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Smart Irrigation Based on Soil Moisture Sensors with Photovoltaic Energy for Efficient Agricultural Water Management: A Systematic Literature Review †

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Abstract

A smart irrigation system based on soil moisture sensors supported by photovoltaic energy is an innovation to address water use efficiency in the agricultural sector, especially in remote areas. This technology utilizes photovoltaic panels as a renewable energy source to operate water pumps, while soil moisture sensors provide real-time data that is used to automatically manage irrigation according to plant needs. This technology not only increases the efficiency of water and energy use but also supports environmental conservation by reducing dependence on fossil fuels. This research was conducted using a Systematic Literature Review (SLR) approach guided by the PRISMA framework to analyze trends, benefits, and challenges in implementing this technology. The analysis results show that this system offers various advantages, including energy efficiency, reduced carbon emissions, and ease of management through the integration of Internet of Things (IoT) technology. Several challenges remain, such as high initial investment costs, limited network access, and obstacles. Technical matters related to installation and maintenance. Various solutions have been proposed, including providing subsidies for small farmers, implementing radiofrequency modules, and using modular designs to simplify implementation. This study contributes to the development of a conceptual framework that can be adapted to various geographic and socio-economic conditions. Potential further developments include the integration of artificial intelligence and additional sensors to increase efficiency and support the sustainability of the agricultural sector globally.

Keywords: smart irrigation; soil moisture sensor; solar energy; renewable energy; water management; agricultural automation

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1. Introduction

Water is a vital resource that underpins global agricultural production, accounting for nearly 70% of total freshwater withdrawals worldwide [1]. However, the continued reliance on inefficient traditional irrigation methods has led to substantial water losses and heightened stress on water resources, particularly in arid and semi-arid regions [2]. This situation is further aggravated by the growing impacts of climate change, which disrupt hydrological patterns, and by rising global food demand driven by population growth [3]. To address these challenges, the adoption of data-driven smart irrigation technologies

has emerged as a promising solution for improving water use efficiency and supporting sustainable agricultural practices.

Soil moisture sensor-based technology provides a precision approach for more efficient water management [4]. These sensors provide real-time data about soil conditions, such as moisture levels, which can be used to automatically adjust irrigation according to plant needs. This smart irrigation system not only increases water use efficiency and optimizes crop yield, but when powered by renewable energy sources such as photovoltaic (solar) panels, it also reduces dependency on fossil fuels. The integration of renewable energy enhances the sustainability and feasibility of deploying such systems in off-grid or remote agricultural areas.

The integration of smart irrigation technology with photovoltaic energy adds a significant dimension of sustainability [5]. Photovoltaic energy reduces dependence on environmentally unfriendly fossil fuels while reducing operational costs in the long term [6]. While some studies have explored smart irrigation systems and solar-powered systems separately, there is a limited comprehensive synthesis of how these technologies are applied together, particularly in the context of real-time sensor-based automation in remote or off-grid farming settings [7]. In addition, previous literature reviews often lack a systematic analysis of the challenges and opportunities involved in scaling such integrated systems [8]. With this gap, we highlight the need for a systematic literature review to explore the current unresolved trends, benefits, and challenges in implementing smart soil moisture-based irrigation powered by renewable energy.

Although smart irrigation technology based on sensors and photovoltaic energy has experienced significant developments, studies assessing the effectiveness and efficiency of these systems in various geographic and socio-economic conditions are still limited. Factors such as variations in solar radiation intensity, soil type, and climatic conditions influence the performance of these technologies, while socio-economic barriers, including high initial investment costs and limited technical skills of farmers, pose major challenges to their implementation. Therefore, a comprehensive approach is needed to understand how this technology can be adapted and applied in various regions with diverse needs and challenges.

This research aims to address gaps in previous studies by exploring the latest trends and innovations, evaluating the advantages and barriers in implementing these technologies, and designing a conceptual framework that can be adapted to various contexts. With an approach that integrates data and various scientific disciplines, this research is expected to make an important contribution to increasing the efficiency of water management in the agricultural sector in a sustainable manner.

