AUTOMATED IRRIGATION WITH PHOTOVOLTAIC SYSTEM: SUSTAINABILITY AND EFFICIENCY IN THE RURAL AREAS OF PIAUÍ STATE

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Abstract

The main environmental benefit of a photovoltaic system is the use of a clean, renewable, and autonomous energy source, significantly reducing dependence on fossil fuels. Furthermore, this type of system also offers sustainability and efficiency, leveraging solar energy to ensure continuous operation even in locations without access to the electrical grid. Intelligent privacy, integrated into the system, helps reduce water waste by monitoring soil moisture levels in real time using sensors and specific software. Based on this data, the system automatically adjusts safety, applying the exact amount of water needed for healthy plant development. In this study, conducted in the state of Piauí, in the municipality of José de Freitas, resistive sensors were used that automatically activate when the soil reaches a predefined moisture level. From this point on, the system precisely activates or interrupts the monitoring process, preventing both excess and shortages of water. This automation provides greater efficiency in the use of water and energy resources, resulting in more sustainable agricultural production. In addition to optimizing supervision management, the technology reduces operational costs for farmers and helps mitigate greenhouse gas emissions, promoting a smarter, more economical, and environmentally responsible agricultural model.

Keywords: agriculture, irrigation, photovoltaic system, sustainability, energy efficiency.

1. Introduction

The technology of photovoltaic systems integrated with irrigation systems has emerged as an innovative proposal that significantly promotes sustainability within family farming. Combined with these factors, solar energy projects financed in rural areas have generated positive impacts on development in various aspects, directly improving the Human Development Index (HDI), advancing education, increasing employment rates, and preserving the environment (CAF, 2023). Thus, adopting sustainable technologies like solar energy not only strengthens agricultural production but also fosters the social, economic, and environmental development of rural communities with diverse realities (Rumbayan *et al*., 2025).

The adoption of automated irrigation systems powered by solar energy has proven to be a promising alternative for reducing operational costs and optimizing the use of water resources on small and medium-sized rural properties. Recent studies show that automation enables precise control of the volume of water applied to crops, ensuring greater efficiency in agricultural management and reducing losses due to evaporation and infiltration (Silva *et al*., 2023). This precision is especially important in semi-arid regions, such as Piauí, where water scarcity represents a recurring challenge for subsistence agriculture. The integration of moisture sensors, intelligent controllers, and photovoltaic panels allows for sustainable, cost-effective, and autonomous management of irrigation systems (Moraes & Oliveira, 2024).

Moreover, the use of solar energy in automated irrigation contributes to the climate resilience of rural communities by reducing dependence on fossil fuels and unstable power grids. The decentralization of energy production strengthens farmers' autonomy and lowers long-term operating costs (Lima *et al*., 2022). This model of clean and distributed energy production has the potential to boost the local economy and attract investments in sustainable technologies, promoting a just and inclusive energy transition in rural regions (Rodrigues *et al*., 2024). Thus, the photovoltaic system not only meets the energy demands of irrigation but also represents a strategic pillar for the sustainable development of rural areas.

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Although several studies have explored the use of photovoltaic systems in irrigation and the application of automation technologies in agriculture, many rural properties in semi-arid regions still operate with manual irrigation systems that do not integrate real-time soil monitoring with solar-powered energy systems.

In addition, most studies focus either on photovoltaic energy generation or irrigation automation separately, with limited research addressing their practical integration in small-scale family farming environments. Therefore, this study seeks to fill this gap by proposing and evaluating an automated irrigation system powered by photovoltaic energy combined with soil moisture sensors and microcontroller-based control. The system is designed to operate under the economic and technical constraints typical of rural properties in the semi-arid region of northeastern Brazil.

Therefore, this study aims to design and evaluate an automated irrigation system powered by photovoltaic energy and controlled by soil moisture sensors and a microcontroller-based platform. The proposed system is specifically developed for small-scale family farming conditions in the semi-arid region of northeastern Brazil, seeking to provide an accessible and sustainable technological solution that improves water-use efficiency and reduces dependence on conventional energy sources.

