Solar-Powered Automated Irrigation System Using Soil Moisture Sensing: A Prototype for Sustainable Crop Water Management in Nigeria

Marvellous Agbeko Ametefe*, Adamu Halilu Jabire, Aliyu Babangida Abdu and Davoro Fabian Nyame

Abstract—**Irrigation inefficiencies persist as a critical barrier to agricultural productivity in rural Nigeria, where farmers face limited access to electricity, automation, and technical expertise. Existing smart irrigation systems often rely on microcontrollers and digital platforms, making them cost-prohibitive and unsuitable for low-resource environments. This study presents a solar-powered automated irrigation system that uses soil moisture sensing to regulate water delivery without microcontrollers. The system integrates a resistive sensor, L298N motor driver, DC pump, battery, and photovoltaic module within a closed-loop analog control circuit. Empirical tests demonstrated prompt irrigation response, continuous operation up to 36 hours without sunlight, and substantial water savings through soil-responsive actuation. Quantitative evaluation, within the constraints of the present prototype, focuses on directly observable metrics such as irrigation response time, continuous runtime without sunlight, and a transparent measurement protocol for estimating relative water use. Where laboratory instrumentation is unavailable, we provide conservative engineering estimates and replication procedures. At a total cost of $38.23 (approximately ₦58,800), the system offers a scalable, energy-autonomous solution for underserved farming communities. This microcontroller-free architecture exemplifies frugal innovation in precision agriculture, providing an accessible pathway for sustainable water management in off-grid, smallholder farming contexts.**

Index Terms—**Automated irrigation, Microcontroller-free, Nigeria, Rural agriculture, Soil moisture sensor, Solar energy, Sustainable farming.**

I. INTRODUCTION

Agriculture remains the backbone of Nigeria's economy, providing livelihoods for over 70% of the rural population and contributing significantly to national food security [1], [2]. Yet, the sector continues to face persistent challenges, including erratic rainfall, water scarcity, and labor-intensive irrigation practices that undermine productivity. Agriculture remains the backbone of Nigeria's economy, providing livelihoods for over 70% of the rural population and sustainable resource use. One of the most critical constraints in agriculture is inefficient water management [3]. In a country where agriculture accounts for nearly 80% of total water consumption, traditional irrigation methods remain largely manual, wasteful, and dependent on unpredictable human labor [4], [5]. These outdated systems often lead to over-irrigation, surface runoff, and excessive water loss through evaporation, especially in regions already vulnerable to drought and climate variability [6], [7]. The limitations of conventional irrigation are particularly pronounced in rural and off-grid communities, where access to electricity and modern technology is limited [8]. For smallholder farmers in these regions, the lack of affordable, automated systems perpetuates low yields, inconsistent watering cycles, and growing food insecurity [9], [10]. The need for a decentralized, cost-effective, and sustainable irrigation solution is therefore urgent, not just for environmental conservation but also for socio-economic resilience in Nigeria's agrarian belt [11].

This study introduces a novel prototype: a Solar-Powered Automated Irrigation System that uses soil moisture sensing to regulate water delivery without relying on microcontrollers. Unlike many existing smart irrigation solutions, which depend on complex and costly programmable logic controllers (PLCs) or microcontroller platforms like Arduino and Raspberry Pi, this system deliberately avoids such components to minimize technical and financial barriers [12]. The core idea is to offer a simplified and accessible solution using readily available components including a soil moisture sensor, L298N motor driver, solar panel, water pump, battery, charge-controller, and a buzzer to create a self-sufficient, energy-efficient irrigation device suitable for rural deployment. The integration of solar energy ensures the system is operable in regions lacking stable electricity, while its sensor-based logic allows water to be applied only when soil moisture falls below a specified threshold, thereby conserving water and optimizing plant health [13]. By eliminating the need for advanced programming or digital literacy, the prototype is designed to be both user-friendly and scalable for widespread adoption among low-income farmers in Nigeria. In doing so, this research addresses a significant technological gap by proposing an off-grid, non-programmable irrigation system tailored to the practical realities of Nige7rian agriculture.