2. Materials and Methods

This research uses the systematic literature review (SLR) method to evaluate and analyze literature [9] related to smart irrigation technology based on soil moisture sensors supported by photovoltaic energy. This method was chosen because it is able to provide a comprehensive overview of research trends, benefits, challenges, and opportunities for implementing this technology. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework is applied as the main guide in implementing SLR, to ensure that the process of identification, screening, eligibility evaluation, and article selection is carried out systematically, transparently, and with structure. The use of this framework aims to increase the accuracy and ease of research replication, thereby providing a strong basis for drawing valid conclusions [10].

The initial stage in implementing an SLR is literature identification, which begins by formulating keywords such as “smart irrigation,” “soil moisture sensor,” and “photo-

voltaic." The search process was carried out through the Scopus database with a publication time period between 2018 and 2024 to ensure the relevance and novelty of the research. Articles found at this stage then go through a screening process, where inclusion and exclusion criteria are applied. Articles that focus on sensor-based irrigation technology and photovoltaic energy, published in reputable journals or proceedings, and available in English or Indonesian, are considered for further analysis. Conversely, articles that were irrelevant, did not provide empirical data, or were duplicate search results were excluded from the process.

Articles that pass the screening stage then enter the eligibility evaluation stage. At this stage, the abstract, methods, and conclusions of each article are reviewed in depth to ensure suitability for the research objectives. Articles that meet all selection criteria are included in the final analysis stage, where important data, such as research methods, results, challenges, and conclusions, are extracted for further analysis. This process allows researchers to construct a holistic synthesis that makes an important contribution to the development of knowledge in the field of photovoltaic-based smart irrigation technology.

2.1. Research Questions

In order to focus on review and analysis, the following three research questions were formulated.

2.1.1. What Are the Main Components That Make up a Photovoltaic-Based Smart Irrigation System?

Various literature mentions various technical components used in photovoltaic-based smart irrigation systems, such as soil moisture sensors, ESP32 or Arduino microcontrollers, radiofrequency modules, solenoid valves, photovoltaic solar panels, batteries, the Thing Speak platform, and MPPT controllers [11,12]. However, until now, there has been no systematic synthesis or classification of these main components in various studies, thus creating the need to identify and organize the building blocks in a structured and comprehensive manner.

2.1.2. How Does Photovoltaic Technology Support Energy Efficiency in Smart Irrigation?

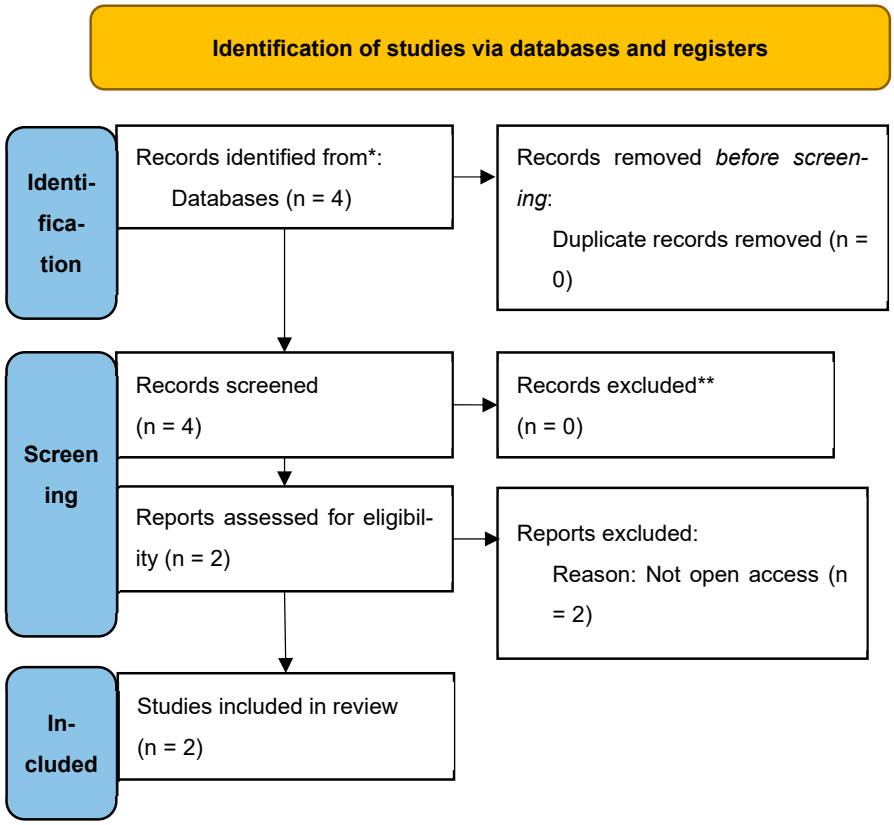
A number of studies have mentioned that photovoltaic (PV) panels are used as an autonomous energy source in smart irrigation systems, but discussions of how PV concretely supports energy efficiency are generally limited to technical descriptions. Therefore, a systematic study is needed that can comprehensively evaluate the role of PV in reducing electricity consumption, reducing CO_2 emissions, and supporting system operations independently, especially in remote areas with minimal access to the electricity grid.

