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A Hybrid Renewable Energy-Powered Automatic Drip Irrigation System for Optimized Water Management

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ABSTRACT

This experimental engineering study designed and tested a hybrid renewable energy-powered automatic drip irrigation system for optimized water management. The prototype combined a solar photovoltaic module and a stream-driven permanent-magnet direct-current generator with a 12-V battery, charge-control circuitry, microcontroller, relays, pumps, soil-moisture sensing, and drip-delivery components. Physical modeling and simulation-based prototyping were followed by five component trials and a three-day field test on a 50-m² string-bean plot in Sitio Alagao, Barangay Minuyan, Norzagaray, Bulacan. Performance was assessed through generator voltage, power and charging calculations, turbine speed limits, pump output, water consumption, irrigation duration, and calculated soil moisture. The first two generator configurations did not provide sufficient voltage, whereas the revised gearing in Trial 3 generated a consistent 25–30 V. The corrected solar configuration in Trial 5 also powered the system successfully. Automatic irrigation consumed 11.5 L per operation compared with 48 L under traditional irrigation, representing approximately 76.0% less water. Irrigation duration was reduced to about 2 min, compared with 12 min for manual watering and 30 min for traditional irrigation. The calculated average solar-charger output was 33.25 W, while the pump delivered an estimated 42 W mechanical output. The system maintained a calculated soil-moisture level of 95.833% for the specified test volume. The findings show that a hybrid off-grid irrigation prototype can reduce water use and manual effort while sustaining sensor-controlled water delivery. The study contributes a practical basis for further field validation, longer-term crop testing, and refinement of renewable-energy irrigation systems.

Keywords: *automatic drip irrigation, hybrid renewable energy, precision agriculture, soil moisture sensing, solar photovoltaic system, water-use efficiency*

INTRODUCTION

Irrigation remains essential where rainfall is insufficient, irregular, or poorly timed for crop requirements. Water may be supplied from surface water, groundwater, or alternative sources, but inefficient delivery can increase withdrawals, evaporation, runoff, and labor demand. Sustainable irrigation therefore requires systems that apply water at the right place, time, and amount while protecting limited water resources (Pereira et al., 2002; Howell, 2001; Jones, 2004; Gleeson et al., 2012).

The Philippine agricultural sector depends heavily on irrigation, particularly for rice, corn, vegetables, and other high-value crops. National Irrigation Administration data cited in the source manuscript describe 10.3 million hectares of agricultural land and 3.1 million hectares of irrigable land, while a World Bank assessment cited in the same source identifies extensive difficult-to-irrigate areas (National Irrigation Administration, n.d.; World Bank, n.d.). Household-level and regional studies likewise show that irrigation conditions influence farm productivity and the persistence of yield gaps in Southeast Asia (Moya et al., 2015; Laborte et al., 2015).

Conventional surface irrigation and manual watering remain common but can use large volumes of water and require continuous human involvement. Automated irrigation offers an alternative by using sensors and controllers to determine watering schedules and operate valves or pumps. Distributed sensing and remote control allow irrigation decisions to respond to field conditions rather than fixed routines, thereby improving timeliness and potentially reducing losses (Kim et al., 2008; Evans & Sadler, 2008; Ahmed, 2021; Abbas et al., 2024).

Energy availability is another constraint in remote agricultural locations. Grid dependence or fuel-powered pumping can increase operating costs and carbon emissions, while a single intermittent renewable source may not provide consistent power. A hybrid arrangement can improve resilience by combining complementary sources and battery storage. The present study addressed these concerns through a prototype that integrated solar photovoltaic generation with a stream-driven permanent-magnet DC generator and sensor-controlled drip irrigation.

The study aimed to design, construct, and evaluate the hybrid irrigation prototype; document the iterative generator and solar-power trials; derive essential mechanical and electrical operating parameters; compare automatic and conventional water consumption and irrigation duration; and identify the environmental and agricultural value of the proposed system. The research retained an experimental, prototype-oriented focus and did not test human perceptions or conduct inferential statistical analysis.

Literature Review

Water Scarcity and Irrigation Efficiency

Water scarcity intensifies the need for irrigation practices that produce more crop output per unit of water. Irrigation management under scarcity requires careful scheduling, appropriate delivery methods, and attention to local hydrologic limits (Pereira et al., 2002). Water-use efficiency can be improved by reducing losses during conveyance and application and by matching irrigation depth to actual crop demand (Howell, 2001). Groundwater-based agriculture also requires careful withdrawal because aquifer depletion may occur when pumping exceeds replenishment (Gleeson et al., 2012).