In this way, the integration of the photovoltaic system is a key ally in the agricultural and environmental context, as reducing the use of fossil fuels — major contributors to greenhouse gas (GHG) emissions — directly helps to lower air pollution. This rise in GHG emissions negatively affects plant yields (Rahman *et al*., 2022), leading to a decrease in crop productivity and significant long-term losses for farmers. Additionally, conventional irrigation systems, when not properly monitored, can waste up to 60% of the water used on farms, directly impacting local sustainability (Santos *et al*., 2020). Therefore, this case study aims to apply automation technology within the context of family farming.

2. Materials and Methods

The project was developed on a rural property in the municipality of José de Freitas, state of Piauí, in a family farming area. The region is characterized by a semi-arid climate and sandy soil, factors that demand efficient water management to maintain agricultural productivity. The proposed system used photovoltaic solar to a submersible pump and an automated irrigation control system to optimize water and energy use.

The property is located in the municipality of José de Freitas (PI), at coordinates 04°45’51’’ S and 42°34’35’’ W. In 2024, watermelon cultivation was selected due to its short production cycle, which allows for financial returns within a few months, as well as its adaptability to the edaphoclimatic conditions of the Semi-Arid region (MDA, 2024). Studies conducted in the Brazilian Northeast have shown that watermelon crops exhibit satisfactory agronomic performance in sandy soils and hot climates characteristic of semi-arid regions (Silva *et al*., 2021).

For the energy sizing of the photovoltaic system, solar irradiation data were obtained from the SunData platform of the Sérgio de Salvo Brito Reference Center for Solar and Wind Energy (CRESESB,2023), which indicate that José de Freitas has an annual average of 5.64 kWh/m²·day, with peaks exceeding 6.52 kWh/m²·day in September. These figures highlight the significant potential that would be wasted without the implementation of solar technologies in agricultural systems.

The general objective was to compare the previous photovoltaic system with its automated version to verify how modernization could generate both environmental and economic benefits. The automated irrigation project with a photovoltaic system was proposed considering the farmers' economic realities and available materials and resources.

The development steps were:

- Data collection on the type of crop cultivated, irrigated area, water availability, and average energy consumption;
- Evaluation of existing infrastructure, pipelines, and solar exposure;
- Collection of solar radiation data for the region, with an average potential of around 5.5 kWh/m²/

day for José de Freitas (INPE, 2017);

- Estimation of daily energy needs based on pump consumption, leading to the selection of a system with 8 panels of 570W each;
- Selection of compatible inverters, controllers, cables, and accessories for the pumping system;
- Simulation of energy production using PVSyst® software to ensure project viability throughout the year (PVSYST, 2021).

Figure 1 presents the photovoltaic system under study located in the municipality of José de Freitas – Piauí.

Figure 1: Irrigation system under study in José de Freitas - Piauí. Source: authors.

Figure 2 shows a schematic representation of the solar-powered automated monitoring system. The system integrates photovoltaic panels connected to a water pump, which draws water from a reservoir to irrigate a crop. An inverter converts the solar energy into a suitable form to power the components. The Arduino UNO R3 microcontroller serves as the central unit, receiving data from a soil moisture sensor installed in the field. Based on the moisture readings, the Arduino communicates with the smart control panel, which automatically activates or deactivates the security system. This configuration ensures efficient water management for fruits such as watermelon, optimizing resource use and adjusting manual intervention, while promoting sustainable agricultural practices through renewable energy.

