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Development and Application of a Solar-Powered Timer Pump for Irrigation Purpose

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ABSTRACT: frequent power outages and expensive electricity bills in developing countries have driven the development of alternative solutions to electricity from the grid to power pumps for irrigation purposes. In line with this, the study aims to design, construct, fabricate and test a solar powdered timer pump for irrigation that successfully mitigates the concerns of unreliable power supply, inefficient water management, over-irrigation, and raised operational expenses in agricultural activities. The system was developed by designing the various components through design calculations of the pump, solar panel, inverter, charge controller, microcontroller, moisture sensor, sprinkler, and various pipe connections. After designing, the fully assembled system was tested under controlled field conditions. The system was programmed to activate the pump at predetermined times and operate in short cycles typically 4-second intervals until the soil moisture sensor indicated that the desired moisture level had been reached. The soil moisture levels varied from 0 to 150 cl and the corresponding pumping duration was determined. The results revealed that when the level of moisture in the soil was high (1400%) compared to when 10 cl of water was added, there was a 100% reduction in the pumping duration to 0 s. As the percentage amount of water increased from 10 cl, there was a corresponding percentage increase in the duration of pumping. However, at a very high percentage increase of about 1150%, the corresponding level of percentage increase in pumping duration was reduced due to high levels of moisture content in the soil. This study demonstrates that the integration of solar energy with automated control systems can successfully resolve the issues associated with traditional irrigation methods.

KEYWORDS: solar-powered timer pump, irrigation, soil moisture, photovoltaic cells.

1. INTRODUCTION

Agriculture, the backbone of many developing nations, faces significant issues in ensuring an efficient water supply for crop irrigation [1]. In places such as Nigeria, the problem is further compounded by frequent power outages and expensive electricity bills, which often require farmers to rely on conventional electrically driven irrigation equipment [2]. These systems, however, usually result in poor water distribution due to irregular power supply and antiquated infrastructure, hence raising operational costs and diminishing crop yields [3]. Moreover, the inefficiencies in water distribution can lead to severe water wastage, further stressing an already scarce resource.

At the same time, global concerns over fossil fuel depletion and environmental deterioration have accelerated the quest for sustainable energy alternatives. The environmental impact of burning fossil fuels ranging from air pollution to greenhouse gas emissions has encouraged governments and industries worldwide to pursue cleaner, renewable energy alternatives [4]. Among these, solar energy has been deemed a realistic choice due to its abundance, sustainability, and small environmental footprint [5].

One way to capture solar energy is through the use of solar panels, composed of photovoltaic cells, which capture sunlight and convert it directly into electrical energy through a process known as the photovoltaic effect [6]. This technology, which was once considered prohibitively expensive, has become increasingly cost-effective as manufacturing costs have dropped and efficiency has improved over the years [7]. In addition, solar energy systems have the added benefit of being scalable, allowing them to be deployed in both small-scale rural settings and large industrial applications [8]. For irrigation purposes, harnessing solar energy has the potential to reduce dependence on erratic grid electricity and also provides a stable, reliable power source in remote areas where traditional energy infrastructure is often lacking or non-existent [9].

Consequently, many research works have focused on harnessing solar-powered pump for irrigation purposes by maximizing the energy efficiency of PV cells. Some of these works have been on applying sensors to detect the position of the sun and the period of the day thereby aligning the solar panels perpendicularly to the solar beams for effectively charging the battery [10], some have employed PV systems for drip irrigation system [11] and simulated smart sensors for automatic irrigation using computer software [12] while some have focused on reviews of the application of possible solar-powered irrigation in specific developing countries [13, 14]. However little has been done on the actual hardware fabrication and implementation of such systems in monitoring the moisture level and other parameters to achieve an automatic irrigation system.