Climate adaptation research emphasizes that irrigation expansion should be accompanied by technologies and management practices that reduce environmental pressure and avoid maladaptation (Rosa, 2022). Drip delivery is relevant because it targets the root zone and can reduce evaporation and runoff. In this study, water efficiency was operationalized through the volume consumed per irrigation operation and the duration required to irrigate the same 50-m^2 test area.

Automated Irrigation and Sensor-Based Control

Automated irrigation uses sensing, communication, and control devices to reduce dependence on continuous human observation. Wireless sensor networks have been applied to remote irrigation monitoring and control, allowing soil and environmental data to guide system operation (Kim et al., 2008). More recent Internet of Things architectures support distributed monitoring and responsive decision-making across agricultural sites (Ahmed, 2021).

Automatic sensing and control devices can schedule irrigation according to crop and soil conditions rather than fixed time intervals (Abbas et al., 2024). Agricultural robotics and digital-farming systems further demonstrate how sensors, controllers, actuators, and data-processing components can be combined into integrated farm-management platforms (Shamshiri et al., 2018). The present prototype used a microcontroller, soil-moisture sensing, relays, pumps, and drip components to automate water delivery.

Renewable Energy for Off-Grid Agricultural Systems

Renewable-energy irrigation can reduce dependence on fossil fuels and grid electricity, especially in locations with limited infrastructure. Solar photovoltaic modules are widely suited to agricultural pumping because they can charge batteries and power low-voltage controllers and pumps during daylight. However, solar output varies with irradiance, which supports the use of energy storage and complementary generation sources.

Hybridization can improve power continuity by combining sources whose availability differs across time and weather conditions. In the source prototype, the solar module was paired with a stream-driven generator using a permanent-magnet DC motor, gears, a chain drive, rectification, voltage regulation, and battery charging. This arrangement reflected the broader digital-farming objective of using automation and clean energy to support reliable field operation (Shamshiri et al., 2018; Evans & Sadler, 2008).

Philippine Agricultural Context and Precision Water Management

Philippine agriculture includes rice, corn, fruit, and vegetable systems that differ in water requirements, field conditions, and access to infrastructure. Long-term household surveys document changing rice-farming practices and the continuing importance of irrigation to agricultural livelihoods (Moya et al., 2015). Regional yield-gap research also shows that water management remains one factor affecting production potential in Southeast Asia (Laborte et al., 2015).

Crop statistics reported by the Philippine Statistics Authority (2023) reinforce the diversity and economic importance of national crop production. Precision water management is therefore relevant not only for large irrigation systems but also for small plots where farmers may benefit from reduced labor, targeted delivery, and off-grid operation. The prototype was tested on a 50-m² string-bean plot to establish a practical, small-scale proof of concept before wider deployment.