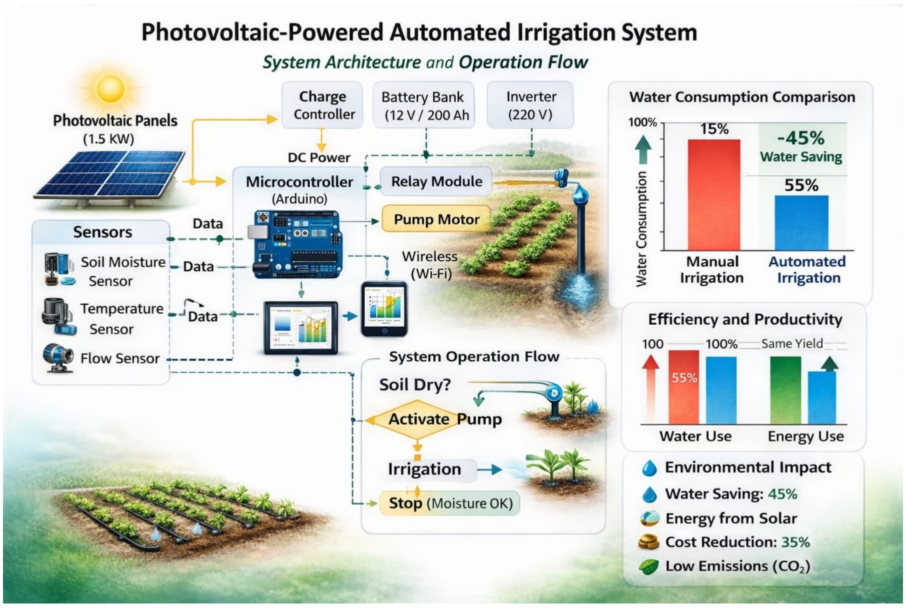

Figure 2: Study transparency system in graphical representation. Source: authors.

Figure 2 presents the schematic representation and operational flow of the photovoltaic-powered automated irrigation system implemented in this study. The system integrates photovoltaic panels, sensors, a microcontroller (Arduino Uno R3), and a pump control module. Soil moisture data are continuously monitored, and when levels fall below a predefined threshold, the microcontroller activates the pump via a relay module, initiating irrigation. Once adequate moisture is reached, the system automatically interrupts the process. This configuration was experimentally applied in a rural area of José de Freitas (PI), demonstrating efficient water management and optimized energy use through real-time monitoring and automation.

The system includes a 3 hp three-phase submersible pump from Lion Model 4R3IB – 23 320, ensuring continuous operation even with fluctuations in solar irradiance. The control panel and protection kit (surge protection, circuit breaker, and grounding) ensure electrical safety.

Before detailing the operational aspects of the proposed system, it is essential to present the main components that make up the photovoltaic-powered irrigation infrastructure. These elements were selected to ensure high efficiency, durability, and compatibility with rural environmental conditions typical of the semi-arid regions of Piauí. Each component plays a crucial role in the system's performance — from energy generation and storage to the automation and control of water distribution. Table 1 lists the components of the system.

Table 1: Components of the photovoltaic system under study. Source: authors.

Description	Technical Information
08 Solar Panels	Era Solar, 570W Mono Eco
01 Three-Phase Inverter	Powtran, 220V – 2 kW
01 MC4 Connector Pair	1 male e 1 female
10 m Solar Cable	Black and red, 6,0 mm²
01 Surge Protection Device	Exatron, 1000 VDC 3P
01 Circuit Breaker	SGV, 32A 1000VDC
01 Grounding Kit	3/8 X 1,20mts e Conic Pvc C Cover 230x200x180
01 Control Panel	Carbon Steel Beige RAL 7032, 400x300mm
01 Pump	Lion Model 4R3IB, 3 Cv
01 Arduino R3 Uno Board	Microcontroller system
01 Soil Moisture Sensor	Operating voltage: 3.3V ~ 5V

The technical specifications of the submersible motor pump used in the irrigation system are presented in Table 2. This is the Lion 4R3IB – 23 320 model, responsible for pumping water in the irrigation system. The main operational data were obtained directly from the manufacturer (Leão Motobombas, 2024), as summarized below.

Table 2: DataSheet Pump Lion Model 4R3IB – 23 320. Source: Leão (2025).

Description	Technical Information
Power	3 Cv
Voltage	220 V
Model	4R3IB – 23 230
Energy phases	three-phase
Frequency	60 Hz
Cooling system	Oil
Maximum Flow Rate	3.600 liters per hour

The system under study also includes a soil moisture sensor module, which contains a device capable of measuring moisture at a given location, working in conjunction with microcontroller boards (including Arduino, PIC, AVR, and ARM). This module is represented in Figure 4, where the sensor is divided into two parts. The first consists of a sensor that, using two probes, measures moisture by measuring the electrical current between them; the second is a circuit with a trimpot, which allows for adjustable sensitivity.

The soil moisture sensor module, together with a microcontroller board, is capable of measuring soil moisture and, when it reaches a certain level, can automatically activate irrigation equipment or even emit sound and light signals — functions that depend on programming and the application of additional accessories. In addition, due to its ease of use, the module is ideal for projects and can be applied by both students and professionals, as shown on the website plantasinfo.com.br for the moisture sensor. Table 3 presents the main information from the datasheet of the Moisture Sensor model: HL-69 or HW-080.