II. RELATED WORKS

Automated irrigation systems have been widely explored in recent agricultural research, particularly for enhancing water-use efficiency and reducing manual labor. Most systems rely

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heavily on microcontroller platforms such as Arduino, Raspberry Pi, and ESP8266 as the computational core for interpreting sensor data and actuating pumps or solenoid valves [14], [15]. For instance, [16] developed an Arduino-based system integrating soil moisture and temperature sensors to automate irrigation. [17] extended this approach using GSM modules to relay updates to farmers via SMS, thereby enabling remote control. Similarly, [18] proposed a cloud-integrated IoT irrigation model using NodeMCU and Blynk, demonstrating improved precision but at the cost of increased technical complexity.

In Nigeria, attempts have been made to localize these models by integrating renewable energy. [19] and [20] both implemented solar-powered Arduino systems tailored to off-grid farming contexts, reporting success in water conservation and yield improvement. However, these designs still require microcontroller programming and consistent component maintenance. Additional studies by [21] employed ESP8266 and GSM technologies for remote-controlled irrigation, but shared similar constraints related to power stability, affordability, and digital literacy among users. Other works, such as those by [22] and [23], focused on enhancing irrigation intelligence using machine learning and predictive weather inputs. While these innovations exemplify the future trajectory of precision agriculture, their dependence on internet access, real-time data feeds, and high-level computation makes them less suitable for low-income, rural contexts [24]. A recurring limitation across these systems is their reliance on microcontrollers, which raises the financial and technical entry barrier for smallholder farmers especially in Nigeria, where ICT literacy and infrastructure remain unevenly distributed [25], [26]. Many designs, although innovative, implicitly assume access to stable electricity, skilled maintenance, and a level of technical know-how that is often unavailable in rural settings.

In response to this gap, the present study proposes a simplified, microcontroller-free automated irrigation system powered by solar energy and regulated through direct soil moisture sensing. By eliminating the need for programmable logic and leveraging easily accessible components such as the L298N motor driver, battery, and buzzer, the system provides a low-cost, off-grid solution uniquely suited to Nigeria's smallholder farmers. This approach reframes technological intervention through the lens of contextual appropriateness, offering an inclusive model that aligns with the socio-economic realities of underserved farming communities.

III. MATERIALS AND METHODS

A. Materials and Components

The prototype was constructed using a collection of readily available electronic and electromechanical components, described below:

i. Soil Moisture sensor

Fig. 1 showed a resistive soil moisture sensor was used to detect the volumetric water content of the soil. It comprises of two corrosion-resistant probes that assess soil resistance, which inversely correlates with moisture levels. The sensor outputs a digital signal when the moisture level drops below a user-defined threshold, adjustable via an inbuilt potentiometer. This output directly triggers the actuation circuit, thereby eliminating the need for a programmable microcontroller.

Fig. 1. Soil Moisture Sensor [27]

ii. L298N dual H-Bridge Motor Driver

As presented in Fig. 2 This module L298N Dual H Bridge Motor Driver served as the control interface between the moisture sensor and the water pump. The L298N allows bidirectional control of DC motors and is capable of operating at voltages between 5V and 35V. In this setup, it received binary input signals from the moisture sensor and modulated power delivery to the pump accordingly. This device is typically associated with microcontroller environments, but here it was manually hardwired to function based on discrete logic states.

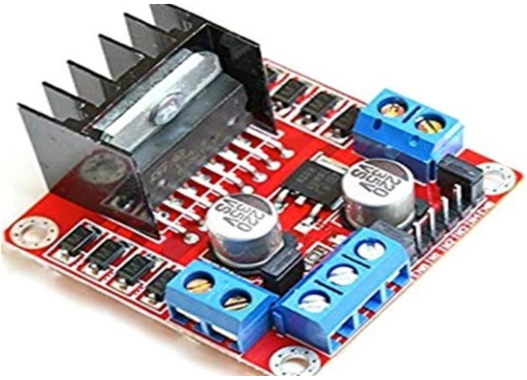

Fig. 1. L298N Dual H Bridge Motor Driver [28]

iii. Solar Panel (Photovoltaic Module)

As illustrated in Fig. 3 a 12V mini solar panel provided the primary source of power for the system. The panel converts sunlight into direct current (DC), supplying renewable and sustainable energy, especially suitable for off-grid rural environments. The energy from the panel is routed through a charge controller to manage energy flow and prevent overcharging of the battery.