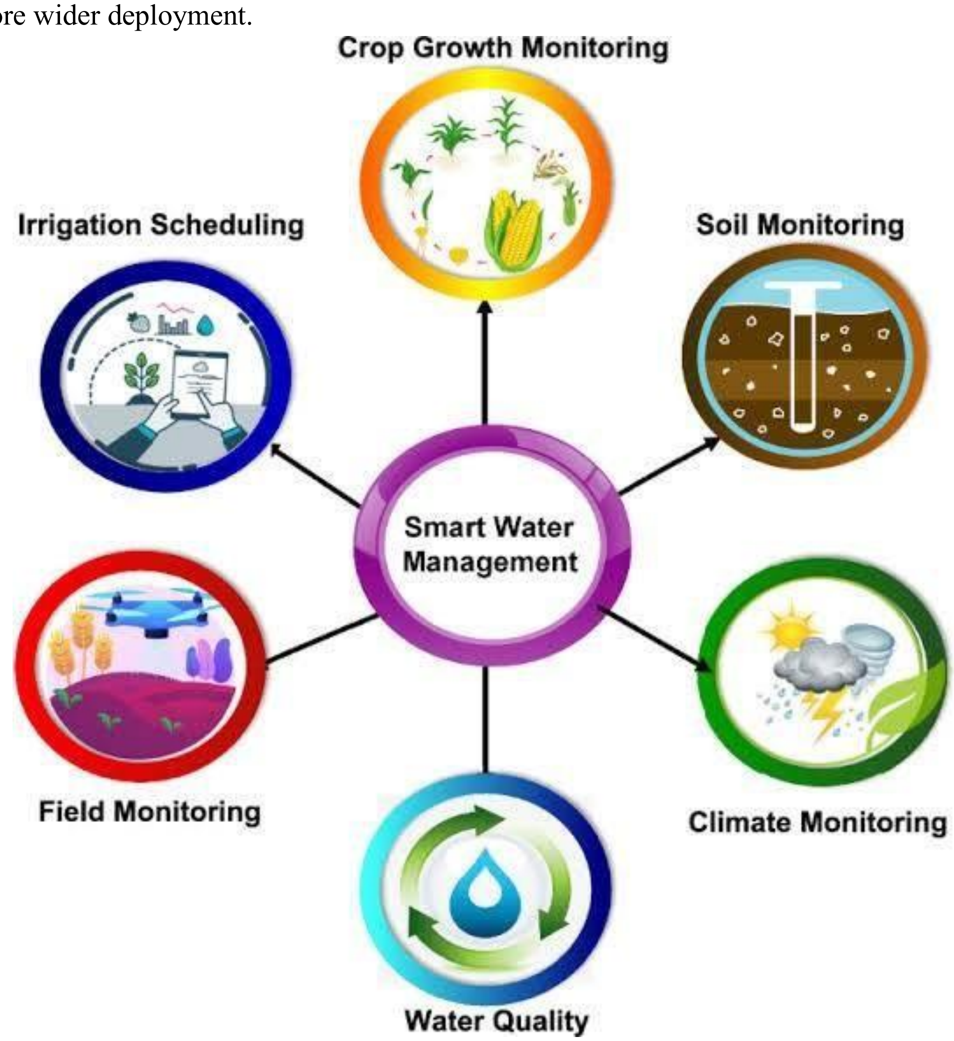

Figure 1. *Smart water management in agricultural and environmental systems (retained from the source manuscript).*

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METHODS

Research Design

The study used an experimental engineering design supported by physical modeling and simulation-based prototyping. Successive configurations were constructed, tested, evaluated, and refined until the system supplied sufficient voltage and operated the irrigation components. The design process included requirements analysis, component selection, project management, cost and resource considerations, physical construction, programming, operation, and performance testing.

Research Locale

Field testing was conducted in Sitio Alagao, Barangay Minuyan, Norzagaray, Bulacan. The site contained streams that could drive the renewable generator and provided a 50-m² plot planted with string beans. The final field data were gathered over three days while irrigation schedules were adjusted to maintain soil moisture under changing conditions.

Participants and Sampling Technique

The study did not involve human respondents or sampling. The experimental unit was the hybrid irrigation prototype installed on the 50-m² string-bean plot. Five sequential prototype trials served as the development and testing cases: three generator and gearing trials and two solar-power wiring trials.

Research Instrument and System Components

The prototype consisted of a solar photovoltaic module, stream-driven turbine and permanent-magnet DC motor used as a generator, chain-and-sprocket gearing, regulator-rectifier circuitry, LM317 voltage regulation, charge controller, 12-V battery, microcontroller, relays, soil-moisture and environmental sensors, pumps, garden hoses, spray nozzles, and drip-delivery components. The microcontroller interpreted sensor data and switched the pumps to deliver water when the established soil condition required irrigation.

