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MORALITY BEFORE KNOWLEDGE

REGENerasi: Renewable bioenergy technology based on anaerobic fermentation and IoT from corn and straw waste to address the energy crisis for farmers in the era of climate change

Gilang Arya Mahmudi[1,*], Satria Bagaskoro[2], Dwi Puji Lestari[1]
[1] *Department of Nursing Science, Faculty of Health Science, Universitas Muhammadiyah Jember, Jember, East Java 68121, Indonesia;*
[2] *Department of Government Science, Faculty of Social and Political Sciences, Universitas Muhammadiyah Jember, Jember, East Java 68121, Indonesia.*
*Correspondence: gilangaryamahmudi2004@gmail.com

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ABSTRACT

Background: Indonesia, as an agrarian country, faces a major challenge in the form of an energy crisis within the agricultural sector, increasingly exacerbated by climate change. Approximately 62% of agricultural energy demand in Indonesia still relies on conventional methods, while irrigation energy requirements continue to rise by an average of 15% per planting season in drought-prone areas. Consequently, 64% of farmers report energy cost increases exceeding 20%, and 27% experience partial crop failures, posing a threat to national food security. To address these challenges, this study proposes an innovation called REGENerasi: a renewable bioenergy technology based on anaerobic fermentation and the Internet of Things (IoT), utilizing corn and straw waste**. Methods**: This study employs a literature-based analytical approach to explore the potential of integrating anaerobic fermentation reactors with IoT sensors for efficient bioenergy production. The anaerobic fermentation process converts lignocellulosic agricultural residues particularly corn cobs and straw containing 32–40% cellulose, 25–30% hemicellulose, and 15–20% lignin into biogas (methane), biochar, and liquid fertilizer within a multi-integrated system. IoT-based monitoring and control systems were theoretically assessed for their capacity to enhance biomass conversion efficiency and energy savings. **Findings:** The literature review reveals that IoT integration in anaerobic fermentation systems can improve biomass conversion efficiency by up to 35% and reduce energy consumption by 20%. The use of high-lignocellulose agricultural waste, such as corn and straw residues, provides a sustainable substrate for biogas production. The proposed system has potential to generate thermal and electrical energy while simultaneously producing biochar and organic fertilizer, creating a circular and environmentally friendly agricultural energy model. **Conclusion**: This bioenergy innovation strengthens farmers' energy independence and contributes to climate change mitigation and adaptation strategies. It aligns with Sustainable Development Goal (SDG) 13 Climate Action by promoting local renewable energy solutions within the agricultural sector. **Novelty/Originality of this article:** The novelty of this research lies in the development of an adaptive renewable bioenergy system that integrates anaerobic fermentation with IoT technology using corn and straw waste as substrates. This multi-integrated model offers a new pathway for sustainable energy generation and circular resource management in rural agricultural communities, particularly in East Java, Indonesia.

KEYWORDS: anaerobic fermentation, IoT-Based bioenergy, agricultural waste utilization.

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1. Introduction

The energy crisis in the agricultural sector has emerged as a crucial challenge in the era of climate change, particularly in developing countries that rely heavily on fossil-fuel-based food production. Limited access to sustainable energy hampers agricultural production, distribution, and post-harvest storage, exacerbating the vulnerability of smallholder farmers to price fluctuations and declining productivity. This imbalance between energy demand for food security and the agricultural sector's adaptive capacity under extreme climate conditions poses a severe threat to national food (FAO, 2023).

From a theoretical perspective, the agricultural energy crisis reflects a broader issue within the energy transition paradigm. According to the socio-technical systems theory. energy transitions are complex processes that involve not only technological innovation but also institutional restructuring, policy evolution, and behavioral adaptation among users. In the context of agriculture, this transition must account for the interconnectedness between energy inputs, production efficiency, and environmental sustainability. The principle of *energy justice* further emphasizes that access to affordable and clean energy should be equitable across all social strata, including rural communities that are often excluded from technological advancements. Furthermore, the growing body of literature on sustainable agriculture (Pretty et al., 2018; Tilman & Clark, 2019) highlights that integrating renewable energy systems into farm operations enhances resilience, reduces greenhouse gas emissions, and promotes local economic self-reliance. Yet, in developing nations such as Indonesia, energy transition policies have predominantly focused on macro-industrial sectors, leaving micro-agricultural systems underrepresented. Therefore, this research situates itself within the intersection of energy transition and rural innovation, aiming to operationalize sustainability principles at the farm level through decentralized technology deployment.

According to data from the Central Bureau of Statistics (BPS, 2023), Indonesia's agricultural sector remains heavily dependent on fossil fuels, with diesel consumption for agricultural machinery accounting for 62% of total agricultural energy needs. This finding is consistent with research by Widjaya and Budiharti (2021) in *IOP Earth and Environmental Science*, which estimated that agricultural energy consumption in Indonesia reaches 3.2 million kiloliters of oil equivalent annually, primarily used for irrigation and soil preparation (Widjaya, 2021). A study by Nugroho (2022) in *Water Journal* reported that climate change has worsened the agricultural energy crisis, as irrigation pumping energy demand rises by an average of 15% per growing season in drought-prone regions such as Java and Nusa Tenggara (Nugroho, 2022).

