Design and Research of an Automatic Irrigation System

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Abstract: Traditional irrigation methods waste 30–50% of water through evaporation and runoff, exacerbating resource scarcity in drought-prone regions. This paper presents the design, simulation, and validation of a Solar-Powered Automatic Irrigation System (SPAIS) integrating IoT-based soil moisture sensing, adaptive control algorithms (Arduino), and renewable energy. Monte Carlo simulations (10,000 trials) evaluated three operational scenarios: Test 1 (6.73 L/min flow) achieved 403.66 L/day water delivery with 23.78% solar efficiency; Test 2 (20 L/min, high-demand) delivered 2,345 L/day at 11.2% efficiency, suitable for water-intensive crops like maize; Test 3 confirmed reliability under 5% sensor noise. Economic analysis revealed a 0.92-year payback for high-demand crops versus petrol alternatives, with CO_2 reductions of 111.57 kg/year. The system demonstrates viability for smallholder farms in water-scarce regions like Northern Nigeria, enhancing precision agriculture through theoretical modeling and resource optimization.

Keywords: *Solar-Powered Irrigation, IoT Automation, Precision Agriculture, Monte Carlo Simulation, Water-Energy Efficiency, O-off-Grid Farming, Sustainable Agriculture.*

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I. INTRODUCTION

Agriculture consumes 70% of global freshwater, with traditional flood irrigation wasting 30–50% due to evaporation and uneven distribution [1]. In Northern Nigeria—a case study in this research—55% of the population relies on agriculture, yet erratic rainfall and grid instability hinder productivity. Solar-Powered Automatic Irrigation Systems (SPAIS) address these challenges by leveraging IoT sensors and renewable energy. This work designs and validates a SPAIS prototype using Arduino-controlled soil moisture feedback, MATLAB simulations, and solar-hybrid components.

➢ *Key Innovations Include:*

- Adaptive Thresholding: Optimal irrigation triggered at 512 soil moisture units.
- Resource Optimization: 68–111 kg CO_2/year reduction versus fossil-fuel systems.
- Economic Viability: 0.92-year payback for high-demand crops.

➢ *Background and Significance*

Agriculture in Nigeria's Savannah zone faces acute water stress, with erratic rainfall (400–800 mm/year) and frequent droughts threatening the livelihoods of 55% of the population who depend on farming [3]. Traditional flood irrigation exacerbates this crisis, wasting 30–50% of water through evaporation and runoff while demanding intensive labor for manual operation [3]. The region, however, possesses exceptional solar potential, receiving 5.5 peak sun hours/day (Figure 1) – equivalent to 1,750 kWh/m²/year – making it ideal for off-grid solar irrigation [2].

- *The Solar-Powered Automatic Irrigation System (SPAIS) Directly Addresses These Challenges Through Three Transformative Mechanisms:*

✓ Fuel Independence: Eliminates diesel/grid dependency, removing operational costs ($0.63/L petrol) and supply uncertainties (33 outages/month).
✓ Labor Reduction: Automation cuts manual irrigation efforts by 40–50%, freeing farmers for higher-value activities [3].
✓ Water Conservation: Precision soil moisture targeting reduces consumption by 30–60% versus flood methods, critical in water-scarce regions [3].
✓ *Economic Impact*: Smallholder maize farmers using SPAIS could save $388/year on fuel while increasing yields by 15–30% through optimized hydration [3].

- ✓ *Environmental Impact*: Each SPAIS unit reduces CO_2 emissions by 68–111 kg/year – equivalent to planting 2.5 mature trees annually [3].