The fundamental purpose of this project is to design, construct, fabricate and test a solar timer pump for irrigation that successfully mitigates the concerns of unreliable power supply, inefficient water management, over-irrigation, and raised operational expenses in agricultural activities. The main objectives are to integrate solar energy with automated control systems utilizing a photovoltaic panel, battery storage, a charge controller, an inverter, and a microcontroller-based pump; to evaluate the system's performance under diverse soil moisture conditions; and to scrutinize the economic viability and scalability of the developed system. The results of this research have scientific and commercial implications. First, the research enhances comprehension of the combination of renewable energy and sensor-based automation in irrigation systems, providing a basis for subsequent optimization and innovation in sustainable agriculture technology. Commercially, recognizing and executing an effective solar-powered irrigation system will decrease operational expenses, improve crop yields, and encourage the utilization of locally sourced, sustainable technologies. Consequently, this can foster the development of small-scale agricultural operations, generate employment possibilities, and diminish reliance on imported energy solutions.

2 MATERIALS AND METHODS

2.1 Materials

The components used for the fabrication of the solar timer pump were sourced from local suppliers and verified for compliance with design specifications. The materials include a 12V, 100 W monocrystalline solar panel (Fig. 1*a*), 100 Ah battery (Fig. 1*b*), 40 A charge controller (Fig. 1*c*), 2000 W transformerless inverter (Fig. 1*d*), an Arduino-based microcontroller with an integrated timer module (Fig. 1*e*) and a soil moisture sensor (Fig. 1*f*). All pipings, 0.5 HP alternating current (AC) pump (Fig 1*g*), water tank (Fig. 1*h*), water sprinkler (Fig. 1*i*), 2.5 mm copper flex cables, and galvanized steel frames were purchased at vendor shops within Lagos, Nigeria.

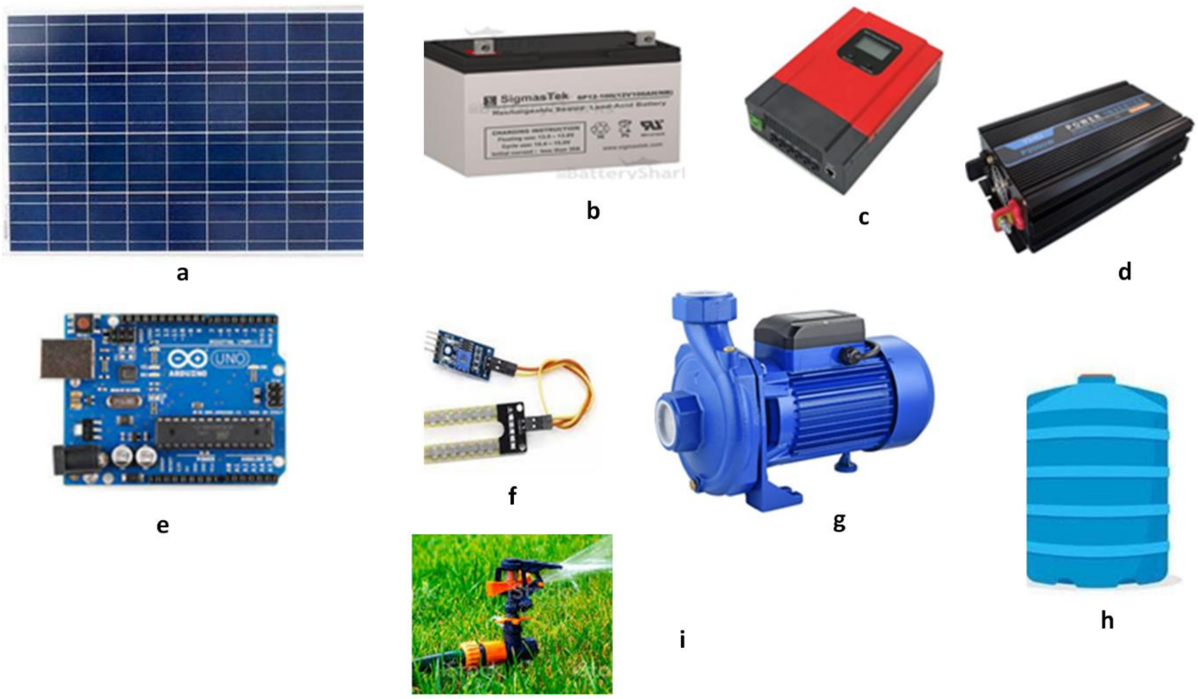

Fig. 1 Solar Timer Pump System Components – Solar Panel (*a*) Battery (*b*) Charge Controller (*c*) Inverter (*d*) Microcontroller (*e*) Soil Moisture Sensor (*f*), pump (*g*), tank (*h*), sprinkler (*i*).