Table 3: DataSheet do Sensor de umidade modelo: HL-69 ou HW-080. Source: UsinaInfo (2025).

Description	Technical Information
Model	HL-69 ou HW-080
Interface (4 wires)	VCC/GND/DO/AO
Operating voltage	3.3V ~ 5V
Sensor dimension with probes (CxL)	~60x20mm
Circuit dimension with trimpot (CxL)	~31x14mm

To enhance water and energy efficiency, an automation module based on a microcontroller was incorporated. The main goal was to ensure irrigation occurred only when necessary, avoiding water waste and optimizing energy use.

The automation system was implemented using an Arduino Uno R3 in Figure 5, programmed to control the submersible pump based on soil moisture levels. Resistive moisture sensors were strategically installed and sent real-time data to the microcontroller. The programmed logic ensured that when the moisture level fell below a reference threshold (experimentally determined for the specific crop), the pump would automatically activate. When optimal moisture was restored, the pump would shut off.

The pump operated for an average of 2 to 3 hours per day, during peak sunlight hours (between 10 a.m. and 3 p.m.), as programmed. The daily energy demand was met without the need for batteries, as the system operated in direct mode (on-grid with a variable frequency solar inverter).

The Arduino Uno R3 microcontroller board, responsible for processing the signals sent by the humidity sensors and automatically activating the submersible pump. The main technical specifications of the datasheet used are presented in Table 4.

Table. 4: DataSheet da placa Uno R3. Source: Arduino (2025).

Description	Technical Information
Model	Arduino-compatible UNO R3 board
Microcontroller	ATmega328p
Operating voltage	5V
Input voltage (recommended)	7-9V
Voltage limits	6 a 20 Volts
Clock speed	16MHz
Dimensions (CxLxA)	68x53x10mm
Weight	55g

3. Results

System tests were conducted throughout September 2024, during the transition from the dry season to the onset of rains in José de Freitas – PI. This period was chosen as it represents a challenging scenario of high temperatures, intense solar radiation, and low soil moisture, requiring greater irrigation demands.

The communication between the Arduino, moisture sensors, and power relay was secure, with proper isolation to protect low-voltage circuits. An LED alert system indicated the pump's operational status (on/off), facilitating local maintenance and monitoring.

To better illustrate the improvement in irrigation efficiency, a comparison between the previous manual irrigation system and the automated photovoltaic irrigation system was performed. The automated system significantly reduced water consumption while maintaining the same level of crop productivity.

The results demonstrated a significant improvement in irrigation efficiency after implementing the automated photovoltaic irrigation system. Water consumption was reduced by approximately 45% compared to the previous manual irrigation method, while maintaining the same crop productivity level.

Similar reductions in water consumption have been reported in studies using soil moisture–based irrigation systems. For example, Silva *et al*. (2023) observed reductions between 30% and 50% when automated irrigation was applied in semi-arid agricultural environments.

The results obtained in this study therefore confirm that the integration of photovoltaic energy and soil moisture sensors can significantly optimize water management in small-scale farming systems.

In addition to reducing water waste, the system improved energy efficiency by operating only during periods of sufficient solar irradiance. This operational strategy minimized unnecessary pump activation and reduced mechanical wear. To evaluate the performance of the proposed system, a comparative analysis of water consumption was conducted. As shown in Figure 3, the automated photovoltaic irrigation system demonstrated a significant reduction in water usage compared to the conventional manual method. The automated system consumed approximately 55% of the water required by the manual approach, representing a reduction of about 45%. This improvement is attributed to the use of soil moisture sensors and real-time control, which enable irrigation only when necessary, thereby minimizing water waste and enhancing overall system efficiency.

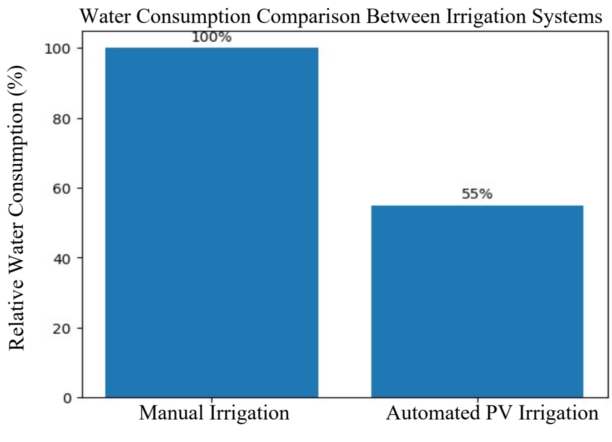

Figure 3: Comparison of water consumption between manual irrigation and automated photovoltaic irrigation system. Source: authors.