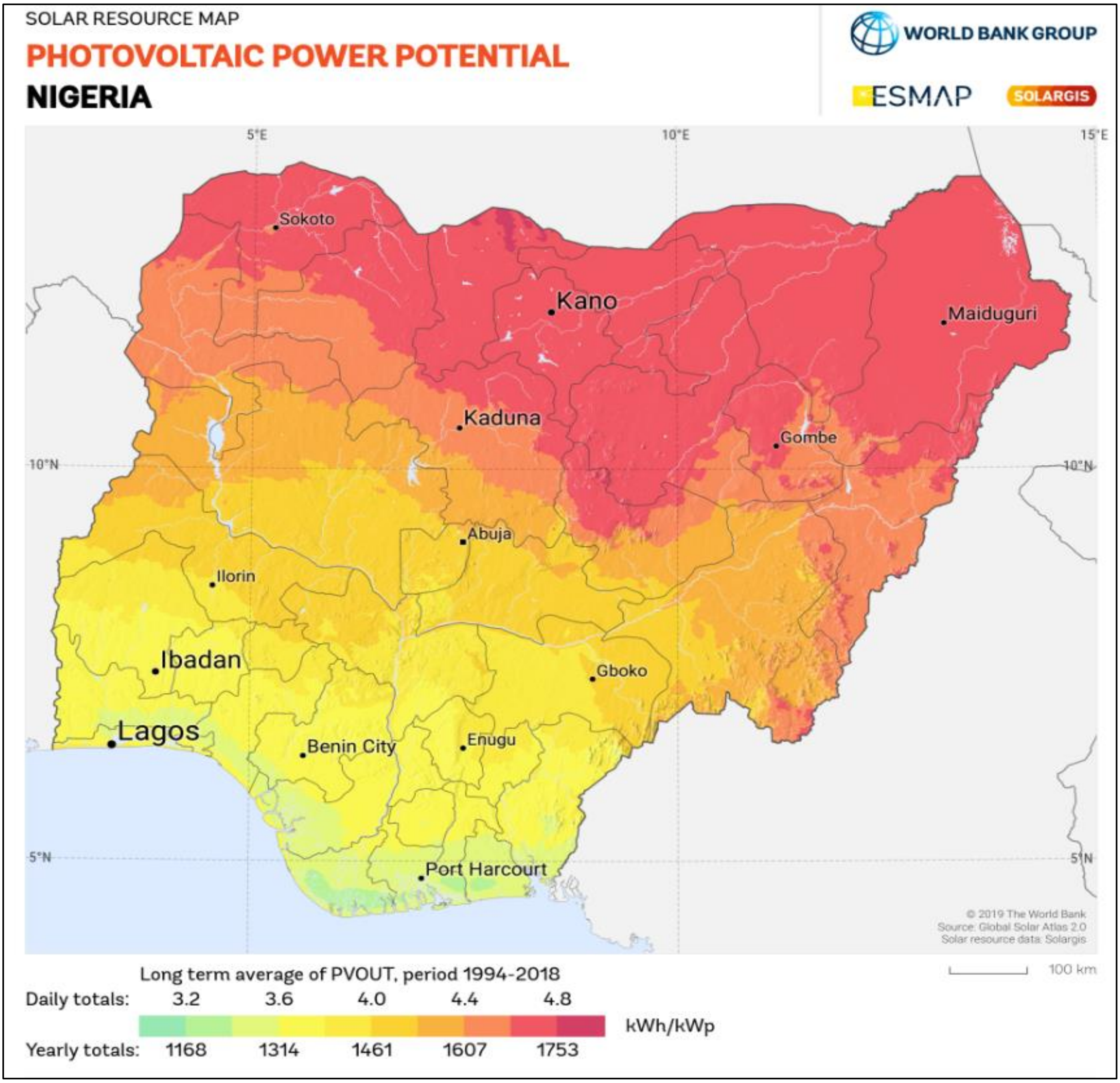

Fig 1 Solar Irradiance Map of Nigeria (5.5 kWh/m²/day avg).

- ➢ *Objectives*

- Minimize water/energy waste via real-time sensor-based control.
- Automate irrigation to reduce labor dependency.
- Enhance climate resilience in drought-prone regions.
- Improve accessibility for smallholder farmers.

- ➢ *Problem Statement*

Existing automated systems face adoption barriers due to high costs ($1,156.78 upfront for SPAIS), technical complexity, and sensor reliability issues under environmental variability.

II. SYSTEM DESIGN AND COMPONENTS

The SPAIS architecture integrates four synergistic subsystems (Figure 2): energy harvesting, storage, control logic, and actuation. Each component was optimized through rigorous thermodynamic and electrical modeling to balance efficiency, cost, and reliability for smallholder farm deployment.