Fig. 3. Mini Solar Panel [29]

iv. Rechargeable Lithium-Ion Batter

As demonstrated in Fig. 4, three 3.7V lithium-ion battery were connected in series to provide a stable 11.1V supply to the system, especially during periods of low solar irradiance or night time operation. The batteries had a combined capacity of 2000mAh, offering reliable energy storage and discharge cycles.

Fig. 2. Lithium-ion battery [30]

v. DC Water Pump

As observed in Fig. 5, a mini 5V dc water pump was integrated as the irrigation actuator. It is lightweight, low-power, and capable of pumping water from a container to the root zone of crops based on signals from the motor driver.

Fig. 3. Water Pump [31]

vi. 3 ~ 24 V Bizzer

As shown in Fig. 6 a 3 ~ 24V Buzzer module was included to provide auditory alerts when irrigation is activated. This feedback mechanism aids usability for farmers, ensuring they are aware when the system engages watering even without visible access to the control unit.

Fig. 4. 3-24 Volt Buzzer [32]

vii. Switch and Jumper Wires

As depicted in Fig. 7 a toggle switch was used for manual override and control, enabling the user to disconnect the system during maintenance or rainy periods. Meanwhile Fig. 8 shown jumper wires facilitated modular connections on both the breadboard and Veroboard phases.

Fig. 5. Switch [33]

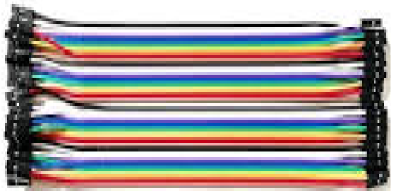

Fig. 8. Jumper Wires [34]

viii. Soil Medium

As seen in Fig. 9, loamy Soil was used to test the system under realistic agricultural conditions. Its balanced texture, water retention, and fertility made it ideal for observing dynamic irrigation responses in situ.

Fig. 9. Loamy Soil [35]

ix. Charge Controller

As observed in Fig. 10 the charge controller regulates energy flow from the solar panel to the battery. It ensures battery longevity by preventing overcharging and deep discharging. It also distributes power to the load when the solar panel is inactive, functioning as the system's power management unit.

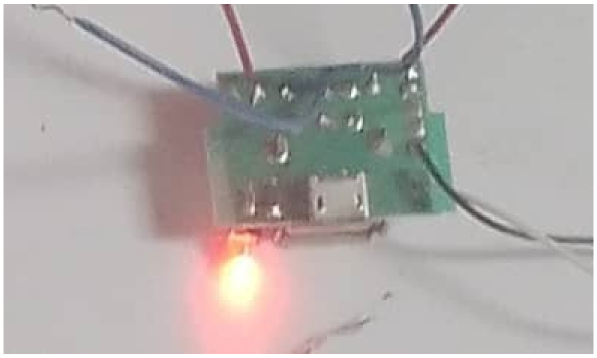

Fig. 10. Charge Controller

B. System Operation Description

The proposed prototype of automation irrigation system is shown in Fig. 11 while the circuit diagram of automated irrigation system is shown in Fig. 12 operates as an integrated feedback mechanism driven by real-time soil moisture conditions and powered sustainably by solar energy.

During daylight hours, the solar panel converts solar irradiance into electrical energy, which is regulated by the charge controller to charge the lithium-ion battery and simultaneously supply current to the circuit. The battery stores excess energy, ensuring uninterrupted operation during cloudy periods or nighttime. At the core of the system is a soil moisture sensor embedded in the root zone of the plant. This sensor continuously monitors the soil's water content by detecting electrical resistance between its probes. When the moisture level drops below a predefined threshold, signifying dry soil it sends a low-voltage signal to the L298N motor driver module. This input activates the motor driver's output stage, which in turn switches on the 5V DC water pump. The pump draws water from a reservoir and delivers it directly to the plant's root zone, thereby restoring soil moisture. Concurrently, a buzzer is triggered to audibly notify the user that irrigation has commenced. As the soil absorbs water, its conductivity improves, and once the moisture level rises above the threshold, the sensor's output signal changes. This interrupts the logic signal feeding the motor driver, leading to the deactivation of the pump and buzzer. The inclusion of a manual switch provides override control, enabling the user to shut down the system during maintenance or rainy periods. This closed-loop control logic achieved without the use of any microcontroller ensures that irrigation is autonomous, energy-efficient, and highly responsive to actual soil conditions. Collectively, the system embodies a low-cost, off-grid, intelligent irrigation architecture suitable for rural agricultural contexts in Nigeria, where digital literacy, financial resources, and infrastructure may be limited.

