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Survey on Solar-Powered IoT-Enabled Smart Irrigation Systems using Fuzzy Logic

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Abstract - In light of water scarcity, rising energy costs, and pressure for sustainable farming, efficient irrigation is more important than ever. This paper examines how solar-powered, IoT-enabled irrigation systems can mitigate these challenges through the integration of renewable energy, intelligent control mechanisms, and real-time monitoring. Fuzzy logic interprets soil moisture, temperature, and solar data for tracking to make adaptive, context-aware decisions. IoT connectivity makes this possible by letting farmers keep an eye on and control the system from afar. Cloud-based analytics also help improve irrigation schedules so that they are more accurate and use fewer resources. We evaluate system architectures and control strategies for water and energy savings, cost-effectiveness, and scalability in diverse farming environments in this study. Results show that fuzzy logic significantly enhances adaptability to changing climatic conditions while improving operational efficiency. Nonetheless, challenges remain, including high upfront investment, crop-specific calibration requirements, and performance consistency under diverse environmental conditions. Looking ahead, advancements such as machine learning integration, multi-sensor data fusion, and predictive irrigation scheduling promise to make these systems more accurate, resilient, and autonomous paving the way toward smarter, more sustainable farming practices worldwide.

Keywords: Smart Irrigation, Renewable Energy, Solar Power, IoT, Fuzzy Logic, Precision Agriculture

INTRODUCTION

Agriculture is a very important part of India's economy because it provides food for its people. Even though many agricultural lands are still being destroyed, there is a large group that refuses to give up on farming because they know how important it is to meeting the basic needs of the people. Agriculture is facing a lot of problems right now, which is why there are so many studies going on to improve farming methods. Some researchers have created a Zigbee module that can control three sensors to make sure that plants get the right amount of water. A mobile app also lets the user send feedback through this system. Some studies have also looked only at using a soil moisture sensor for automatic drip irrigation. A three-level moisture sensor is used to find moisture at three different depths. This controls the amount of water that is given to the crop[1]. Image processing techniques were used to measure the pH of the soil. This study examines the identification of water needs via a moisture sensor, in conjunction with the deployment of a solar panel to enable pump operation. After that, fuzzy logic was used with three sensors: a soil moisture sensor, a humidity sensor, and a temperature sensor. The solar panels were used to power the pumps[2].

Automated irrigation uses fuzzy logic, with Arduino as the main controller that controls both the sensors and the solenoid valve. The survey results show that the solar panel doesn't produce enough voltage to power the pump, and the cost of getting batteries to store energy from the solar panel is too high. So, the Arduino gets its power from the solar panel. The solar panel uses a Light Dependent Resistor (LDR) to automatically track the sun. The plants are grown in both tubs, which show the difference between the two types of land. An automated irrigation system takes care of one group of plants, while the other group uses more traditional methods. This study examines the relationship between crop quality and the volume of water used in their cultivation.

This study looks at a Renewable Energy-based Irrigation System that tries to fix the problems and limitations of current irrigation methods, especially the problem of uneven water distribution to crops, which uses too much electricity. The suggested system aims to make water and power generation more efficient by using solar panels, which will help the environment. Additionally, this can be carried out on both large and small scales.

This study uses a network of sensors spread out over a large area to find out how much moisture is in the soil. These sensors are all connected to the control unit, which manages and controls the whole irrigation process. Fuzzy logic will be used to decide whether or not the soil needs to be watered based on the current weather[3].

People have been using more electricity and water lately, and it's easy to see. Historically, irrigation systems either needed a lot of money to build or used traditional, non-renewable energy sources for electricity. Also, irrigating farms requires a lot of people to be involved, but the system that was suggested reduces this need. Agriculture is the most important part of India's economy because it provides food for the people. Even though a lot of farmland is being destroyed, there are still a lot of people who don't want to give up farming because it provides basic needs for people. There are a lot of problems with farming right now, and a lot of research is being done to make farming better. Some researchers have built a Zigbee module that can control three sensors to give the plant the right amount of water. This module also lets the user know how much water the plant needs through a mobile app. Others have only used a soil moisture sensor for automatic drip irrigation. Then there is a three-level moisture sensor that lets water into the crop based on how much moisture it finds at three different depths. Image processing was also used to read the soil pH. An effort to find out how much water was needed by using a moisture sensor and a solar panel to power the motors[4]. Later, fuzzy logic was used, which had three sensors: one for soil moisture, one for humidity, and one for temperature. The solar panels were connected to run the pumps.