2.2 Design Analysis and Calculations

The design of the solar timer pump system was based on several key calculations that ensure that each component is compactible within the integrated system and efficiently works to carry out the desired load. The pump capacity determines the maximum volumetric discharge flow rate of water and the discharge head. The discharge head determines the height of the piping to the sprinkler. The capacity of the pump also determines the inverter size and the discharge time of the battery. The battery size also determines the specifications of the solar panel used.

2.2.1 Pump sizing

The pump's performance was characterized by its flow rate, pressure head, and power consumption. For a 0.5 hp surface pump, the manufacturer’s pump rating is a maximum volumetric flow rate of 5.8 l//min (0.9665 x 10^{-4} m^3/s), discharge pressure of 2.5 bar, expected power consumption of 372.85 W and a 75% efficiency. The pressure head and total head of the pump were then calculated by first determining the discharge velocity of the fluid using Equation 1

$$V = \frac{Q}{A} \quad (1)$$

Where Q is the volumetric flowrate, A is the cross-sectional area, and V is the velocity of the fluid.

The cross-sectional area of the pump is given as Equation 2

$$A = \frac{\pi D^2}{4} \quad (2)$$

Where D is approximately 0.03 m for a 1-inch pump

At a Q value of 0.97×10^{-4} m^3/s, A was computed as 5.07×10^{-4} m^2, and V as 0.40 m/s

Using the calculated V, the pressure head and total head (h) of the pump, were determined using equations 3 and 4.

$$h = \frac{P}{\rho_w g} + z + \frac{v^2}{2g} \quad (3)$$

Where h is the total pump head, P is the fluid pressure, ρ_w is the fluid density, g is the acceleration due to gravity, z is the elevation which is the assumed vertical distance from the tank to the pump, and v is the fluid velocity.

In equation 3, the expression $\frac{P}{\rho_w g}$ is the pressure head of the pump and $\frac{v^2}{2g}$ is the kinetic term

Therefore the calculated pressure head is 50.97 m and the kinetic term is 0.007884 m and taking z to be 3ft (0.91 m), h is 51.89 m.

Therefore, the pressure head and the total head are 50.97 m and 51.89 m respectively.

Validating the manufacturer pump power rating,

$P_{out} = h \times \rho \times g$

Where h is the pump head (m), ρ is the density of water, g is the acceleration due to gravity and P_{out} is the outlet pressure.

Assuming $\rho = 1000$ kgm^{-3}, and g = 9.81 m/s^2

$P_{out} = 50.9$ bar

The output pressure of the pump is approximately the same as the pressure of the pump.

2.2.2Piping

The cross-sectional area of the pipe was determined using Equation 4 below:

$$A = \frac{\pi d^2}{4} \quad (4)$$

Where d, the diameter of the pipe, is 0.018 m. The resulting area of the pipe of 2.55x10-4 m^2 is less than that of the pump, hence a reducer was used to change the diameter of the pump to fit with the pipe's diameter.

2.2.3Solar inverter

The inverter was meant to power the pump of 372.85 W, which implies that the inverter has a free capacity of 1627.15W. The free power capacity space is needed for the starting current of the pump. In inverter usage, it is advisable to always power a load less than 75% of the power capacity of the inverter. Hence, an inverter capacity of 2000 W was used. This implies that at the running state of the pump, 18.64% of the inverter capacity will be used. At start up 2.4 A at 230 V (552 W) will be used amounting to 27.6% inverter capacity.

2.2.4 Charge Controller

The solar charge controller that was used for the project fabrication was a 12V, 40A pulse width modulation (PWM) solar charge controller. It would give an output of about 14.1V and a maximum value of 40 A. However, the output current of this device would be the output current of the solar panel which is about 5.29 A.