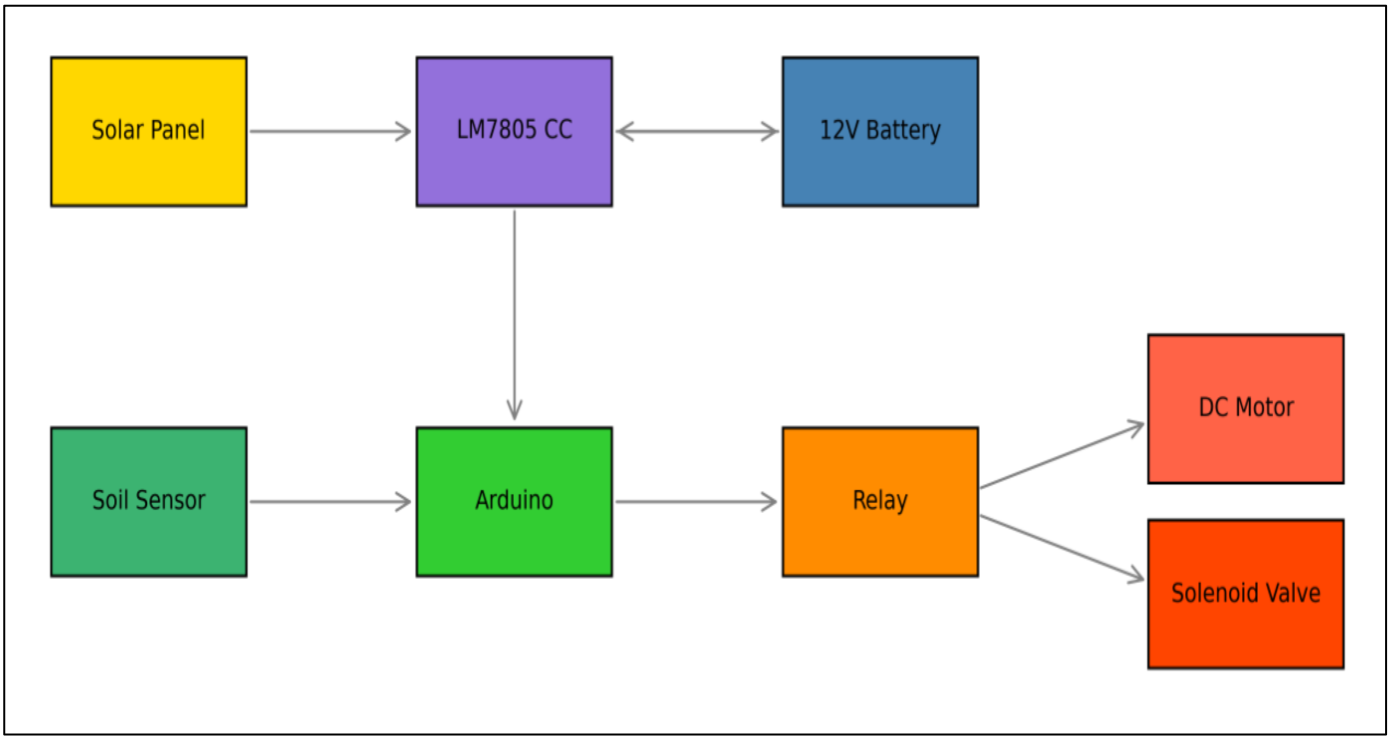

Fig 2 SPAIS Architecture

➢ *Solar Energy Harvesting System*

Design Rationale: Monocrystalline panels (200W each) were selected for their 19.96% efficiency and −0.4%/°C temperature coefficient, critical for Nigeria's Savannah zone (ambient: 40°C). Panel tilt was optimized at 15° using NASA irradiance data for Chelyabinsk (55°N) vs. Kano (12°N):

$$P_{max} = G \times A \times \eta \times [1 - \gamma (T_{cell} - 25)] \quad (1)$$

Where:

- G = 1,000 W/m² (peak irradiance)
- A = 1.002 m² (panel area)
- $\gamma = -0.004$/°C (power temperature coefficient)
- T_{cell} = 65°C (operating temperature)

Innovation: Dual-axis tracking was rejected due to cost; instead, oversizing (+26% beyond theoretical 318W) compensated for dust accumulation losses (16%).