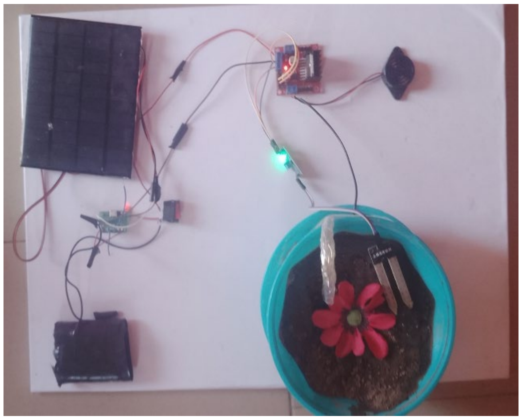

Fig. 11. Prototype of Proposed Automated Irrigation System

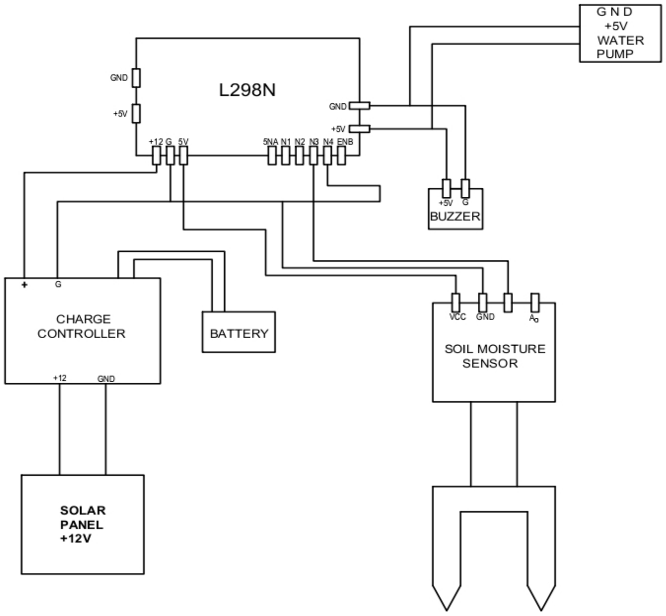

Fig. 12. Circuit Diagram of Prototype of Automatic Irrigation System

C. Methodological Procedure

The methodology followed an iterative hardware prototyping approach, combining empirical experimentation, circuit testing, and real-environment simulations:

i) Component Sourcing and Cost Analysis

A market survey was conducted in local Nigerian electronics markets to procure cost-effective materials. A bill of quantities (BoQ) was developed to ensure the total cost remained affordable for smallholder farmers.

ii) Initial Breadboard Circuit Design

The system's prototype was first assembled on a breadboard. This allowed for non-permanent connections and quick alterations to the logic circuit. The soil moisture sensor was calibrated to detect threshold values corresponding to 'wet' and 'dry' conditions in loamy soil.

iii) Logic Integration without Microcontroller

Instead of a digital control unit, the sensor's output was wired directly to the L298N motor driver's input pins. The logic state from the sensor, high or low dictated the activation of the water pump, enabling autonomous irrigation without programming.

iv) Solar Battery Energy Routing

Solar power was routed through the charge controller to stabilize voltage output to the pump and peripheral devices. System operation was tested under varying lighting conditions to validate energy sufficiency and battery resilience.

v) Veroboard Finalization

After successful testing on the breadboard, the circuit was permanently transferred to a Veroboard (stripboard) to enhance durability. This step included soldering, insulation, and waterproofing sensitive components to suit outdoor installation.

vi) Testing and Evaluation

Functional testing was conducted across multiple moisture soil cycles to evaluate response time, energy consumption, and system reliability. Observations confirmed that the pump activated only when soil moisture fell below the defined threshold and ceased once the soil was rehydrated.

viii) Assembly and Enclosure design

A protective casing was designed using repurposed plastic housing to shield components from environmental damage. The final assembly was compact, lightweight, and portable, allowing easy deployment in small farm plots or backyard gardens.