2.2.5 Battery Specification

A 100 Ah battery capacity was used for the project construction. This can discharge 100 A per hour at full charge. In this project, the solar panel is giving out 5.29A per hour amounting to 31.14 A if the sun shines up to 6 h on a sunny day. At the start-up of the pump, it will take a 100 Ah battery to dissipate for 41.6 h at 2.4 A per hour while at a running state of 1.62 A, it will take 61.7 h to dissipate a fully charged 100 Ah battery. However, this can only be true when the battery is fully charged. For a 100 W solar panel charging the battery to 31.14 A for 6 h, it will take approximately 13 h to dissipate the battery at start-up and 19 h at running state and

2.2.6Solar panel area

The effective area of the photovoltaic cell which is crucial for estimating the energy conversion potential under standard test conditions, was calculated using the dimensions provided by the manufacturer. The area (A) was determined as 1.35 m^2 using equation 5

$$A = \text{Length} \times \text{Breadth} \quad (5)$$

Where the length is 1.5 m and the breadth is 0.9 m

2.2.7Solar panel inclination angle

The optimal tilt angle of the solar panel was determined using the solar declination (δ) in equation 6, which varies throughout the year. The declination

$$\delta = 23.45° \times \sin\left(\frac{2\pi(284 + n)}{365}\right) \quad (6)$$

Where n is the day number of the year. For instance, on the 365th day of the year, this calculation helps ensure that the panel is positioned to maximize solar irradiance, thereby enhancing energy capture.

2.2.8Control logic and timer settings

To ensure that the pump operates when necessary, minimizing energy consumption and preventing over-irrigation, a microcontroller was programmed using the Arduino platform. The programming involved setting up a digital clock from 7 AM and 7 PM. At those times, the microcontroller initiates the pump by sending a signal through a digital output pin connected to a relay controlling the pump. The data then enters a loop where it turns the pump on for short bursts typically 4-second cycles and continuously reads the analog input from the soil moisture sensor. This sensor reading is compared against a predefined moisture threshold. If the sensor value indicates that the soil is still below the desired moisture level, the microcontroller repeats the 4-second cycle; otherwise, it turns off the pump.

2.3Fabrication and assembly procedure

The computer-aided design (CAD) diagram (Fig. 2) of the solar timer pump system was first carried out to make fabrication and assemblage easier. The solar panel was mounted on the galvanized steel frame at an optimal tilt angle determined through prior calculations to maximize solar irradiance (equation 6). The panel's output wiring was then connected to the 40 A charge controller, which regulates the voltage and current supplied to the 100 Ah battery, thereby establishing the energy storage subsystem. The inverter was subsequently connected to the battery to convert the stored DC energy into a stable 230V AC output, which is required for the pump operation. The 0.5 hp AC pump was installed adjacent to the water storage tank, with 1-inch pipes channelling water from the tank to the pump and ½-inch pipes delivering water from the pump to the sprinkler system to ensure uniform distribution. Finally, the Arduino-based microcontroller was integrated into the system, programmed with preset irrigation schedules, and connected to the soil moisture sensor, which was embedded in the test field to provide real-time feedback for automated control.