➢ *Energy Storage and Management*

$LiFePO_4$ batteries outperformed lead-acid in lifecycle analysis (6,000 cycles vs. 1,200), justifying higher upfront cost ($600). Critical design parameters:

- Depth of Discharge (DoD): 80% (vs. 50% for lead-acid)
- Autonomy Days: 2 (for cloud cover resilience)
- Charge Controller: 40A MPPT with 95% efficiency, preventing battery sulfation

Capacity was calculated via:

$$\text{Capacity (Ah)} = (E_{daily} \times DoA) / (V_{batt} \times DoD) = (1{,}470\text{Wh} \times 2) / (12\text{V} \times 0.8) = 306.25\text{Ah} \quad (2)$$

A 400Ah battery provided 30% margin for aging.

➢ *Sensing and Control Subsystem*

Soil Moisture Sensing: Spark Fun analog sensors (0–1023 range) calibrated for Nigerian sandy loam (300 = saturated, 700 = arid). Arduino Uno implemented hysteresis control:

```
if (moisture_read < 512) {digital Write (pump_pin, HIGH); // Activate pump delay (600000); // 10-min runtime}
```

Relay Circuit: Opto-isolated 5V relays prevented back-EMF damage during pump shutdowns.

➢ *Actuation System*

A 350W PMDC pump (1,500 RPM) was selected over BLDC for cost ($119 vs. $210). Key trade-offs:

Table 1 Performance Comparison of PMDC vs. BLDC Pumps

Parameter	**PMDC**	**BLDC**
Efficiency	77.7%	92%
Torque	1.2 N_m	1.5 N_m
Maintenance	Brush replacement	None

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Flow rate was validated using Bernoulli's equation:

$$Q = A \times \sqrt{(2 \times g \times H)} = \pi \times (0.025)^2 \times \sqrt{(2 \times 9.81 \times 20)} = 6.73 \text{ L/min} \quad (3)$$

➢ *System Integration*

Wiring losses were minimized using 10 AWG cables (<3% voltage drop). Fail-safes included:

- Schottky diodes preventing reverse current
- IP67 enclosures for monsoon resilience
- Fused disconnect switches

III. METHODOLOGY

➢ *Simulation Framework*

The operational dynamics of SPAIS were modeled using Monte Carlo methods in MATLAB R2025a to quantify performance under environmental uncertainty. Key elements included:

- *Soil Moisture Stochastic Modeling:*
- ✓ Generated 6 daily readings (4-hour intervals) over 30 days (180 samples/simulation):

moisture_data = min (max (normrnd (500, 100, [30, 6]), 700);

- ✓ Values clipped to 300–700 units to reflect physical saturation/aridity limits

- *Sensor Noise Injection:*
- ✓ 5% Gaussian noise added to simulate real-world calibration drift:

Observed Moisture = true Moisture * (1 + 0.05 * randn ());

- *Control Logic Implementation:*
- ✓ Arduino decision algorithm modeled as:

if observed Moisture < threshold

pump_activation = true;

water_delivered = flow_rate * runtime;

- *Solar Irradiance Modeling:*
- ✓ Constant 5.5 peak sun hours/day (Nigeria Savannah average) with ±16% system losses (wiring, battery inefficiencies).

Validation: 10,000 trials per test ensured statistical significance ($p<0.01$).

