AGRISTEC: SMART AGRIVOLTAIC WASTEWATER RECYCLING SYSTEM FOR DECENTRALIZED LOW-CARBON ENERGY BUSINESS IN RURAL AREAS

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Abstract. *Indonesia's rural agriculture, particularly in Praya Barat, Lombok, faces critical challenges from unreliable irrigation and centralized diesel-based electricity. Despite high solar potential (5.24 kWh/m²/day), over 6,287 hectares of rice fields suffer from drought, while key water sources are contaminated by domestic and agricultural waste. Limited access to sustainable energy further undermines productivity and food security. The proposed solution, AGRISTEC, a decentralized agrivoltaic wastewater treatment system integrating bifacial PV, solar-powered electrocoagulation, and IoT automation. It consists of a 600W bifacial panel, 72V/100Ah $LiFePO_4$ battery, MPPT controller, 12V submersible pump, and electrolysis cell managed by an ESP32 microcontroller. Real-time monitoring via TDS, pH, and ORP sensors enables dynamic voltage and flow rate adjustments for irrigation-grade water. System performance was analyzed using HOMER Pro simulation for energy modeling and Excel-based calculations for techno-economic analysis. AGRISTEC generates 8.63 kWh/day and treats up to 960 L/day of wastewater, achieving 99.9% E. coli inactivation and 95% contaminant removal. Lifecycle emissions are reduced to 123.8 gCO_2/kWh over 24.5 times lower than diesel-based alternatives (3,336 gCO_2/kWh). Land-use efficiency is enhanced through vertical APV integration, covering only 12.93 m² per user (45% shading ratio), allowing dual land productivity for food and energy. Cost analysis reveals a 36.8% reduction in total ownership cost compared to diesel-based systems over 25 years. AGRISTEC offers a scalable, low-carbon solution for enhancing water-energy resilience in Indonesia's underserved agricultural communities.*

Keywords: *agrivoltaic system; decentralized renewable energy; electrocoagulation technology; low-carbon agriculture; wastewater recycling;*

INTRODUCTION

The agricultural sector in Indonesia especially in semi-rural regions such as Praya Barat, Central Lombok faces intensifying challenges in securing reliable access to water and energy. Agriculture in this area supports thousands of farmers, yet remains vulnerable to water scarcity, fluctuating rainfall, polluted reservoirs, and costly, unreliable electricity from centralized diesel-based power grids. Based on the 2023 report from BPS NTB, over 6,287 hectares of productive rice fields in Praya Barat are exposed to seasonal droughts, endangering food supply chains and household incomes. Simultaneously, critical water infrastructure such as the Watu Jai Dam has been degraded by domestic and agricultural pollution, further reducing irrigation quality.

This crisis occurs despite the region's high solar potential daily global horizontal irradiance (GHI) averages 5.24 kWh/m²/day, representing a vast, underutilized resource for decentralized renewable energy solutions (Aoun, 2024). However, most rural communities lack access to affordable solar systems or efficient water treatment. The dual burden of dirty water and expensive diesel fuel contributes to low productivity, weak climate resilience, and rising food insecurity.

This study addresses the gap between abundant solar resources and underdeveloped energy-water systems in rural farming. It proposes a low-carbon, decentralized, and scalable solution AGRISTEC a smart agrivoltaic wastewater recycling system that integrates bifacial photovoltaics, solar-powered electrocoagulation, and IoT-based monitoring. AGRISTEC offers simultaneous improvements in irrigation reliability, water quality, and energy access using an integrated technological and social approach tailored to the needs of smallholder farmers in rural Indonesia.

To this end, this study seeks to answer how a decentralized, low-carbon system can simultaneously address energy, water, and agricultural productivity gaps in underserved regions like Praya Barat. Building on five core research questions spanning system design, technology integration, IoT-based monitoring, and sustainable business models this research develops and evaluates AGRISTEC as a scalable agrivoltaic

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wastewater recycling prototype. The findings aim to contribute an interdisciplinary framework for the energy water agriculture nexus in rural Southeast Asia, while empowering smallholder farmers through cooperative ownership and accessible digital technology.