Table 5 summarizes the performance comparison between the conventional irrigation method and the automated photovoltaic irrigation system. The automated system demonstrated significant improvements in water use efficiency and operational control. The use of soil moisture sensors allowed irrigation to occur only when necessary, preventing excessive water use and reducing operational costs.

Table 5: Performance comparison between irrigation system. Source: authors.

Parameter	Manual Irrigation	Automated Irrigation
Water consumption	100%	55%
Water saving	0%	45%
Energy efficiency	Medium	High
Irrigation control	Fixed schedule	Soil moisture based
Operational cost	Higher	Lower
System monitoring	Manual	Automatic

The results obtained in this study demonstrate that the integration of photovoltaic energy and automated irrigation technologies can significantly improve water use efficiency in small-scale agricultural systems. The implementation of soil moisture sensors allowed irrigation to occur only when necessary, reducing water consumption by approximately 45% compared to the previous manual irrigation system.

Similar results have been reported in previous research on sensor-based irrigation systems. According to Cardenas-Lailhacar *et al*. (2005), irrigation systems controlled by soil moisture sensors can reduce water consumption by 20% to 50%, depending on soil conditions and crop type. The results obtained in the present study fall within this range, confirming the effectiveness of sensor-based irrigation control.

Studies on precision agriculture also highlight the importance of real-time monitoring technologies in improving irrigation efficiency. Jones (2019) reports that automated irrigation systems based on soil moisture monitoring significantly reduce water losses caused by fixed irrigation schedules, particularly in semi-arid climates where evapotranspiration rates are high.

In addition to water savings, the use of photovoltaic energy contributes to the sustainability of agricultural systems. According to Li *et al*. (2023), solar-powered irrigation systems represent an effective strategy for reducing greenhouse gas emissions and improving energy autonomy in rural areas lacking stable electrical infrastructure.

Furthermore, research conducted by Kumar *et al*. (2024) demonstrates that solar irrigation systems can reduce long-term operational costs for farmers by decreasing dependence on conventional electricity sources. This economic advantage is particularly relevant for small-scale farmers operating in remote regions.

Finally, the integration of renewable energy technologies with automation platforms such as microcontrollers and IoT-based monitoring systems has been identified as a key element for the development of smart agriculture systems. According to FAO (2021), the adoption of intelligent irrigation technologies is essential for improving water management and ensuring food security in regions affected by climate variability and water scarcity.

Therefore, the results of this study reinforce the potential of photovoltaic-powered automated irrigation systems as a sustainable and accessible technological solution for improving water and energy efficiency in family farming systems in semi-arid environments.

4. Conclusion

This study evaluated the implementation of an automated irrigation system powered by photovoltaic energy for small-scale family farming in the semi-arid region of José de Freitas, Piauí. The results demonstrated that the integration of renewable energy with low-cost automation technologies can significantly improve water management efficiency in rural agricultural environments. The proposed system reduced water consumption by approximately 45% compared to traditional manual irrigation practices while maintaining the same level of agricultural productivity. These results highlight the potential of combining soil moisture monitoring, microcontroller-based automation, and photovoltaic power generation as a sustainable technological solution for regions facing water scarcity and limited access to reliable electricity. In addition to improving irrigation efficiency, the system contributes to the adoption of sustainable agricultural practices by reducing dependence on conventional energy sources and optimizing the use of water resources. Such solutions are particularly relevant for family farming systems in semi-arid regions, where resource limitations often constrain agricultural productivity and resilience.

Despite the positive results, this study was conducted in a single experimental area and during a specific crop cycle, which limits the generalization of the findings. Future research should investigate long-term system performance, economic feasibility, and the integration of remote monitoring technologies such as Internet of Things (IoT) platforms to enhance system scalability and operational control. Overall, the proposed approach represents a promising pathway for promoting sustainable agriculture and improving resource efficiency in semi-arid rural environments, contributing to the development of more resilient and energy-efficient agricultural systems.

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