2.1.3. What Are the Main Benefits Gained from Implementing This System?

Previous studies have touched on the benefits of implementing photovoltaic-based smart irrigation systems, such as improved water use efficiency, automation in monitoring land conditions, increasing agricultural yields, and contributing to the reduction in carbon emissions. However, these benefits are still spread across studies with different contexts and approaches; they have not been compiled in the form of organized and systematic findings.

2.2. Screening and Selection Process

The selection process is carried out by following the PRISMA flow, as shown in Figure 1. A total of four initial documents were successfully identified, and after the implementation of inclusion and exclusion criteria, the number was further screened.



* Literature search was conducted using SCOPUS
** Years of article limitation (2018–2024)

Figure 1. PRISMA flow diagram for literature selection.

2.3. Data Extraction and Analysis

From the collection of articles selected in the final stage, relevant data are retrieved related to

- Research objectives and methodologies;
- System components and configurations;
- Technologies and sensors used;
- Key findings and contributions to PV-based smart irrigation systems.

A qualitative thematic analysis was conducted to identify recurring patterns in technological implementation, system architecture, and the functional roles of each component. The following thematic areas were the primary focus of the analysis:

- Photovoltaic-Based System Architecture;
- Core Components and Technologies;
- Role of PV in Supporting Energy Efficiency;
- Benefits of Smart Irrigation Implementation;
- Identified Gaps and Challenges.

The comparative thematic analysis consolidates key insights on how PV-based smart irrigation systems are structured and operated. The recurring use of soil moisture sensors, low-power microcontrollers, and autonomous power supply demonstrates the maturity of this technology at prototype and early deployment stages.

3. Results

3.1. What Are the Main Components That Make up a Photovoltaic-Based Smart Irrigation System?

A photovoltaic-based smart irrigation system consists of several main components designed to support efficiency and automation in water resource management (see Figure 2). The following are these components:

1. Photovoltaic Panels: Serving as the main energy source, these panels convert solar energy into electricity to drive submersible pumps [13].
2. Submersible Pumps: These pumps are used to draw water from sources such as wells or rivers, utilizing the power generated by photovoltaic panels.
3. ESP32 Microcontroller: The microcontroller acts as a control center that processes data from soil moisture sensors and coordinates the functions of other components.
4. Soil Moisture Sensor: This sensor detects soil moisture levels at certain depths (3.5 cm and 7 cm in this study), providing data that determines when irrigation should be carried out.
5. Solenoid Valve: Functioning to regulate water flow to the irrigation area, this valve is operated automatically based on soil moisture data received from the microcontroller.
6. Radiofrequency (RF) Module: Used for communication between system blocks in remote locations, the RF module allows control and monitoring without an internet connection [14].