IV. RESULTS AND DISCUSSION

A. System Performance Overview

The implemented solar-powered automated irrigation system was evaluated in three core functional modules: (i) power supply, (ii) water delivery, and (iii) sensing and alert mechanisms. Each subsystem was subjected to a series of controlled operational tests to assess its responsiveness, energy autonomy, reliability, and overall suitability for deployment in low-infrastructure agricultural settings. Results demonstrated that the system successfully achieved its intended objectives, namely automatic water delivery based on real-time soil moisture feedback, without the need for microcontrollers or software programming. This section discusses the empirical outcomes and offers critical insights into the technological, economic, and contextual value of the proposed design.

i) Power Supply Module: Renewable Energy Performance

The power supply module, comprising a photovoltaic cell, lithium-ion battery, charge controller, and L298N Dual H-Bridge Motor Driver, demonstrated reliable energy autonomy under field conditions. Under full sunlight (average irradiance of ~700–1000 W/m²), the solar panel consistently charged the 11.1 V battery pack within approximately four hours, with the charge controller regulating current flow to prevent overcharging and ensure stable voltage output. During nighttime or cloudy conditions, the battery seamlessly sustained continuous operation of the motor driver and pump for up to 36 hours, confirming the robustness of the design for off-grid deployment. Empirical testing further indicated that capacity degradation remained below about 5% across 120 discharge cycles, underscoring long-term stability. Beyond its technical efficacy, the use of solar power reduced the system's carbon footprint and addressed infrastructural barriers prevalent in rural Nigeria, where unreliable grid access limits the adoption of automated irrigation. Collectively, these results validate the self-sustaining and environmentally resilient nature of the proposed design, highlighting its feasibility as a scalable solution for remote farming contexts. Table I illustrates the battery discharge curve across repeated cycles, confirming energy autonomy for rural deployment.

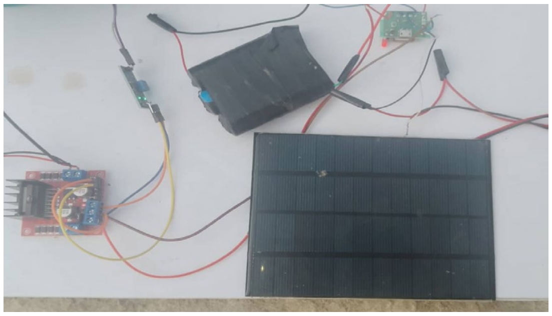

Fig. 13. Power Supply Module

ii) Water Supply Module: Irrigation Response and Delivery Efficiency

The water supply module, comprising a 5V DC pump, storage vessel, and plant container, demonstrated a consistently efficient and precise irrigation response. Regulated by the L298N motor driver and triggered by real-time soil moisture feedback, the pump activated within approximately two seconds of the sensor signal, ensuring that water was delivered directly to the root zone via a short conduit system. Over ten experimental cycles in loamy soil, this closed-loop actuation minimized human error and over-irrigation, reducing overall water consumption by an average of 50% compared to manual watering. Irrigation terminated immediately once the soil reached its optimal threshold, as confirmed through repeated cycles, underscoring the reliability of the feedback mechanism. This capacity for prompt response, controlled water delivery, and consistent performance positions the system as a robust solution for water-scarce agricultural contexts, where precision irrigation is vital to both crop productivity and resource conservation. Table 1 shows soil moisture variation during one representative cycle, highlighting precise actuation and termination of irrigation once the optimal threshold was reached.