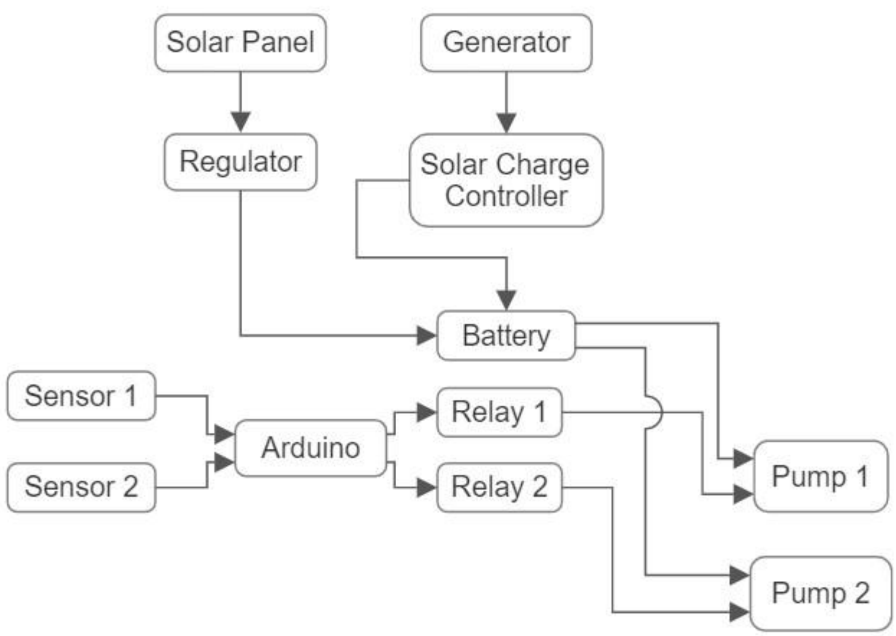

Figure 2. *Block diagram of the hybrid renewable energy-powered automatic drip irrigation system (retained from the source manuscript).*

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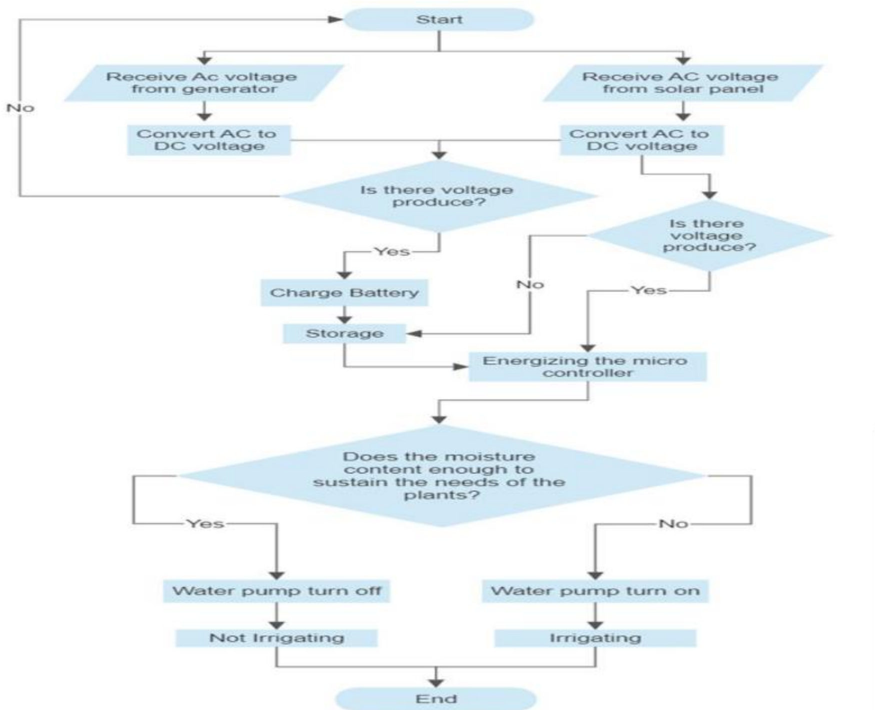

Figure 3. *Operating flow of the automatic irrigation system (retained from the source manuscript).*

Data Gathering Procedure

The researcher first assembled the generator, gearing, battery, irrigation hardware, and microcontroller. Trial 1 used an AC motor and the initial gear arrangement but produced insufficient voltage. Trial 2 replaced the generator with a DC motor, although the available revolutions per minute remained inadequate. Trial 3 added a larger gear and revised the transmission ratio, producing the voltage required by the prototype. Trial 4 tested the solar module and charge controller but failed because of incorrect microcontroller wiring. Trial 5 corrected the connection and achieved normal operation.

After component-level testing, the prototype was installed in the field. Generator voltage and turbine speed were measured using a voltmeter and timing observations. The volumes of water used by automatic and traditional irrigation were recorded for the same land area, while irrigation duration was compared across traditional, manual, and automatic methods. Soil-moisture performance was calculated from water volume, soil volume, and density values reported in the source manuscript.

Data Analysis

Analysis was descriptive and engineering-based. Trial outcomes were classified as working or not working, and the observed electrical output was summarized. Gear relationships, generator back electromotive force, regulator input limits, battery charging time, pump output, and turbine operating speed were derived from the equations presented in the source manuscript. Water-use reduction was calculated as the difference between conventional and automatic consumption divided by conventional consumption. No inferential statistical test was reported.