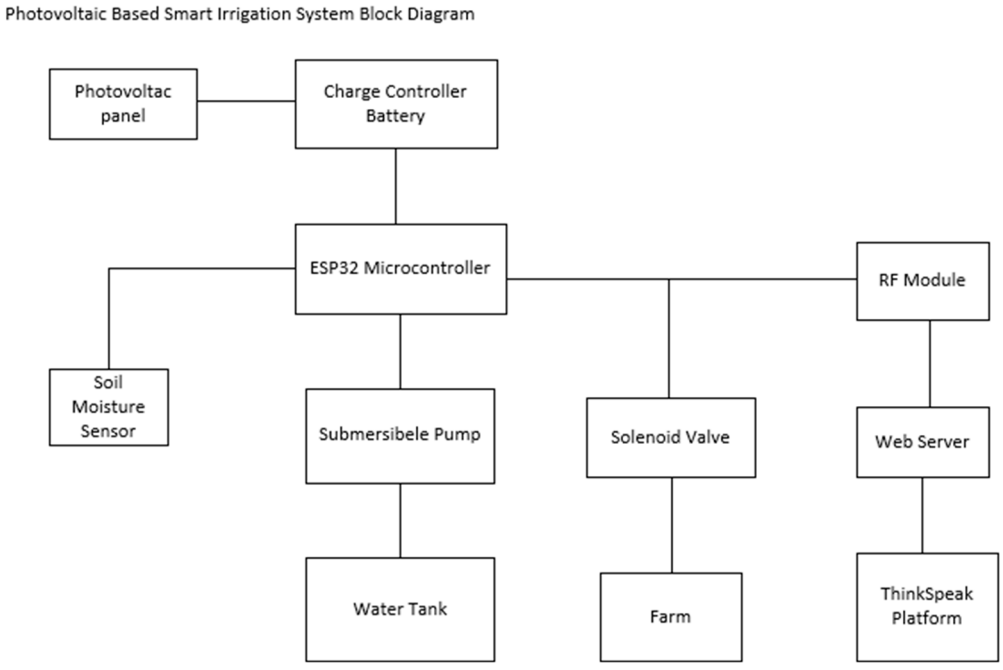


Figure 2. Block diagram of a photovoltaic-based smart irrigation system.

Thing Speak Web Server and Platform: The ESP32-based server enables real-time monitoring via a digital interface, either via a computer or smartphone. The Thing Speak platform is used to store data and analyze parameters such as soil moisture and temperature.

Charging Controller and Water Tank: This controller ensures that charging from the photovoltaic panels to the battery is efficient, while the water tank serves as a backup for irrigation needs.

This system is designed to support operations in remote areas where it is difficult to access the internet or GSM network, with the RF module as an effective communication solution. This system uses a soil moisture threshold of 45% to regulate irrigation efficiently,

thereby saving water and maintaining plant health. With a stable design and easy maintenance and equipped with digital monitoring, this system improves energy and water efficiency while providing sustainable benefits to the agricultural sector.

The image above is a block diagram of a photovoltaic-based smart irrigation system, which illustrates the relationship between the main components such as photovoltaic panels, charge controller, battery, ESP32 microcontroller, sensors, solenoid valves, submersible pump, RF module, Thing Speak platform, and water tank.

3.2. How Does Photovoltaic Technology Support Energy Efficiency in Smart Irrigation?

Investigation of how photovoltaic technology supports energy efficiency in smart irrigation shows that this technology significantly increases energy efficiency by utilizing solar energy as the main source of electricity, which is renewable, reliable, and cost-effective. Photovoltaic panels convert solar energy into electricity to operate submersible pumps and other irrigation devices without dependence on conventional electricity grids, thereby reducing fossil fuel-based energy consumption and reducing operational costs. The system optimizes energy use by integrating a microcontroller, such as the ESP32, which automatically regulates irrigation device operation based on real-time data from soil moisture sensors. This ensures that the system only operates when needed, avoiding energy waste. This technology also supports operational independence in remote areas that have limited electricity infrastructure by utilizing the abundant potential of solar energy.

The data displayed in the Figure 3 is an illustrative representation based on the results and general discussion of research related to photovoltaic technology in smart irrigation, which was discussed previously.