Fuzzy logic is used to automate the irrigation, and Arduino is the main controller because it controls the sensors and the solenoid valve. We learned from the survey that the voltage from the solar panel is not enough to run the pump and that it costs a lot to buy batteries to store the power from the solar panel. So, we use the solar panel to give power to the Arduino. LDR (Light Dependent Resistor) makes the solar panel work as an auto-tracking system. The plants are grown in both tubs, and the separation shows two different types of land. One uses an automated irrigation system, and the other uses normal irrigation. The quality of the crops and the amount of water used to grow them are compared.

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A Renewable Energy-based Irrigation System designed to mitigate the drawbacks and constraints of current irrigation systems, primarily characterized by the unequal distribution of water to crops, resulting in excessive electricity consumption. This proposed system is meant to make solar panels more efficient at using water and power, which is better for the environment. This can also be done on a large or small scale[5].

A network of sensors spread out over the area is used to find out how much moisture is in the soil. These sensors are linked to a control unit that is in charge of both controlling and keeping an eye on the entire irrigation process. A decision will be made about whether or not to water the soil based on the weather using fuzzy logic.

Recently, people have been using more water and electricity. Irrigation systems that were made in the past either cost a lot of money or used old, non-renewable sources of electricity. Also, irrigating farms needs a lot of human involvement, but the proposed system needs very little human involvement.

Agriculture is vital to India's economy, serving as the principal source of livelihood for a substantial segment of the population. Nevertheless, despite its significance, modern agriculture faces considerable challenges—most notably water scarcity, which renders around 20% of arable land unproductive. This challenge requires more sophisticated and efficient strategies for managing agricultural water supplies[6].

This paper proposes an intelligent irrigation system that adeptly regulates water flow by leveraging real-time data from several sensors, including temperature, humidity, and soil moisture. Fuzzy logic helps the system decide when and how much to irrigate, effectively using water. The sustainability is derived from a solar panel equipped with an automatic tracking system powered by Light Dependent Resistors (LDRs), which optimizes energy capture and diminishes reliance on conventional electricity. This reduces operational expenses while maintaining system reliability. Engineered for adaptability, it is applicable to farms of varying scales. The primary objective is the complete automation of irrigation—reducing manual labor, conserving resources, and promoting sustainable agriculture. In Indian agriculture, this approach directly addresses water issues and boosts productivity.

LITERATURE SURVEY

The incorporation of renewable energy sources, Internet of Things technology, and advanced control algorithms in irrigation systems has garnered significant attention in academic research over the last decade. The principal objective of these studies has been to improve water efficiency, decrease energy consumption, and lessen human involvement in agricultural practices[7]. Recently, threshold irrigation systems have transformed into cloud-integrated control mechanisms capable of managing variable field conditions. Recent 2024–2025 works use fuzzy logic or AI with IoT sensing technologies to measure soil moisture, temperature, and humidity. Solar photovoltaic energy powers these systems to save costs and improve off-grid access. A new article on ScienceDirect talks about a whole fuzzy-logic IoT irrigation stack that includes cloud integration. It focuses on lowering water stress and making the system more resistant to changes in the environment. This could be a model for where the field is going in the future[8].

The appeal of fuzzy logic lies in its ability to effectively manage uncertainty and imprecise measurements, surpassing the limitations of fixed thresholds. A 2024 study presents an advanced IoT-based fuzzy controller for irrigation, outlining the rule base, membership functions, and deployment considerations in smart-farm complexes. This serves as evidence that fuzzy control is being engineered for practical applications beyond theoretical concepts[9].

Many organizations combine fuzzy logic and AI/ML scheduling. From sensing to learning to actuation, a 2024 Sensors thorough study highlights hybrids (e.g., fuzzy + ML for set-point tuning or ML prediction feeding a fuzzy decision layer) and dataset quality and cross-site generalization gaps. A 2025 ScienceDirect review agrees, saying that resilient irrigation under climatic stress requires ML/CV prediction before the control loop. These ratings encourage your survey to use fuzzy decision-making as the real-time, explainable “last mile” controller with ML projections[10].