METHODOLOGY

This study combines literature review, field data, simulation, and prototyping to design AGRISTEC. Energy modeling used HOMER Pro, and economic analysis was done in Excel-based calculations. The overall research framework is illustrated in Figure 1, while the prototype design is visualized in Figure 2.

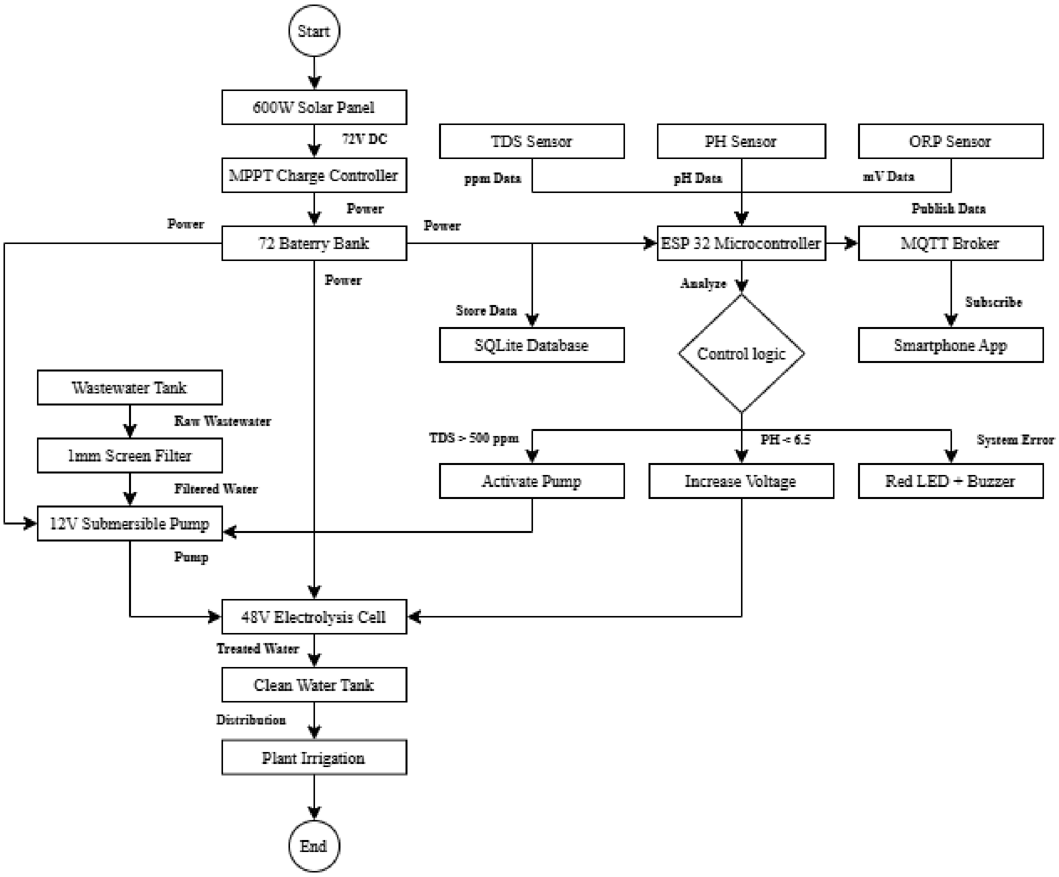

Figure 1. Research framework AGRISTEC.