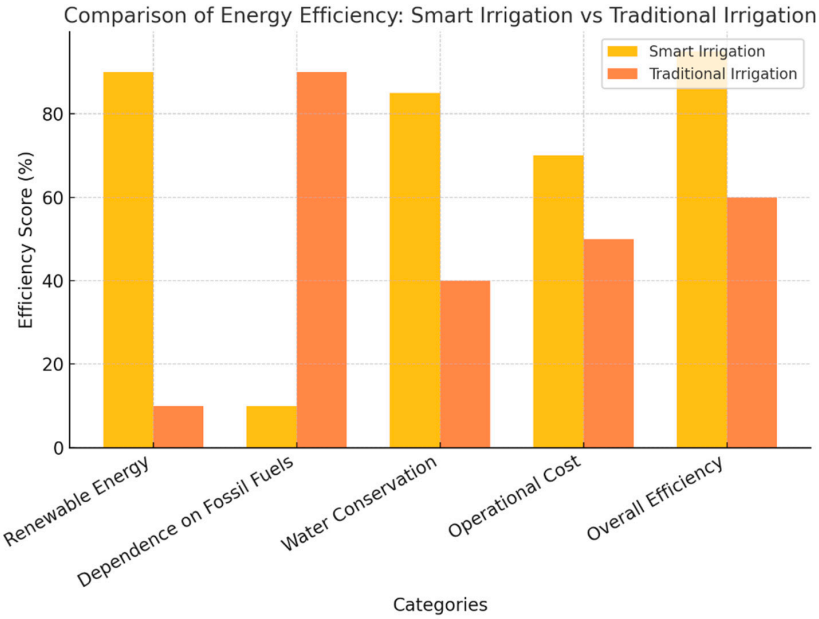


Figure 3. Energy efficiency comparison between smart irrigation and traditional irrigation.

Specifically, this data is taken from the following points.

3.2.1. Smart Irrigation

The use of renewable energy in this system relies almost entirely on photovoltaic panels [15]. Water efficiency is achieved through automatic control using soil moisture sensors. Operational cost savings are realized by reducing the reliance on fossil fuels and minimizing maintenance requirements. Overall efficiency is enhanced as the system is designed to operate as needed with IoT-based monitoring.

3.2.2. Traditional Irrigation

There is a high dependency on fossil fuels or traditional electricity grids. Water usage is often excessive due to manual control or the absence of automated systems. Operational costs tend to be higher because of significant energy consumption and more intensive maintenance requirements.

3.3. What Are the Main Benefits Gained from Implementing This System?

The implementation of photovoltaic-based smart irrigation systems offers various key benefits that contribute to energy efficiency, environmental sustainability, and improving the quality of irrigation management. One of the significant benefits is the use of solar energy as a power source, which directly reduces dependence on conventional electricity and fossil fuels. This not only reduces operational costs but also supports efforts to reduce carbon emissions, making it an environmentally friendly solution.

The system is equipped with a soil moisture sensor that enables efficient water management. Irrigation is only activated when soil moisture levels are below a predetermined threshold, thereby reducing water waste and supporting water resource conservation. This technology is also ideal for remote areas that do not have access to the electricity grid, as photovoltaic panels provide operational independence by harnessing abundant solar energy.

In addition, the integration of Internet of Things (IoT) technology enables real-time monitoring and control of the system remotely, making it easier for users to manage irrigation. With full automation, this system is able to increase work efficiency, reduce manual intervention, and maximize agricultural production results.

Designed with a focus on ease of installation and maintenance, this system is an economical and innovative solution to overcome irrigation challenges in various geographic conditions. The use of free renewable energy and resource optimization make this system superior in supporting the sustainability of modern agriculture, while creating a significant positive impact on energy efficiency, water conservation, and environmental sustainability.

3.4. What Are the Obstacles Found in Previous Research, and What Solutions Have Been Proposed?

Research on photovoltaic-based smart irrigation systems has identified several main challenges faced in their implementation, and it offers solutions to overcome them. One of the main challenges is limited internet or GSM network access in remote areas, which hinders communication between devices. The solution implemented is the use of radiofrequency (RF) modules as a communication alternative, allowing system control without requiring internet connectivity.

Energy efficiency constraints are also a concern, especially in maintaining the performance of photovoltaic panels in environments with fluctuating sunlight intensity. The solution is the integration of a charge controller that ensures optimal energy storage in the battery, as well as the use of intelligent sensors to regulate system operation based on real needs.

Another problem is the technical complexity of installation and maintenance, especially for users who lack technical knowledge. The research suggests a modular and simple system design, which makes it easy to install and replace components if necessary. Clear technical documentation is also a solution to support users.