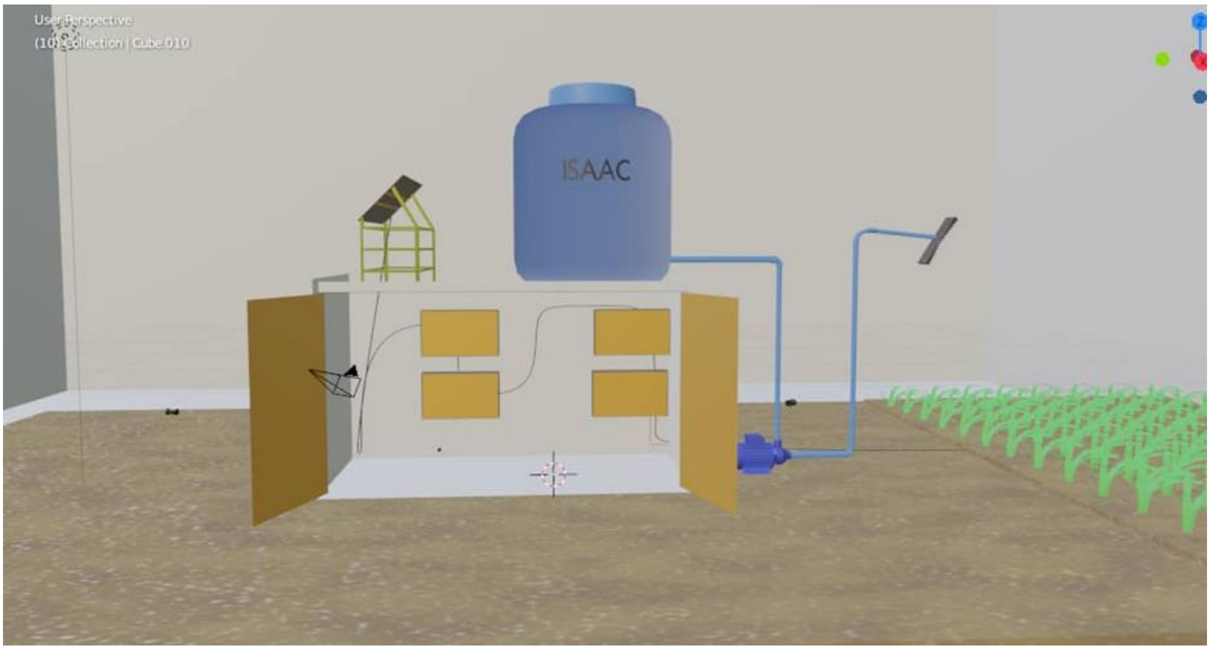

Fig. 2Computer-Aided Design (CAD) diagram of the solar timer pump

2.4 Analysis

To evaluate the performance of the solar timer pump, analysis was conducted. First, the energy conversion efficiency of the solar panel was determined by comparing the electrical output under standard test conditions with the energy stored in the battery. Next, the pump's flow rate and pressure head were measured and compared to the theoretical values calculated during the design phase (see Section 2.2). Data from the soil moisture sensor were correlated with the pump's activation time to confirm that the automated control logic effectively prevented over-irrigation. Finally, an economic analysis was performed by compiling the costs of all individual components and calculating the overall system investment, which serves as a benchmark for future scalability and commercialization efforts.

2.5 Operation and Testing Procedure

Once fully assembled, a series of operational tests were carried out under controlled field conditions. The system was programmed to activate the pump at predetermined times and operate in short cycles typically 4-second intervals until the soil moisture sensor indicated that the desired moisture level had been reached. During testing, key performance parameters were recorded, including the pump's activation time, water flow rate, and overall energy efficiency. These measurements were taken using calibrated flow meters and data loggers, ensuring that the operational behaviour of the system closely matched the design expectations.

3 RESULTS AND DISCUSSION

3.1Design results and analysis

The calculated design parameters and the evaluated properties of the fabricated solar timer pump system (Fig. 3) under controlled conditions are summarized in Table 1. The solar panel consistently delivered an optimum operating voltage of approximately 18.9 V and produced a power output close to its rated 100 W under peak sunlight. The charge controller maintained a stable charging current to the 100Ah battery, ensuring reliable energy storage. The inverter successfully converted DC power to a stable 230 V AC output, which is critical for the proper functioning of the 0.5 HP pump. Moreover, the pump had a consistent flow rate of approximately 5.8 litres per minute during continuous operation.

Fig.3 Diagram of the fabricated Solar Timer Pump System

Table 1 Design results and operational parameters of the Solar Timer Pump System

Parameter	**Design parameters**	**Measured Value**	**Specification/Expected Value**
Solar panel			
Voltage (V)		18.9	18.9 (optimum Operating voltage)
Area (m^2)	13.5		
Power Output (W)	100	100	100
Charging current (A)	5.29		
Battery Capacity (Ah)		100	100
Charge Controller Rating (A)		40	40
Inverter			
Output voltage (V)		230	230
Power (W)	2000		
Pump			
Total head (m), hydraulic head (m)	51.89, 50.97		
Power Consumption		372.85 W (running)	0.5 HP (372.85 W)
Discharge flow Rate (l/min)		~5.8	5.8
Temperature Range (°C)		25–35	25–35 (operational range)
Pipe height (m)	0.914		

3.2Water delivery yield

The water delivery yield for each experimental run measured as a function of the duration of the pump operation under various soil moisture conditions is presented in Table 2. In general, the duration of pump operation varied with the initial soil moisture content and the corresponding response of the soil moisture sensor. Under extremely dry conditions (with 0 cl of added water), the pump operated for approximately 105.4 seconds before the sensor detected sufficient moisture. When the level of moisture in the soil was high (1400%) compared to when 10 cl of water was added, there was a 100% reduction in the pumping duration to 0 s.