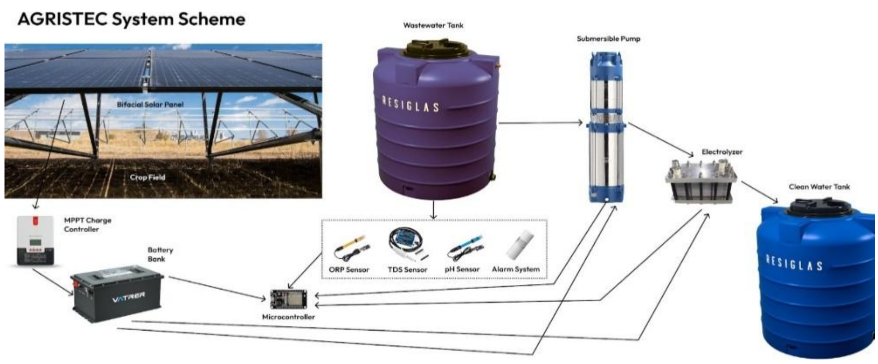

Figure 2. The prototype design AGRISTEC.

Agri-Photovoltaic Systems

Agri-photovoltaics (AgriPV) is a dual-use land model that integrates solar photovoltaic energy generation with agricultural land use. In regions with land-use constraints or high solar irradiance but water insecurity

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such as Praya Barat, Lombok AgriPV enables electricity production without displacing food crops. AGRISTEC applies a vertical bifacial PV structure that optimizes solar energy capture from both front and rear sides, improving generation by up to 30–50% (Cuevas et al., 1982; Widmer et al., 2024).
Furthermore, elevated PV structures help reduce evapotranspiration and soil temperature, indirectly enhancing water efficiency for crops. With a land-use footprint of just 12.93 m² per system and a 45% shading ratio, AGRISTEC maximizes productivity per hectare by co-locating energy and agriculture.

IoT-Based Automation and Tirta Surya Integration

The AGRISTEC system incorporates Tirta Surya, an ESP32-based Internet of Things (IoT) platform that enables dynamic control of wastewater treatment processes. It utilizes sensors for Total Dissolved Solids (TDS), pH, and Oxidation-Reduction Potential (ORP) to monitor water quality in real-time. These values are processed locally via microcontroller logic and uploaded to a cloud-based mobile app using MQTT protocol.

This allows farmers and technicians in remote areas to receive alerts, track performance, and optimize system operation remotely. The IoT layer ensures that electrocoagulation treatment is only activated under conditions that meet defined safety and efficiency thresholds, thus minimizing energy use and ensuring irrigation-grade water output. Such automation aligns with emerging smart agriculture and decentralized infrastructure trends (Strazzabosco et al., 2019).

Techno-Economic Analysis

To evaluate the economic feasibility of AGRISTEC deployment in rural communities, a detailed techno-economic analysis is conducted. This involves
calculating the Purchase Equipment Cost (PEC), Total Investment Cost (TIC), Net Present Value (NPV), and Payback Period (PBP). The following equations apply: The purchase equipment cost (PEC) of the system equipment is calculated as:

$$PEC = PEC_{ref}\frac{CEPCI_{2022}}{CEPCI_{ref}} \quad (1)$$

The total investment cost (TIC) is determined using the following equation:

$$TIC = (IC + B + C) \times W_{neff} \quad (2)$$

Where IC is the installed cost, B is the contingency, and C represents additional costs such as land acquisition and permitting. The NPV of the project is calculated as:

$$NPV = \sum_{t=1}^{N}\frac{C_{in} - C_{out}}{(1+r)^t} - TIC \quad (3)$$

The payback period (PBP) is another important financial metric for assessing the viability of the project. It is calculated as the ratio of the total installed cost (TIC) to the net cash inflows minus the cash outflows, as shown in the equation:

$$PBP = \frac{TIC}{C_{in} - C_{out}} \quad (4)$$

Where c_{in}represents the cash inflows and c_{out} represents the cash outflows, as defined in the following equations:

$$C_{in} = T \times p^c \times W_{net} + T \times p^c \times mco_2 \quad (5)$$

$$C_{out} = P_{bio} + 0.17C + (Tp^2 + P^8) \times mco_2 \quad (6)$$

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Environmental Life Cycle Assessment (LCA)