On the other hand, the initial cost of implementing the system is a challenge in wider adoption. To overcome this, the study recommends collaborating with governments or supporting organizations to provide incentives or subsidies for small farmers, so that this technology can be accessed by more users.

Finally, data management and IoT system security are important issues in ensuring reliable system performance. The solution offered is the use of an IoT platform with strong security features, such as data encryption, as well as the integration of cloud-based monitoring technology to analyze and optimize system performance in real-time.

With the solutions that have been identified, photovoltaic-based smart irrigation systems have great potential for widespread implementation, provided that these challenges can continue to be overcome through continuous innovation and technical support.

4. Discussion

Referring to Table 1, the implementation of a photovoltaic-based smart irrigation system presents a promising solution for improving energy and water efficiency in agricultural practices, particularly in remote or off-grid areas. The system integrates various components such as photovoltaic panels, ESP32 microcontrollers, soil moisture sensors, submersible pumps, solenoid valves, RF modules, and cloud-based platforms like Thing Speak. This combination enables automated and efficient irrigation management by leveraging renewable solar energy and real-time monitoring [15,16].

Table 1. Challenges and solutions in implementing a photovoltaic-based smart irrigation system.

Challenge	Solution
Limited internet/GSM network access	Use of RF module for communication without internet
Energy efficiency at low solar intensity	Control integration, clear technical documentation
Technical complexity of installation and maintenance	Modular design, clear technical documentation
Initial costs of system implementation	Subsidies or incentives for small farmers
IoT data security and management	IoT platform with encryption and cloud monitoring

Photovoltaic technology plays a central role by replacing traditional energy sources with a sustainable, cost-effective alternative. By converting solar energy into electricity, the system significantly reduces dependency on fossil fuels and conventional power grids, resulting in lower operational costs. Additionally, the integration of IoT and smart sensors ensures irrigation is performed only when necessary, based on actual soil moisture data, thus minimizing water waste and enhancing crop health [17,18].

Compared to traditional irrigation systems—which are often characterized by excessive water use, high energy consumption, and labor-intensive maintenance—smart irrigation systems demonstrate a superior performance in terms of energy efficiency, water conservation, and operational simplicity. These benefits are especially valuable in agricultural settings where resources are limited or where sustainable practices are prioritized [19,20].

However, the implementation of such systems is not without challenges. Limited internet or GSM network access in rural areas can hinder system communication. This issue is addressed through the use of RF modules, allowing device communication without internet access. Other obstacles include inconsistent solar energy availability, technical complexity during installation and maintenance, and high initial costs. Solutions such as charge controllers, modular system design, technical documentation, and financial support through subsidies are proposed to enhance system adoption and performance [21,22].

Security and data management within IoT systems are also critical concerns. To address these, secure platforms with encryption and cloud-based monitoring are recommended to ensure system reliability and data integrity [23,24].

In summary, photovoltaic-based smart irrigation systems offer a sustainable and technologically advanced approach to irrigation management. With continuous innovation and the implementation of proposed solutions, these systems have significant potential to

transform agricultural practices and contribute to environmental sustainability and food security [25,26].

5. Conclusions

Smart irrigation systems based on soil moisture sensors that use photovoltaic energy offer various advantages in increasing the efficiency of water management in the agricultural sector. By utilizing solar energy as a renewable resource, this system drastically reduces the dependence on fossil fuels, reduces operational costs, and supports environmentally friendly practices [27]. The integration of soil moisture sensors ensures that irrigation is carried out only when needed, thereby reducing waste and optimizing the use of water resources. This system also supports autonomous operations in remote areas and enables efficient management in real-time through integration with Internet of Things (IoT) technology, making it a superior solution for irrigation in the modern agricultural sector [28].

For further development, this system can be equipped with additional sensors, such as temperature, soil pH, and weather sensors, to provide more in-depth data and enable more precise irrigation. Artificial intelligence (AI) technology can also be integrated to analyze environmental data and weather patterns to accurately predict irrigation needs and enable automated decision-making [29]. In addition, optimizing energy storage, developing flexible and modular designs for various agricultural scales, and improving IoT security through stronger encryption protocols are important steps. This innovation will expand the benefits of the system, increase irrigation efficiency, and make a significant contribution to the sustainability of the agricultural sector globally [30].

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