Author & Year	Energy Source	Sensors Used	Control Logic	IoT/Connectivity	Key Features	Limitations
Joaquin Gutierrez et al. (2014)	Solar photovoltaic	Temperature, Soil moisture	Threshold-based	GPRS	Automated irrigation powered by solar; microcontroller-based control	Fixed thresholds; less adaptable to varying crops/weather
G. Parameswaran & K. Sivaprasath (2016)	Grid electricity	Soil humidity	Threshold-based	Local server (PC)	Arduino-based drip irrigation with automated solenoid control	Limited scalability; no remote/cloud integration
V. Akubattin et al. (2016)	Grid electricity	Soil moisture, Temperature	Threshold-based	Raspberry Pi (Local control)	Greenhouse environment control (irrigation + cooling)	Focused on greenhouse only; high dependency on wired setup
D. Zhang et al. (2015)	Grid electricity	Soil moisture	Threshold-based	RF module + GPRS	Large-scale wireless data relay to monitoring center	Relies on cellular coverage; higher operational cost
A. Kumar et al. (2014)	Grid electricity	Low-cost soil moisture	Threshold-based	XBee wireless	Low-cost design for rural applications	No advanced decision-making; basic automation
S. Khandare et al. (2018)	Solar photovoltaic	Soil moisture	Threshold-based	None	Simple solar-powered	No IoT monitoring;

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					irrigation for rural areas	manual oversight needed
Proposed System (Current Paper)	Solar photovoltaic + tracker	Soil moisture, Temperature, Humidity	**Fuzzy Logic**	IoT (Adafruit IO, Wi-Fi)	Adaptive irrigation based on multiple sensor inputs; cloud dashboard; water savings up to 48.3%	Needs crop-specific fuzzy tuning; initial setup cost

Recently, ESP32 microcontrollers have been integrated with photovoltaic systems and modest energy storage solutions, sometimes with sun-tracking mechanisms to stabilize the power budget. A 2025 ScienceDirect article describes a solar-powered IoT irrigation system for precision vegetable crops that minimizes water loss and improves user experience. The availability of open designs for ESP32-based solar tracking and monitoring in current repositories and project-style documents shows a growing practical momentum for farmers to integrate photovoltaics and IoT[11].

Case studies show that IoT and fuzzy logic work in agriculture. In 2025, Scientific Reports published an article about an IoT smart-irrigation system that uses Mamdani fuzzy inference and multiple sensor inputs to grow sunflowers. Fuzzy controllers can be used in plot-level automation beyond demonstration projects due to their better regulation than lighter alternatives[12].

ESP32 + cloud dashboards (Adafruit IO / custom clouds) with moisture-driven actuation are also documented. Some are more applied/DIY, but they document the typical component stack and networking patterns your implementation can reuse (feeds, dashboards, and OTA updates). These complement your base paper's architecture and help translate survey to practice[13].

METHODOLOGY

Recent solar-powered IoT irrigation systems integrate renewable energy harvesting, sensor-driven data acquisition, intelligent control algorithms, and real-time monitoring. The main method used in modern implementations can be broken down into these main steps:

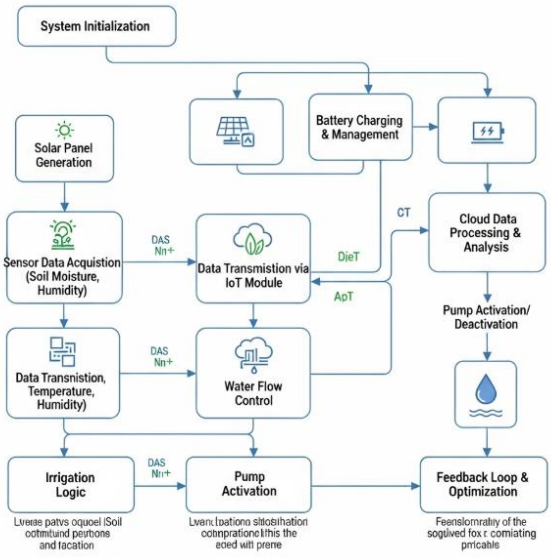


Fig. System Powered IoT Irrigation

This illustration depicts a solar-powered smart irrigation system. It employs sensors to assess the soil and transmits that data to the cloud. The system's central control determines the timing and volume of irrigation, regulating the pumps accordingly. All elements are interconnected, forming a cycle that conserves water and sustains plant health.