Environmental sustainability is assessed using a cradle-to-grave Life Cycle Assessment (LCA), which accounts for emissions from raw material extraction, system manufacturing, transportation, operation, and end-of-life treatment. The specific life-cycle CO_2 emission per unit energy produced is calculated as:

$$\varepsilon = \frac{\sum C_{tg} - \sum C_{tc}}{P_{tn}} \quad (7)$$

RESULTS AND DISCUSSION

The AGRISTEC system is designed as a decentralized, agrivoltaic-based wastewater recycling unit that utilizes solar power for water treatment in rural agriculture. The system integrates high-efficiency bifacial solar panels, lithium iron phosphate ($LiFePO_4$) batteries, a smart control unit, electrocoagulation based water purification technology, and real-time environmental sensing. This architecture ensures the system can operate off-grid, respond dynamically to environmental conditions, and provide irrigation-grade water for farming communities in areas such as Praya Barat, Lombok.

A key differentiator of AGRISTEC lies in its use of 600W bifacial monocrystalline solar panels, which capture both direct (incident) and reflected (albedo) solar radiation. Unlike conventional monofacial panels, bifacial modules feature a transparent backsheet and dual-sided open metallization grid, allowing illumination from both front and rear surfaces. This design not only enables up to 50% more power generation under agrivoltaic settings but also operates at lower cell temperatures due to reduced infrared absorption boosting both performance and longevity. The bifacial module architecture, featuring texturized wafers, anti-reflective coatings, and screen-printed contacts, is shown in Figure 3, which illustrates the standard n-type and p-type crystalline silicon bifacial cell cross-sections.

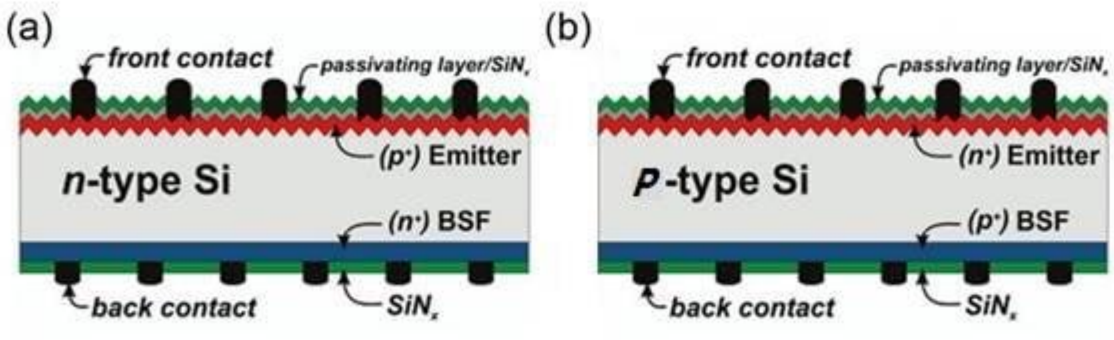

Figure 3. Cross-section view of standard n-type and p-type bifacial crystalline silicon solar cells.

The energy produced is regulated and stored using a 72V/100Ah $LiFePO_4$ battery through a 72V/60A MPPT charge controller with 98% conversion efficiency. These components comply with IEC, UN38.3, and CE safety standards, ensuring durable and secure operation in field environments.

Wastewater treatment begins with pre-filtration using a 1mm screen filter made of 316L stainless steel, capable of removing 85% of turbidity. The filtered water is then pumped using a 12V submersible magnetic pump into a 20-liter electrolysis chamber. Inside this chamber, titanium electrodes coated with PbO_2 (compliant with NSF/ANSI 61) perform electrocoagulation, generating aluminum ions and hydroxyl radicals for coagulation and disinfection. Optimal treatment occurs when conductivity exceeds 800 µS/cm, with contaminant removal efficiencies reaching 95%, and 99.9% E. coli inactivation under field-tested thresholds.