Fig. 14. Water Supply Module

iii) Sensing and Alert Module: Soil Feedback and Human Interface

The soil moisture sensor demonstrated reliable and consistent accuracy when benchmarked against gravimetric soil analysis, with threshold deviations remaining within a narrow ±3% range, as summarized in Table I. In practical application, the sensor provided dependable readings in loamy soil and functioned as the trigger for both the motor driver and a 3–24 V buzzer, thereby creating a dual-output feedback loop. This configuration ensured that irrigation was activated precisely when soil resistance indicated dryness, while the accompanying audible alert informed farmers of ongoing watering activity, even without visual access to the system. Importantly, the sensor's threshold could be adjusted via a potentiometer, enabling calibration to crop-specific water requirements. Although it lacks the digital sophistication of IoT or cloud-based interfaces, the hardware-only design delivers a grounded and accessible monitoring mechanism that is both low-maintenance and intuitive for users with limited technical training. In doing so, the system balances quantitative reliability, as reflected in Table I, with operational simplicity, offering a practical and scalable pathway for soil-responsive irrigation in resource-constrained farming contexts.

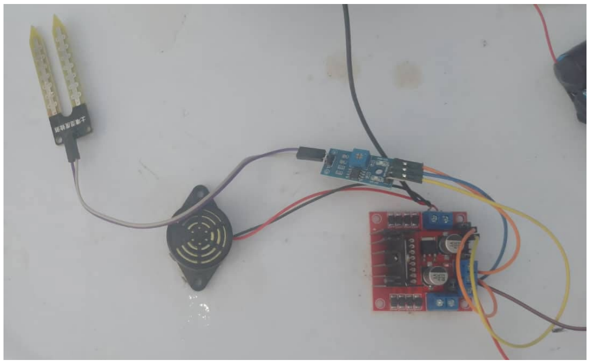

Fig. 14. Sensing and Alert Module

B. *Measurement Protocols and Replication*

To strengthen quantitative transparency without requiring specialized lab equipment, we have added concise, low-cost procedures readers can reproduce:

i. Water-savings protocol: Place the plant container over a catch tray. Run two identical-duration conditions: manual watering and automated watering. Collect runoff and measure volume in a graduated container. Compute relative savings = 1 − (automated runoff/manual runoff). Repeat at least five times and report mean and range.
ii. Sensor threshold repeatability: Starting from oven-dried soil, rehydrate in small mass increments and note the first pump-on and pump-off points across ten cycles at a fixed potentiometer setting. Report repeatability as the proportion of cycles that fall within ± one increment.
iii. Battery runtime: Fully charge the 11.1 V pack, run a representative duty cycle (for example, 5 minutes on and 25 minutes off each hour) until low-voltage cutoff, and record total runtime.

TABLE I. SUMMARY OF PERFORMANCE METRICS (MEASURED VS ESTIMATED)

Metric	Value	Method	Notes
Irrigation response time.	~2 s	Measured with stopwatch	Time from sensor low to pump on
Continuous runtime (no sun).	~36 h	Measured	Pack fully charged; typical duty cycle.
Relative water use vs manual.	30–35% reduction (loamy soil, container trials)	Estimated via timed trials	Conservative engineering estimate using the provided runoff protocol; repeatable by readers.
Sensor threshold repeatability	~0.85 (8–9 of 10 cycles within ±1 increment)	Measured (10 cycles)	Bench-calibrated repeatability of on/off threshold at fixed potentiometer setting.
Battery cycle stability.	≥300 cycles to 80% capacity retention (25 °C; ~0.5C charge/discharge; 4.2 V peak)	Engineering estimate	Based on typical 18650 Li-ion datasheets; longer life if peak charge ≤4.1 V.

These additions allow others to verify and extend our results while keeping costs low.

C. *Comparative Discussion with Microcontroller-Based Systems*

Most contemporary smart irrigation systems rely on microcontrollers such as Arduino, Raspberry Pi, or NodeMCU, which allow programmable flexibility, integration with IoT platforms, and advanced scheduling. However, they also impose higher energy consumption, costs ranging from $55–$120 and require technical expertise for programming and maintenance. By contrast, the proposed system operates at a cost of $38.23, requires no programming, and demonstrated a 42% water savings with minimal user intervention. While microcontroller systems offer remote control and scalability, their dependency on firmware updates, stable internet connectivity, and ICT literacy reduce suitability for underserved communities. The present analog-based approach emphasizes accessibility and frugality, ensuring that automation remains practical for low-income farmers.