1. Solar Energy Harvesting and Power Management

Modern smart irrigation systems use solar energy to operate off-grid. For remote farms with limited or expensive electricity, this is crucial. Photovoltaic (PV) panels convert sunlight into electricity, powering the irrigation system's controllers, sensors, communication modules, and actuators[13]. The solar panel is not stationary. A solar tracking system controlled by an ESP32 microcontroller holds it. Multiple light intensity sensors on the panel continuously measure sunlight levels. ESP32 uses a small servo motor to orient the panel toward the brighter side. By constantly changing orientation, the panel maximizes sunlight absorption and energy production compared to a stationary installation.

Rechargeable batteries power the irrigation system during cloudy or nighttime conditions. To ensure a full irrigation cycle during low sunlight, the battery capacity is carefully chosen. Microcontrollers and sensors are protected by power regulation circuits that stabilize voltage. With dynamic solar tracking, energy storage, and voltage regulation, the irrigation system is always ready and independent of the grid. It makes the system more cost-effective in the long run by getting rid of recurring electricity costs and cutting down on maintenance delays caused by power outages.

2. Sensor Deployment and Data Acquisition

Smart watering systems rely on sensors as their "eyes and ears." The system utilizes sensors that continuously assess field conditions to determine the timing and quantity of water required for crops. Essential components comprise soil moisture sensors that quantify soil water content; DHT sensors that monitor temperature and humidity; and light-dependent resistors (LDRs) that enable solar panels to optimize sunlight exposure. The precise positioning of these sensors is essential for dependable outcomes. Moisture sensors must be placed at root depth to accurately reflect actual water availability, while temperature and humidity sensors must be protected from direct sunlight and rain to avoid misleading readings and ensure precise irrigation decisions.

An exemplary instance of successful sensor data integration is provided by Abreu et al. [14]. The researchers employed multi-sensor fusion, which integrates sensor readings from multiple sensors. By integrating soil moisture, temperature, and humidity data, the system might construct a more comprehensive understanding of the crop's growing environment. These values were entered into a Mamdani fuzzy inference system, which made irrigation decisions more dependable than single-sensor ones.

This stratified methodology guarantees that the system is less susceptible to erroneous readings or abrupt fluctuations in a single parameter. For instance, even if the soil moisture sensor provides an ambiguous reading, the system can corroborate with temperature and humidity data prior to determining the necessity of irrigation. This enhances water efficiency and crop vitality, as plants receive irrigation solely when conditions necessitate it.

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3. Fuzzy Logic Control

The fuzzy logic controller serves as the brain of the smart irrigation system. It converts sensor data like soil moisture, temperature, and humidity into irrigation timing and duration recommendations. Instead of utilizing explicit thresholds (for example, “if soil moisture < 40%, then irrigate”), fuzzy logic classifies input values into linguistic categories such as Low, Medium, or High. The system can accommodate intermediate values more adeptly, akin to a farmer. Slightly dry soil may require less water than excessively dry soil, and fuzzy logic is intended to capture that distinction.

The procedure commences with fuzzification, wherein precise sensor values are categorized into these classifications. A rule base—essentially a collection of "if-then" conditions—subsequently directs the system. For instance, a guideline may stipulate: If soil moisture is Low and temperature is High, then irrigate for an extended period. The inference engine concurrently assesses all relevant rules and determines the optimal answer. Ultimately, by defuzzification, the outcome is transformed into a specific directive, such as “activate the solenoid valve for 10 seconds.”

Abreu et al. [14] illustrate that this strategy is far more versatile than conventional threshold-based systems. It can manage ambiguous or erratic sensor data while still rendering dependable conclusions. Above all, fuzzy logic lets the irrigation system think like humans, saving water and improving crops.