System control is maintained by an ESP32 microcontroller featuring a dual-core 240 MHz processor, WiFi/Bluetooth connectivity, and internal flash memory. A triparametric sensor array (TDS, pH, ORP), compliant with ISO 15839, monitors real-time water quality and dynamically adjusts operational parameters. For example, if TDS rises above 500 ppm, the system increases the pump flow from 8 to 12 L/min. When pH

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drops below 6.5, the system raises the voltage to 50V, enhancing electrochemical activity. The agrivoltaic installation itself also contributes to environmental resilience by lowering soil temperature by 1-4°C, improving water-use efficiency by up to 47%, and supporting crop yield gains benefits validated in agrivoltaic field studies summarized in Figure 4.

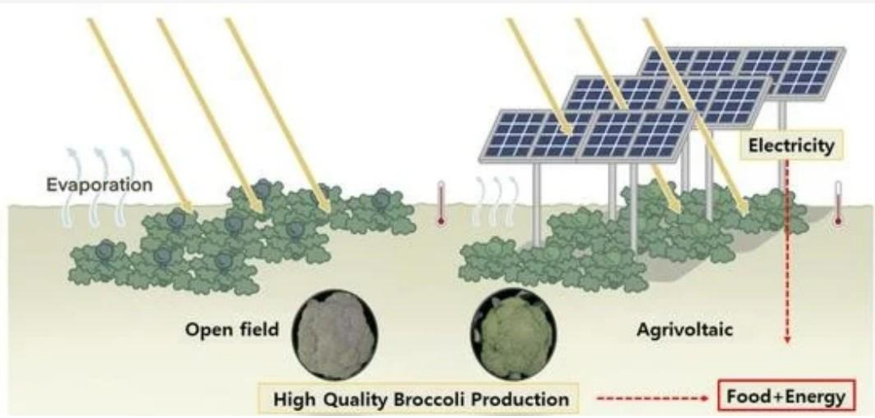

Figure 4. Agrivoltaic Scheme.

Treated water is stored in dual 500L HDPE tanks, certified by FDA and NSF/ANSI for agricultural reuse. Operational safety is supported by an 85 dB audible buzzer and LED alarm system (EN 54-3 certified), which activate during sensor violations or device malfunctions. A comprehensive overview of the system's components, materials, technical specifications, and compliance standards is presented in Table 1.

Table 1. AGRISTEC System Components Summary.

Category	Component	Material/Model	Key Specifications	Quantity per 1m³/day Unit	Compliance Standards
Energy Supply	Bifacial 600W Solar Panel	Monocrystall ine Si	72V OC, 8.3A SC, 23% efficiency	1	IEC 61215, IEC 61730
Energy Supply	72V $LiFePO_4$ Battery	72V/100Ah	5,000+ cycles, 95% DoD	1	UN38.3, IEC 62619
Energy Supply	MPPT Charge Controller	72V input, 60A	98% efficiency, IP65	1	CE, RoHS
Water Treatment	Ti/PbO_2 Electrodes	Titanium substrate, PbO_2 coating	10x20cm, 5mm thick, 2A/cm² density	2 plates	NSF/ANSI 61
Water Treatment	Electrolysis Chamber	UV-stabilize d polypropylene	20L capacity, 30min HRT	1	FDA 21 CFR
Water Treatment	Submersib le Pump	12V DC, magnetic drive	10 L/min, 5m head, IP68	1	IP68, CE
Filtration	Screen Filter	316L stainless steel mesh	1mm pore size, 85% turbidity removal	1	ISO 9001
Control System	ESP32 Microcontr oller	WiFi/Blueto oth 5.0	Dual-core 240MHz, 4MB flash	1	FCC, CE
Control	TDS/pH/O	Food-grade	±2% TDS,	1 each	IP68, ISO

Tirta Surya Mobile Application

To enhance operational reliability and provide end-users particularly rural farmers with real-time control and insights, the AGRISTEC system is integrated with the Tirta Surya mobile application.