As the volume of water introduced into the soil sample was increased, the operating time decreased. For instance, when 10 cl of water was added, the pump activation time reduced to 94.98 seconds; at 25 cl it was 83.81 seconds; at 50 cl, 55.87 seconds; at 75 cl, 27.94 seconds; at 100 cl, 11.17 seconds; at 125 cl, 1.21 seconds; and finally, with 150 cl of water, the pump did not activate at all (0.00 seconds). As the percentage amount of water increased from 10 cl, there was a corresponding percentage increase in the duration of pumping. However, at a very high percentage increase of about 1150%, the corresponding level of percentage increase in pumping duration was reduced (Fig. 4). This might be because the moisture senses saturation levels at high levels of moisture content in the soil.

Table 2 Irrigation performance as a function of water delivery yield of the pump

S/N	Soil (KG)	Water Added (cl)	Time (Sec)
1.	20	-	105.4
2.	20	10	94.98
3.	20	25	83.81
4.	20	50	55.87
5.	20	75	27.94
6.	20	100	11.17
7.	20	125	1.21
8.	20	150	0.00

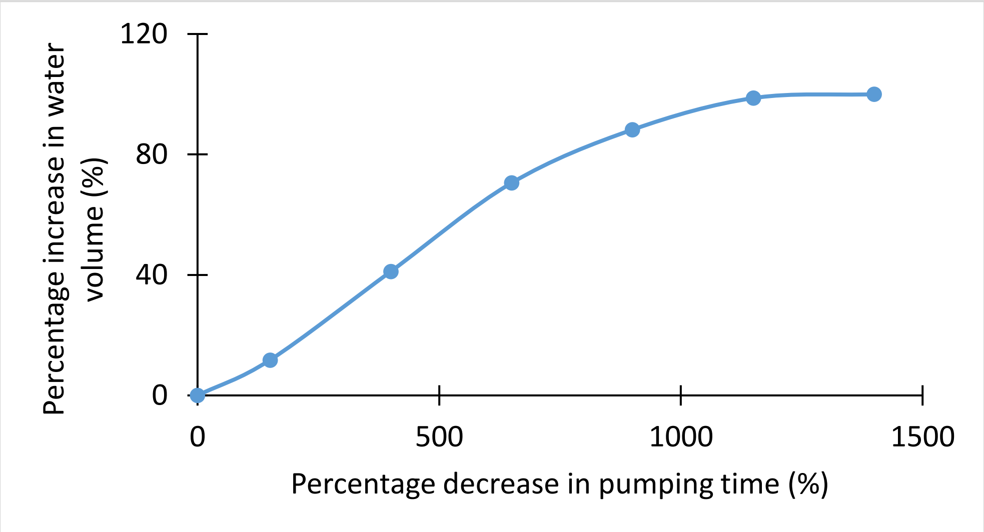

Fig. 4 Relationship between the percentage increase in moisture level above 10 cl and percentage pumping time

3.3 Energy efficiency and electrical performance

The evaluated energy efficiency of the solar timer pump system which is a measure of the electrical performance of the inverter and battery is presented in Table 3. This surge capacity is well within the 2 KVA rating of the inverter, ensuring that the system can accommodate transient power demands without performance degradation. Furthermore, the battery was capable of supporting up to 6 hours of continuous operation under full sunlight conditions, as confirmed by monitoring its charge-discharge cycles during the experiments.

Energy conversion efficiency was further quantified by comparing the solar panel’s theoretical output with the actual energy stored in the battery and subsequently delivered to the pump. The system demonstrated an overall energy conversion efficiency of approximately 80%, which is indicative of effective power management across the solar panel, charge controller, battery, and inverter subsystems.