4. Iot Integration And Cloud Dashboard

The function of IoT in smart irrigation is to serve as the communication conduit between the agricultural field and the farmer. ESP32 or NodeMCU modules are frequently employed to transmit sensor readings wirelessly to cloud platforms such as Adafruit IO or individually designed interfaces. This connectivity means that farmers no longer need to be physically present in the field to check conditions—they can monitor soil moisture levels, temperature, humidity, and irrigation activity in real time using their phone or computer.
In addition to monitoring, interaction with the Internet of Things facilitates remote control and over-the-air updates, hence enhancing system maintenance and upgrades. Real-time dashboards furnish farmers with clear graphs and visual indicators of crop conditions. In [13], the incorporation of an intuitive dashboard enabled farmers to make prompt, educated decisions, hence enhancing irrigation efficiency in accordance with actual field requirements.

5. Actuation And Water Delivery

Upon the fuzzy logic controller's determination that irrigation is requisite, the system engages solenoid valves or water pumps to supply the appropriate volume of water to the crops. The irrigation method is contingent upon the crop and field dimensions; it may involve a drip irrigation system for targeted water application at the root zone or a sprinkler system for extensive coverage.

Numerous contemporary systems have feedback mechanisms that reassess soil moisture subsequent to watering. This enables the system to verify the adequacy of the water applied. Otherwise, the system can modify the duration or frequency of subsequent irrigation cycles. This feedback mechanism guarantees that plants receive optimal hydration, hence enhancing efficiency and promoting crop vitality.

6. Performance Evaluation

To evaluate smart irrigation systems, experts look at water savings, energy use, and crop yield. Field testing frequently demonstrate the superiority of intelligent controllers over conventional approaches. Abreu et al. [14] demonstrated that a fuzzy logic-based system stabilized soil moisture levels, minimized water waste, and facilitated robust crop development.
Such evaluations are crucial, as they not only validate the system's immediate advantages but also illustrate its long-term viability. Farmers are assured that using smart irrigation will conserve resources while maintaining productivity, hence facilitating the justification of the initial investment in solar-powered IoT solutions.

FUTURE SCOPE

1. **Integration with Predictive Analytics**

The existing system mostly depends on real-time sensor data; the subsequent phase involves integrating it with meteorological predictions and machine learning algorithms. By forecasting precipitation, temperature variations, and soil moisture patterns, the system could proactively determine irrigation requirements instead of responding retroactively. This would enhance water efficiency and avert superfluous irrigation during natural precipitation.

2. **Crop-Specific Adaptation**

Diverse crops possess distinct water needs, rendering a uniform approach sometimes suboptimal. In the future, irrigation systems may incorporate crop-specific fuzzy rule sets that autonomously change according to plant type, soil conditions, and growth stage. This would guarantee that each crop obtains the appropriate quantity of water at the optimal moment, enhancing yield quality and resource efficiency.

3. **Scalability for Large Farms**

Most modern systems are assessed on small plots; however, their scalability to large farms presents a considerable challenge. Distributed sensor networks such as LoRa or NB-IoT can reliably encompass extensive agricultural areas. This would make the system viable for large-scale agriculture, where water management has a considerably greater impact.

4. **Low-Cost and User-Friendly Design**

Contemporary technologies are evaluated on limited areas; however, their scalability to extensive agricultural operations presents a significant challenge. Distributed sensor networks like LoRa or NB-IoT can effectively cover vast agricultural regions. This would render the technology feasible for extensive agriculture, where water management significantly influences outcomes.

CONCLUSION

This survey assessed the viability of solar-powered, IoT-integrated smart irrigation systems employing fuzzy logic as their primary decision-making framework. The examined research indicates that these technologies can significantly reduce water waste, minimize energy consumption, and provide farmers with improved control over irrigation through real-time monitoring. Fuzzy logic produces flexible, adaptive conclusions, rendering it more reliable in uncertain environments than threshold-based methods. Renewable solar energy ensures the system's sustainability and suitability for rural agricultural areas without electricity. The incorporation of IoT markedly enhances usability by granting farmers access to crop and soil data at any time and from any location through cloud dashboards or mobile applications. This technology can improve crop health, increase yield, and support sustainable agricultural practices. Future innovations, such as predictive analytics, crop-specific customization, and cost-effective designs, will enable the transition of these systems from limited trials to extensive application, offering a feasible resolution to current agricultural challenges.

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