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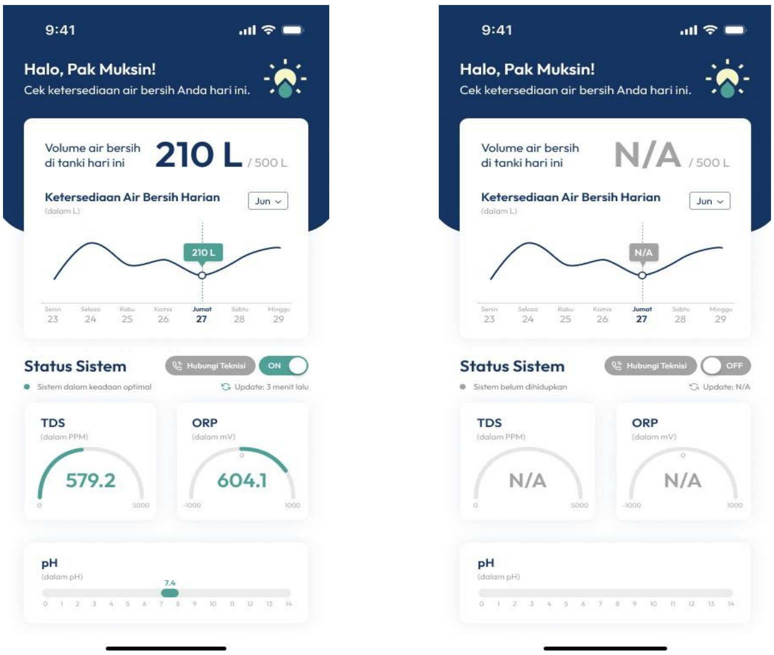
Splash Screen and Home Dashboard

Figure 5. Splash Screen Tirta Surya App.

Upon launching the app, users are greeted with a minimalist splash screen showcasing the Tirta Surya logo a combination of a water droplet and a sun symbolizing the integration of water and solar energy. The main dashboard displays the daily clean water volume stored in the tank, accompanied by a historical line graph showing daily water availability trends over the past seven days

System Status and Sensor Readings

Below the dashboard is a System Status Panel, which displays whether the system is active (ON), inactive (OFF), or encountering errors (FAULT). It includes real-time visual dials for three critical water quality parameters:



(i) (ii)

Figure 6. System ON (i) and System OFF (ii) Tirta Surya App

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- TDS (Total Dissolved Solids): Measured in ppm, indicating levels of dissolved contaminants.
- ORP (Oxidation-Reduction Potential): Measured in mV, assessing the electrochemical disinfection effectiveness.
- pH: Indicating the water's acid-base balance.

Fault Detection and Emergency Alerts

Figure 7. Fault Detection Tirta Surya App.

If any sensor detects abnormal values such as TDS above 500 ppm or ORP below 600 mV the system will instantly trigger real-time alerts through both visual pop-up notifications in the app and audible/visual alarms on the hardware (85 dB buzzer and red LED). For example, if the ORP sensor fails to respond, the app notifies: "Sistem ORP tidak merespon, Muat ulang sistem atau hubungi teknisi."

Historical Water Analytics

Users can review daily clean water production trends over time to evaluate performance consistency. The app stores and displays historical data points in interactive graphs, helping farmers better understand usage patterns, predict tank refill schedules, and optimize irrigation plans based on treated water availability.

Direct Technician Access

The "Contact Technician" button provides seamless reporting when issues arise. Upon activation, the app sends a full diagnostic log containing device ID, location, and last system state directly to the Schneider Maintenance Team, who are committed to resolving the issue within 1-3 working days. This significantly reduces downtime and enhances trust among rural users with limited access to technical support.

Automated Updates and Connectivity

Tirta Surya syncs with the AGRISTEC hardware every 5 minutes using a 4G/WiFi MQTT gateway, ensuring that the displayed sensor data is always up to date. If the connection is temporarily lost, the app stores the latest data locally and automatically synchronizes when connectivity is restored.