Ethical Consideration

The study involved engineering prototype development and field testing and did not collect data from human or animal participants. The source manuscript did not report a formal human-participant ethics review. Accordingly, this article limits the ethical statement to the non-human experimental context and does not infer procedures that were not documented.

RESULTS AND DISCUSSION

Prototype Development and Trial Outcomes

The iterative trials showed that the reliability of the prototype depended on both electrical source selection and mechanical transmission. The first configuration did not produce enough voltage because the AC motor lacked the required output under the available rotational conditions. Replacing it with a DC motor improved voltage but did not solve the low-RPM problem. The third configuration introduced a larger gear and revised reduction ratio, generating a consistent 25–30 V and providing enough energy to charge the battery and operate the prototype. The solar subsystem also required correction: the source could sustain the load in Trial 4, but a wiring error prevented microcontroller operation; the corrected connection in Trial 5 produced a working system.

Table 1. *Summary of Prototype Trials*

Trial	Primary configuration	Observed result	Outcome
1	AC motor; chain; 36×14×14-tooth sprockets; 12-V battery; irrigation and control components	Insufficient voltage and RPM	Not working
2	DC motor with initial chain-and-sprocket arrangement	Higher voltage than Trial 1, but still below prototype requirement	Not working
3	DC motor; revised 40×36×14×14-tooth gearing	Consistent 25–30 V; sufficient for battery charging and prototype operation	Working
4	PV module; charge controller; 12-V battery; irrigation and control components	Power source was sufficient, but incorrect wiring disabled the microcontroller	Not working
5	PV module with corrected electrical connection	Adequate supply and normal system operation	Working

The progression from failure to successful operation illustrates the value of iterative physical prototyping. Simulation can identify expected behavior, but mechanical losses, insufficient rotation, wiring errors, and component compatibility must be resolved under actual operating conditions. This finding is consistent with engineering approaches to agricultural automation that integrate sensing, actuation, and repeated field validation (Shamshiri et al., 2018).

Mechanical and Electrical Performance

The final gear arrangement produced a motor-shaft speed approximately 7.5 times the turbine speed. Using the measured no-load voltage and turbine speed, the source manuscript derived a generator relation of Ve(rms) = 23.684ft, where ft is the turbine frequency. The practical turbine operating range was estimated at 32.961–55.532 rpm, with operation near the limits discouraged because the approximation did not include all internal voltage losses.

The permanent-magnet DC motor was rated at 2.25 hp, 220 V, and 2200 W. The regulator-rectifier was configured to provide approximately 14 V for battery charging. The estimated charging time using the generator and average regulator current was 73.44 min at the specified battery condition, whereas the solar charger produced an average of 33.25 W and an estimated charging time of 20.34 min. The source therefore concluded that the solar charger supplied more charging power under the stated assumptions.

Table 2. *Selected Derived Operating Parameters*

Parameter	Source-derived value	Interpretation
Motor shaft to turbine speed relation	fr = 7.5ft	Gearing increased generator speed relative to turbine speed
Generator no-load voltage relation	Ve(rms) = 23.684ft	Voltage increased linearly with turbine frequency under the stated model
Allowable turbine speed	32.961–55.532 rpm	Approximate operating range for regulator input

Generator trial output	25–30 V	Sufficient in the successful gearing configuration
Solar charger average output	33.25 W	Based on 13.3 V average and 2.5 A average current
Estimated charging time—generator	73.44 min	Using average regulator current and stated battery assumptions
Estimated charging time—solar	20.34 min	Solar source was faster under the stated assumptions
Pump mechanical output	42 W (0.05632 hp)	Based on 70-W input and 60% assumed efficiency
Theoretical pump displacement	4.296 L/s at 1-m lift	Calculated idealized hydraulic displacement

These values describe prototype-level engineering performance rather than certified component ratings under all field conditions. Several results were calculated from idealized assumptions, including fixed efficiencies, average currents, and negligible armature voltage drop. They should therefore be treated as design estimates that require validation using calibrated instruments and repeated load testing.

Water Consumption and Irrigation Duration

The most direct performance result was the reduction in water consumed per operation. Automatic irrigation used 11.5 L on the 50-m² plot, whereas the traditional method used 48 L for the same area. This difference corresponds to a reduction of approximately 76.04%. The result supports the principle that controlled, targeted irrigation can reduce waste by limiting delivery to the period and location identified by the system (Howell, 2001; Evans & Sadler, 2008).