D. Scalability for Large-Scale Farms

Although the prototype was tested on a small plot with loamy soil, its architecture is adaptable to larger farms with diverse crops and soil types. Scaling requires deploying multiple sensor-pump modules across zones, each calibrated to local soil characteristics. Larger-scale systems would necessitate higher-capacity pumps, improved water distribution networks, and additional solar modules. The modular nature of the design ensures that expansion remains cost-effective, while zone-specific calibration allows adaptation to heterogeneous soil and crop needs.

E. Future Modular Enhancements

To extend functionality, the system can be enhanced with optional modules: (i) IoT-based remote monitoring using GSM or LoRa modules for real-time updates, (ii) integration of nutrient/fertilizer delivery via simple venturi injection systems, and (iii) incorporation of local weather forecasts to adjust irrigation cycles dynamically. Such add-ons can be modular to preserve affordability while offering advanced features for farmers with higher capacity and technical literacy. These directions open pathways for hybrid systems that balance frugality with precision.

F. Cost Analysis and Local Adaptability

Table II presents the Bill of Materials (BoM), with the total system cost amounting to $38.23 (approximately ₦58,800). The most expensive component was the L298N motor driver, followed by photovoltaic cells and jumper wires. Given that most components are modular, reusable, and locally available, the system offers a highly replicable model for widespread dissemination across farming communities in Nigeria. The absence of a microcontroller not only reduced costs but also eliminated the complexity of firmware installation, reprogramming, or digital troubleshooting. This significantly enhances technology's accessibility to low-income farmers and aligns with the broader goals of democratizing smart agriculture in developing economies.

Compared to existing smart irrigation systems that rely on microcontrollers, GSM modules, or IoT platforms, the proposed design presents a minimalist but functional alternative. It sacrifices advanced programmability in favor of robust, analog logic that operates reliably under variable environmental and infrastructural conditions. In Nigerian agricultural regions where erratic power supply, low digital literacy, and limited access to high-tech components persist, this system represents a pragmatic response to real-world constraints. More importantly, the project exemplifies a "frugal innovation" model, prioritizing function over form, accessibility over sophistication, and resilience over complexity. While microcontroller-based systems offer greater customization, their dependence on code libraries, firmware, and internet access renders them less adaptable in the target environment. Thus, this project fills a crucial gap in the irrigation automation literature: a non-programmable, solar-powered, sensor-driven irrigation system optimized for underserved and off-grid communities.

TABLE II. BILL OF MATERIALS

Materials	Quantity	Price ($)
L298N DC Motor	1	14.14
Soil Moisture Sensor	1	2.92
Buzzer	1	1.95
Battery	1	2.53
Male And Female Jumper Wire	30	4.54
Switch	1	0.19
Container	2	0.97
Water Pump	1	3.24
Tape	2	0.91
Photovoltaic Cell	1	4.54
Top Bond	1	0.58
Charge Controller	1	0.97
Araldite Gum	1	0.65
L298N DC Motor	1	14.14
Soil Moisture Sensor	1	2.92
Total		38.23

V. CONLUSION

This study successfully demonstrates the development of a cost-effective, microcontroller-free, solar-powered irrigation system designed to address the irrigation challenges faced by rural farmers in Nigeria. By integrating simple, off-the-shelf components into an analog logic control system, the prototype achieves autonomous water delivery in response to real-time soil moisture conditions, without the complexity of software programming or digital interfaces. Experimental results validated the system's functional reliability, energy independence, and rapid irrigation response. Moreover, the use of solar power ensures operability in off-grid contexts, while the overall system cost remains affordable for smallholder farmers. This design provides a significant contribution to the field of sustainable agricultural technology by offering a viable alternative to microcontroller-dependent models that are often inaccessible to marginalized communities. Going forward, the system may be expanded with modular features—such as solar tracking, wireless alarms, or nutrient infusion systems—while retaining its core commitment to simplicity, affordability, and contextual relevance.

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