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Economic Feasibility and Business Segmentation

To ensure long-term sustainability and replicability, the AGRISTEC system is supported by a cooperative government hybrid business model that lowers capital barriers for rural adoption while enabling local economic empowerment. This model merges financial inputs from government grants (e.g., Dana Desa, EBTKE programs), corporate CSR allocations, and crowdfunding platforms, facilitating initial deployment in underserved regions. Once installed, the system is managed by village enterprises (BUMDes) or agricultural cooperatives, which oversee operations, user interface monitoring, and revenue collection, enabling a circular economic loop at the grassroots level.

Capital Expenditure and Unit Economics

The initial capital cost for a basic AGRISTEC unit (designed for 1 m³/day capacity) is Rp60,030,000, which includes a 600W bifacial solar panel, 72V/100Ah $LiFePO_4$ battery, 20L electrocoagulation unit, and 500L storage tank. Based on a 25-year system life, and very low operational expenditure (limited to monthly cleaning and periodic battery replacement every 8-10 years), the levelized cost of the AGRISTEC solution is substantially more competitive than diesel-based systems.

Cost Comparison with Diesel-Based Energy

To deliver 7.7 kWh/day of energy for small-scale irrigation and water treatment, diesel-based systems incur Rp94,994,900 over 25 years an estimated 58% higher than the AGRISTEC solution. Moreover, diesel setups provide no water treatment benefit and are tied to volatile fuel prices and grid unreliability. In contrast, AGRISTEC offers:

– Dual functionality (energy + water treatment)
– Free solar energy input
– Lower maintenance risks due to fewer moving parts
– Environmental and health benefits by eliminating exposure to polluted water

This results in a net savings of Rp34,964,900 over the system's lifespan, not including external benefits like crop yield improvement or labor time saved.

Market Segmentation and Scalability

AGRISTEC is designed with modular scalability to address varied agricultural demands across community sizes:

Table 2. Market Segmentation AGRISTEC

Key parameters	Community type		
	Small-scale communities	**Medium-scale communities**	**Large-scale communities**
Demographics			
Land Size (ha)	1-5	5-25	> 25
Community characteristics	Individual and small farmer	Group of farmers	Villages or agricultural regions
System adaptation			
Solar panel capacity (W)	600	1500 - 3000	3000 - 5000
Battery storage capacity (V)	72	72	72 - 120
Water storage (L)	500	500 - 3000	> 3000
Electrolysis cell capacity	20 L, 1 unit	20 - 100 L, 1-4 units	100 - 200 L, > 4 units
Pricing			
Pricing (M)	Rp60,030,000	Rp60,030,000 - Rp300,150,000	> Rp300,150,000

These pricing tiers allow rural cooperatives to adapt the system according to their land size and water demand. The wide price range for medium-scale communities reflects modular scalability, where system capacity, infrastructure complexity, and cooperative size drive cost variation. For instance, a 10-hectare paddy irrigation cluster can install 3-5 modular AGRISTEC units, ensuring 3-5 m³ of clean water per day, while benefiting from bulk procurement pricing and cooperative maintenance.

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Revenue and Operational Model

The revenue and operational model of AGRISTEC relies on initial funding from public-private donors, while its long-term sustainability is ensured through community-based financing mechanisms. These include monthly irrigation service fees ranging from Rp5,000 to Rp15,000 per user, strategic partnerships with agricultural product off-takers who offer incentives for certified clean-water usage, and government subsidies allocated for routine maintenance and sensor replacement. With minimal recurring costs of approximately Rp200,000 per month for upkeep and calibration, the system is highly feasible for deployment in remote rural areas with limited financial capacity but strong dependence on agriculture.