Table 3. *Comparison of Water Use and Irrigation Duration*

Performance indicator	Traditional irrigation	Manual watering	Automatic irrigation	Automatic improvement
Water per operation on 50-m² plot	48 L	Not separately reported	11.5 L	36.5 L less; 76.04% reduction
Irrigation duration	30 min	12 min	2 min	28 min faster than traditional; 10 min faster than manual

Automatic operation also reduced the irrigation period to approximately 2 min, compared with 12 min for manual watering and 30 min for the traditional method. This short operating time indicates reduced direct labor and faster delivery, although the source did not report repeated measures, variability, pressure distribution, emitter uniformity, or seasonal comparisons. The result is therefore a proof-of-concept observation rather than a population-level estimate.

Soil-Moisture Response and Agricultural Implications

Using the water volume, assumed soil volume, and density values reported in the source, the calculated soil-moisture level was 95.833%, which the manuscript interpreted as exceeding the minimum requirement of the test plants. The system was programmed to respond to soil condition and changing weather, thereby reducing the need for the farmer to judge moisture manually. Sensor-guided control is aligned with distributed and automatic irrigation research that uses field data to determine when water should be applied (Kim et al., 2008; Ahmed, 2021; Abbas et al., 2024).

The source discussed potential benefits for crop growth, but it did not present measured yield, biomass, plant height, pod count, crop quality, or a control-group comparison. The defensible conclusion is therefore that the system maintained the reported calculated moisture condition and reduced water and time during the short field test. Claims of increased crop yield require longer-term agronomic measurement.

Environmental and Practical Contribution

The prototype addressed water scarcity by delivering water directly and operating only when the sensor-control logic required irrigation. It also reduced reliance on fossil fuel or grid electricity through solar and stream-based generation. The hybrid configuration offered redundancy because solar availability and stream-driven generation could support battery charging under different conditions. These features are consistent with climate-adaptive irrigation and efficient water management (Rosa, 2022; Pereira et al., 2002).

For farmers, the prototype offers possible reductions in labor and water use, while for future researchers it provides a development sequence, component architecture, and set of preliminary performance values. Its present contribution is best understood as a small-scale engineering proof of concept. Wider application requires durability testing, waterproofing, cost analysis, calibrated flow measurement, emitter-uniformity assessment, crop-response monitoring, and evaluation across dry and wet seasons.

CONCLUSION

The study demonstrated the technical feasibility of a hybrid renewable energy-powered automatic drip irrigation prototype for a 50-m² string-bean plot. Iterative testing resolved inadequate generator output, gearing limitations, and a solar-system wiring error. The successful generator arrangement produced 25–30 V, while the corrected photovoltaic subsystem powered the controller and irrigation components. The final design combined a stream-driven permanent-magnet DC generator, solar photovoltaic charging, battery storage, sensing, microcontroller control, and pump-driven drip delivery.

Within the short field test, automatic irrigation used 11.5 L per operation compared with 48 L under traditional irrigation and reduced operating time to approximately 2 min. The system also maintained the reported calculated soil-moisture condition while reducing direct labor. These findings support the value of sensor-controlled and renewable-energy irrigation as a water-saving, off-grid agricultural technology. However, the evidence is limited to prototype trials and three days of field observation; long-term crop-yield, reliability, economic, and seasonal performance remain to be established.

Recommendation

- Future testing should cover complete cropping cycles, larger plots, different soil types, and multiple crops to determine seasonal reliability and agronomic effects.
- Researchers should measure crop yield, biomass, plant growth, irrigation uniformity, pump pressure, energy production, battery state of charge, and sensor accuracy using calibrated instruments.
- The solar-only, stream-generator-only, and hybrid operating modes should be compared under different weather and stream-flow conditions to quantify the contribution of each energy source.
- The control system should incorporate data logging, remote monitoring, adjustable soil-moisture thresholds, weather-based scheduling, and fail-safe protection against dry running, overcharging, and electrical faults.
- Protective enclosures, waterproof connections, mechanical guards, and field-maintenance procedures should be strengthened before deployment in active farms.
- A cost–benefit and farmer-usability assessment should be conducted to establish affordability, maintenance requirements, payback period, and suitability for community or smallholder adoption.

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