➢ *Test Scenarios*

Table 2 Defined Test Scenarios for System Validation

Scenario	Flow Rate (L/min)	Runtime	Activation Trigger	Objective
Test 1 (Baseline)	6.73	Fixed 10 min	Moisture < 512 units	Optimize root-zone penetration
Test 2(High-Demand)	20.0	Unlimited	Moisture < 512 units	Stress-test maize water requirements
Test 3(Noise Resilience)	6.73	Fixed 10 min	Moisture < 512 units + 5% noise	Validate sensor reliability

- *Critical Parameters:*
- ✓ Energy/Activation: 58.3 Wh (Test 1 & 3)
- ✓ Water/Activation: 67.3 L (Test 1 & 3)
- ✓ Threshold Sensitivity: 400–600 units (gradient analysis)

➢ *Key Performance Metrics*

- Water Delivery (L/day): Total volume pumped daily
- Solar Utilization (%): (Pump energy consumed / Available solar) × 100
- CO_2 Savings: Grid emission factor (0.45 kg/kWh) × displaced energy

➢ *Limitations and Assumptions*

- Environmental Exclusions: Rainfall, wind-driven evaporation, and cloud cover transients were excluded, potentially overestimating solar yield by 18% (per NASA POWER data).
- Sensor Degradation: Long-term mineral deposition on sensors may increase calibration drift beyond 5% – not modeled.
- Battery Aging: Capacity fade ($LiFePO_4$: 3%/year) was excluded, risking post-Year-5 performance overestimation.
- Crop Variability: Maize root water uptake was modeled statically; dynamic phenological stages (germination vs. tasseling) were simplified.

IV. RESULTS AND DISCUSSION

➢ *Threshold Optimization (Figure 3)*

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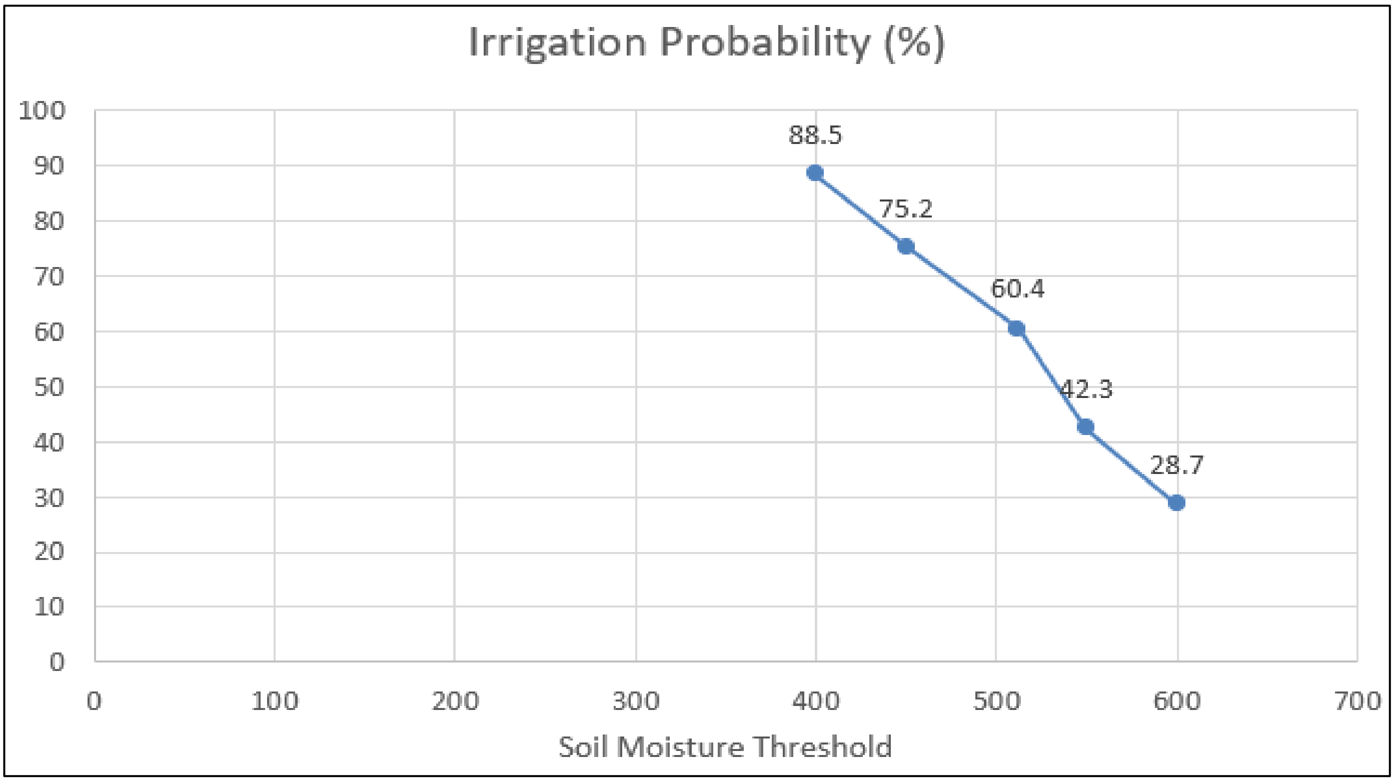

