as waterproof seals, ventilation channels, and surge protection components are also implemented to ensure system reliability under high-temperature and high-humidity conditions common in greenhouse environments. Detailed installation of the system components can be seen in Fig. 5.

Fig. 6. Greenhouse installation process and completed vegetable cultivation setup. Installation of the greenhouse frame structure by researchers and local staff, showing the modular assembly process. Right: Interior view of the completed greenhouse with cultivated leafy vegetables under controlled environmental conditions.

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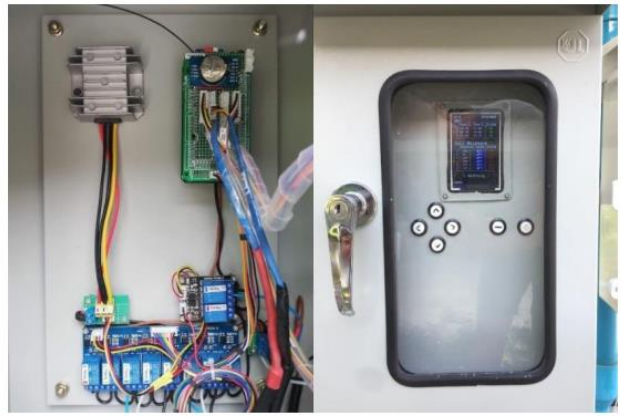

Fig. 5 Control cabinet of the smart irrigation system installed in the greenhouse.

Fig. 6 Installation of the Greenhouse for Vegetable Cultivation.

III. RESULT AND DISCUSSION

To evaluate the efficiency of the system, a controlled experimental setup was established. One section of the greenhouse was managed using traditional manual irrigation, while another section used the sensor-controlled automated system. The metrics used to evaluate system efficiency included total water consumption, crop growth rates, and energy consumption. The study ran for a full growing season (approximately six months), with replication across three different greenhouses to ensure consistency in the results in Fig. 7.

The experimental results reveal significant improvements in water use efficiency, plant growth rates, and energy consumption when using an automated, sensor-controlled watering system compared to the traditional manual irrigation method. Over the full growing season, the automated system resulted in a 30 % reduction in total water use, a 25 % increase in plant growth rate, and a 33 % reduction in energy consumption as in Table I. These findings align with similar studies in the field of precision irrigation and automation in greenhouse environments. The reduction in water consumption can be attributed to the precise delivery of water based on real-time soil moisture data, which minimizes wastage. This is consistent with the findings of [4], who demonstrated that wireless soil moisture sensors in greenhouse farming could reduce water consumption by up to 40% due to their ability to deliver water only when necessary. Similarly, a study by [8] reported water savings of 28% using sensor-based irrigation in organic farming. The 30% reduction observed in this study is in line with these reports, suggesting that automated systems can offer substantial improvements in water efficiency, particularly in organic greenhouses where overwatering can be detrimental to crop health and resource use.

The increase in plant growth rate by 25% further supports the argument that precise irrigation improves overall crop performance. Research by [8]. noted that crops grown under sensor-controlled irrigation systems displayed a 20-30% improvement in growth rate, as optimal moisture levels were maintained consistently. The increased plant growth rate in the current study suggests that the automated system provided more favorable growing conditions by preventing under- or over-watering, which is a common issue with traditional irrigation methods. Finally, the significant reduction in energy consumption (33%) highlights the effectiveness of integrating solar-powered systems with automated irrigation. Solar power is increasingly being used in agricultural systems to reduce dependency on grid electricity, and this study demonstrates its practical benefits in a greenhouse setting. A similar study by [5, 9]. reported a 35% reduction in energy use when solar panels were integrated with automated irrigation, providing further evidence that renewable energy sources, combined with automation, can greatly reduce the operational costs of modern farming systems.

TABLE I
PERFORMANCE COMPARISON BETWEEN TRADITIONAL METHODS AND AUTOMATED SYSTEMS

Criteria	Traditional Watering	Automated	%Improvement
Total Water Use (L)	5280	3220	30
Plant Growth Rate (cm/day)	1.2	1.5	25
Energy Consumption (kWh)	150	100	33

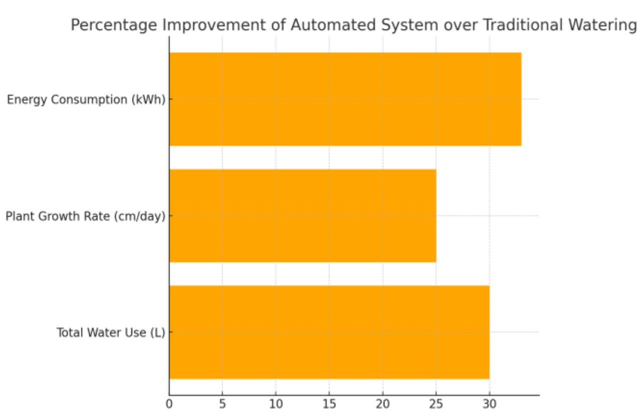

Fig.7 Percentage Improvement of Automated System over Traditional Watering

The findings from this study demonstrate the effectiveness of a technology transfer initiative involving a smart irrigation system equipped with soil moisture and temperature sensors, integrated with solar-powered automation. The technology was introduced to local farmers in the Mekong River region that faces challenges in water management and agricultural labor. Prior to the training, most farmers relied on conventional irrigation methods based on estimation, which often led to inefficiencies in water usage and inconsistent crop development. Following hands-on training sessions, farmers were able to understand and operate the sensor-based system, which enabled precise, demand-driven irrigation. The system also allowed remote monitoring and control via a mobile application. As a result, water usage was reduced by up to 30%, while electricity consumption and labor requirements were significantly lowered. Moreover, crop quality improved, with more uniform sizes and better growth consistency. Yields were reported to increase by approximately 15–20 %, reflecting the system's practical benefits in real-world greenhouse operations. Overall, this research highlights a successful integration of engineering knowledge and digital technology into agriculture through community-level capacity building. It not only reduces production costs and resource use, but also empowers farmers with tools for efficient, data-driven cultivation. This model serves as a practical reference for scaling up sustainable smart farming practices in similar regional contexts.

IV. Conclusion

This study demonstrates that the automated, sensor-controlled watering system powered by solar energy significantly improves efficiency in organic greenhouse farming compared to traditional methods. The system reduced water consumption by 30%, enhanced plant growth rates by 25%, and lowered energy use by 33%. These results align with existing research, confirming that precision irrigation optimizes resource use and improves crop yields. The integration of solar power further supports sustainable energy use, particularly in regions with limited infrastructure. Overall, the findings underscore the potential of smart irrigation technologies to enhance sustainability and productivity in agriculture. Broader adoption of these systems could address critical challenges such as water scarcity and high operational costs, especially in regions like the Mekong Coastal Region. Future research should explore the scalability of this approach across diverse crops and environmental conditions.

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