Table 3 Energy efficiency metrics of the solar timer pump system

Metric	Measured/Calculated Value	Remarks
Pump starting power draw	~552 W	Calculated from 230 V × 2.4 A
Inverter rating	2 KVA	Sufficient to handle surge current
Daily operating time (Full Sunlight)	Up to 6 hours	Battery capacity supports extended operation
Overall energy conversion efficiency	~80% (estimated)	Based on solar panel output vs. battery storage

3.4 Solar timer pump system costing

The total system cost was estimated at 201,000 naira (Table 4) which would form part of the capital investment of the system. In the long run, the system would be economical when applied to irrigation in agricultural farms and would give a basis for further scale-up.

Table 4 Cost analysis of various equipment and materials

S/N	Component/Equipment and Materials used for the design	Cost (N)
1.	Solar Panel (12V, 100W)	21,500
2.	Charge controller (40 A)	9,000
3.	Battery (100 A)	55,000
4.	Inverter (2 KVA)	28,000
5.	Pump	31,500
6.	Microcontroller (timer)	20,000
7.	Soil moisture sensor	6,000
8.	Pipes	4,000
9.	Sprinkler	2,000
10.	Connecting wires	3,000
11.	Tank	12,000
12.	Miscellaneous	9,000
	Overall cost (₦)	**201,000.00**

3.5 Discussion

The experimental data (Table 2) indicate that the pump's operation time is inversely proportional to the soil moisture content. Under dry conditions (0 cl added water), the pump operated for 105.4 seconds. As the moisture content increased, the sensor detected the change more rapidly, resulting in shorter pump cycles. This responsive control mechanism is crucial for conserving water, as it ensures that the pump delivers water only when the soil requires it.

The uniformity in operational parameters as recorded in Table 1 demonstrates that the system components function reliably under varying environmental conditions. The solar panel, battery, charge controller, and inverter consistently operated within their specified ranges, ensuring a stable power supply to the pump. This stability is particularly important in rural areas where fluctuations in power supply can lead to inconsistent irrigation, adversely affecting crop health.

The energy efficiency metrics (Table 3) highlight the system’s capability to manage both steady and surge power requirements effectively. The inverter’s ability to handle the initial 552 W surge, along with the battery’s capacity to support extended operation, results in significant energy savings over conventional irrigation methods. The calculated efficiency of approximately 80% translates into lower operational costs, making the system economically attractive for small-scale farmers. Moreover, the reduced reliance on grid electricity or diesel generators further enhances its economic viability.

In comparison with Conventional Irrigation Systems, the solar timer pump offers various advantages compared to standard electrically driven irrigation systems. Its reliance on sustainable solar energy decreases operational expenses (section 3.4) and environmental impact. The automated control system, which controls pump operation based on real-time soil moisture data, assures exact water delivery, decreasing water wastage and enhancing crop yields. These qualities collectively make the solar timer pump an attractive solution for sustainable farming operations, particularly in places with unreliable power supplies.

4 CONCLUSION AND RECOMMENDATION

This study demonstrates that the integration of solar energy with automated control systems can successfully resolve the issues associated with traditional irrigation methods. The solar timer pump, which includes a photovoltaic panel, battery storage, charge controller, inverter, and a microcontroller-based control system with a soil moisture sensor, effectively provides water according to real-time field circumstances. Experimental assessments demonstrated that the system adaptively regulates pump functionality based on soil moisture levels, markedly decreasing water waste and minimizing operational expenses. Moreover, the system maintained excellent energy conversion efficiency and operational stability under fluctuating sunlight circumstances, underlining its promise as a sustainable alternative for irrigation in places with unstable power supplies.

While the system produced consistent performance, differences in soil moisture and ambient conditions affected the pump's activation time, indicating potential for further refinement in sensor calibration and control logic. Such changes could enhance the system’s reactivity and overall efficiency. Furthermore, the positive results obtained in this study imply the viability of installing solar-powered irrigation systems on a broader scale, thereby lowering dependency on traditional energy sources and contributing to sustainable farming practices.

It is advised that future studies explore alternative energy storage methods and adaptive control methods, such as incorporating improved battery technologies or utilizing machine learning algorithms to enhance irrigation scheduling. Additionally, conducting thorough pilot-scale investigations under real-world agricultural conditions is crucial to validate laboratory findings, analyze process economics, and uncover any scalability problems. These phases will be vital for converting from a prototype to a commercially viable product, which might drive local agricultural development, offer job opportunities, and promote environmental sustainability.

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