Environmental Impact

Carbon Emission Reduction through Clean Energy

AGRISTEC utilizes solar panels that emit only 123.8 g CO_2-eq per kWh over their lifecycle, mainly during raw material extraction (23%) and manufacturing (30%) stages. In contrast, diesel-based generators emit 3,336 g CO_2-eq per kWh, making diesel energy over 27 times more carbon-intensive. To meet the energy requirement for producing 1 ton of rice (2,812.2 kWh/year), AGRISTEC emits only 348.15 kg CO_2-eq, while diesel emits 9,382.91 kg CO_2-eq shown in Table 3

Table 3. Carbon Emission AGRISTEC.

Annualy Agrivoltaics Carbon Emissions			
Raw material sourcing	80.07443324	kg CO2 eq	Carbon emission per kWh * total energy needed
Manufacturing	104.4449129		
Transportation	52.22245646		
Installation	17.40748549		
Operation/maintenane	55.70395356		
End life/ disposal	38.29646807		
TOTAL	348.1497098		

Waste Generation and Material Circularity

The total material waste produced by solar-based AGRISTEC is 28.56 kg/year, most of which is recyclable. In contrast, diesel-based systems generate 1,879.3 kg/year of waste, including non-recyclable emissions and fuel residues. This stark contrast further highlights AGRISTEC's advantage in promoting a circular economy.

Efficient Land Use with Agrivoltaics

Land scarcity in agricultural regions like Praya Barat demands efficient space utilization. AGRISTEC addresses this by installing bifacial solar panels above crop rows (agrivoltaic model) with 45% land coverage, generating 7.7 kWh/day using only 16.14 m² or 6.467 m² of cultivation land. In comparison, diesel-based systems require 21.4 m² of separate land, making AGRISTEC over 30% more land-efficient. Moreover, the agrivoltaic design improves local conditions: it reduces evaporation rates, lowers soil temperature by 1-4°C, and enhances water-use efficiency by 20-47%, contributing to a 6.85% increase in crop yields.

Energy-Efficient Wastewater Treatment

The AGRISTEC system consumes only 2.7 kWh/day to treat between 500–960 L/day of agricultural/domestic wastewater using Ti/PbO_2 electrolysis electrodes. These electrodes enable powerful oxidation of pollutants, microplastics, and pathogens, producing irrigation-grade water on-site. The system requires only 2 units (12.93 m² total) to meet the water demand for a typical 250 m² farmland, which represents 73.3% of farmers in Praya Barat.

CONCLUSION

This study has successfully developed AGRISTEC:

1. AGRISTEC integrates a 600W bifacial solar panel, 72V/100Ah $LiFePO_4$ battery, and a 20L electrocoagulation chamber to recycle up to 960 L/day of wastewater. This system supports decentralized, low-carbon energy and water access for agriculture in areas like Praya Barat, Lombok.

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2. AGRISTEC emits only 123.8 gCO_2/kWh, over 24.5 times lower than diesel (3,336 gCO_2/kWh). For 2,812.2 kWh/year of rice cultivation energy demand, AGRISTEC emits 348.15 $kgCO_2$, compared to 9,382.91 $kgCO_2$ from diesel, while also reducing solid waste generation from 1,879.3 kg to 28.56 kg/year.
3. The bifacial PV panel requires just 16.14 m^2 of land (with 45% shading ratio) to supply 7.7 kWh/day, compared to 21.4 m^2 for diesel-based systems. Additionally, agrivoltaics improves water use efficiency by 20-47%, reduces soil temperature by 1-4 °C, and enhances crop yield by up to 6.85%.
4. Through ESP32 and TDS/pH/ORP sensors, AGRISTEC performs dynamic control e.g., increasing pump flow from 8 to 12 L/min when TDS > 500 ppm, or raising voltage to 50V if pH < 6.5. System alerts are triggered within 15 minutes via buzzer (85 dB) and LED, improving safety and usability.
5. AGRISTEC's capital cost for small scale farmers is Rp60,030,000, with a lifespan of 25 years and only Rp200,000/month in operational costs. This is more economical than diesel-based systems, which cost up to Rp94,994,900 for equivalent energy and offer no wastewater recycling.

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