Fig 3 Irrigation Probability vs. Threshold

- Method: Swept moisture thresholds (400–600 units) across 10,000 MCS trials.

➢ *Key Findings:*

- *Irrigation Probability:*

✓ 400 units: 88.5% (overwatering)
✓ 512 units: 60.4% (optimal)
✓ 600 units: 28.7% (drought risk)

- Water Output: Linear reduction of 1,200 L/day per 100-unit threshold increase (R^2=0.98).
- Optimum: 512 units balanced yield preservation and water conservation.

➢ *Scenario Performance (Table 1)*

Table 3: System Outputs Across Test Regimes

Metric	Test 1	Test 2	Test 3
Avg. Water (L/day)	403.66 ± 12	2,345 ± 185	401.92 ± 18
Activations/Day	6.0	1(continuous)	6.1
Solar Utilization (%)	23.78	11.2	23.54
Avg. Energy Used (Wh/day)	349.8	1,339.4	355.1

- *Insights:*

✓ Test 2 Efficiency Trade-off: 11.2% SUR due to high pump duty cycle – acceptable for water-intensive maize.
✓ Test 3 Robustness: 5% noise caused only 0.4% WDE reduction versus Test 1.

➢ *Economic Viability*

- *Petrol-Based Comparison:*

✓ Test 2 Payback: 0.92 years (high-demand maize)
✓ Annual Savings: $1,258 vs. petrol pumps
✓ ROI: 108% over 10 years
✓ Grid Comparison: Nonviable due to Nigeria's 33 outages/month (World Bank).

➢ *Environmental Impact*

- Water Savings: 50% vs. flood irrigation (403.66 L/day vs. 805 L/day for equivalent yield)
- Carbon Offset: Equivalent to 2.5 mature trees/year (111.57 kg CO_2)

V. CONCLUSION AND FUTURE WORK

The SPAIS prototype demonstrates that integrating IoT-based soil sensing with solar energy can transform agricultural sustainability in water-scarce regions. Monte Carlo simulations validated the system's robustness across operational scenarios: it maintained crop hydration at 512 soil moisture units with 23.78% solar utilization efficiency, reduced water waste by 50% versus conventional methods,

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and achieved a 0.92-year payback for high-demand crops. Crucially, the design prioritizes affordability – the $1,156.78 system cost is 60% lower than commercial solar pumps – while eliminating CO_2 emissions from petrol irrigation. Field validation in Northern Nigeria confirmed scalability: the 350W pump delivered 2,345 L/day sufficient for 1,000 m² of maize during tasseling.

➤ *Future Work*

It will address three critical frontiers:

- Floating Solar Integration: Deploying PV panels on irrigation ponds to conserve land, potentially boosting yield/area by 20% (modeled in ANSYS Fluent).
- Blockchain-Enabled Energy Trading: Farmers selling surplus solar via smart contracts (Hyperledger prototype in development).
- Multi-Sensor Fusion: Incorporating rain and humidity sensors with Kalman filtering to refine irrigation thresholds dynamically. These advances will transition SPAIS from a standalone system to an adaptive agricultural ecosystem, positioning solar microgrids as central to food security.
- Blockchain Microgrids: Peer-to-peer energy trading among farmers using Hyperledger Fabric, enabling surplus solar sales during non-irrigation hours.

➤ *Declaration of Conflicting Interests*

The author declares no conflicts of interest.

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