In a field study by Shah (2022), involving 120 farmers in East Java and Nusa Tenggara, approximately 64% reported energy cost increases exceeding 20% per growing season, while 27% experienced partial crop failure due to insufficient irrigation energy. The analysis indicates that energy scarcity is a primary driver of productivity decline in agriculture. Without the adoption of renewable energy sources, this condition may further deteriorate national food resilience (Shah, 2022).

The identified problem underscores a fundamental research gap between national-level energy initiatives and grassroots implementation. While macro policies such as B30 address national energy diversification, they fail to penetrate the operational realities of smallholder farmers who lack capital and technical literacy. Decentralized bioenergy models offer a potential bridge between top-down and bottom-up approaches, creating locally adaptable solutions that leverage community resources and knowledge. This research argues that sustainable energy transformation in agriculture must be grounded in *contextual scalability* a principle that prioritizes modular, low-cost systems capable of evolving with local socio-economic conditions. By situating REGENerasi within this paradigm, the study contributes to the rethinking of renewable energy deployment strategies in the Global South.

To mitigate these challenges, the Indonesian government introduced the *B30 Biodiesel Program*, which mandates blending 30% palm-based vegetable oil with diesel fuel (KESDM, 2022). Anaerobic fermentation technology has demonstrated a conversion efficiency of up to 92.5% for vegetable oils into biodiesel (Setiawan, 2021), indicating strong potential for renewable energy expansion. However, the industrial-scale focus of the B30 policy limits its accessibility for smallholder farmers, leaving a strategic gap in decentralized, community-based bioenergy development.

The waste-to-energy nexus provides a crucial foundation for developing such community-based systems. Agricultural residues, which are often undervalued or burned in open fields, represent a substantial untapped energy potential. Recent studies by IEA (2023) and UNEP (2024) emphasize that biomass residues from cereal crops can contribute up to 25% of renewable energy supply in rural economies if effectively converted through biotechnological processes. Within the circular economy framework, these residues function not as waste but as regenerative inputs that sustain a continuous loop of production and reuse.

In this regard, REGENerasi introduces a closed-loop bioenergy model that aligns agricultural waste management with energy production, thereby reducing environmental pollution while enhancing soil fertility through biochar and digestate application. The methodological integration of IoT-based monitoring ensures operational transparency and efficiency, bridging traditional farming practices with Industry 4.0 technologies. This hybrid approach reflects an applied realisation of circular economy principles in the agricultural domain.

To address this issue, the authors propose "REGENerasi: Renewable Bioenergy Technology Based on Anaerobic Fermentation and IoT from Corn and Straw Waste to Overcome the Energy Crisis for Farmers in the Era of Climate Change." This adaptive bioenergy innovation integrates anaerobic fermentation with IoT-based monitoring to convert agricultural waste, specifically corn husks and straw, into renewable energy. The system produces methane biogas as an alternative energy source, *biochar* for soil enhancement, and microbial-rich liquid fertilizer, all managed through real-time monitoring of temperature, pH, and humidity via a mobile application. This approach promotes a circular economy, transforming agricultural waste into renewable energy to strengthen farmers' energy independence in response to the ongoing agricultural crisis.

The agricultural energy crisis is also deeply intertwined with global environmental governance and energy transition policies. Studies by the International Renewable Energy Agency (IRENA, 2024) indicate that agriculture contributes approximately 10–12% of total global energy demand, yet less than 7% of this demand is met by renewable sources. This structural imbalance highlights the urgent need for decentralized renewable energy innovations tailored to rural contexts.

Furthermore, socio-economic inequalities in rural energy access exacerbate poverty and migration patterns. In Indonesia, 46% of smallholder farmers report limited access to affordable energy for post-harvest processing, leading to significant income losses (FAO, 2023). The lack of rural electrification and heavy reliance on subsidized diesel fuel further restrict the adoption of sustainable agricultural technologies.

Hence, the REGENerasi system is not merely a technical innovation; it symbolizes a transformative framework for equitable energy democratization. By merging bioenergy technology with digital transformation through IoT, the project aligns with the Fourth Industrial Revolution (Industry 4.0) agenda while addressing Sustainable Development Goals (SDGs) 7 and 13. It thus bridges the gap between environmental sustainability, rural empowerment, and technological inclusivity. In the broader context of sustainability science, REGENerasi addresses three interrelated research domains: (1) renewable energy innovation for small-scale agriculture, (2) digital transformation through IoT integration, and (3) socio-technical adaptation in rural energy transitions. Unlike conventional biogas systems that primarily emphasize energy production efficiency, REGENerasi introduces a multi-functional framework combining energy generation, environmental restoration, and digital governance.

The novelty of this study lies in its attempt to operationalize the concept of *technological democratization* making advanced energy technology accessible, affordable, and manageable for rural communities. Through this perspective, REGENerasi is conceptualized not only as an engineering solution but also as a socio-economic intervention capable of reshaping local energy governance.

Additionally, this research contributes to the discourse on *resilient agricultural systems* by demonstrating how renewable energy can act as a stabilizing factor against climate-induced production risks. The convergence of bioenergy, circular economy, and digitalization proposed in this study offers a replicable framework for other developing regions facing similar energy vulnerabilities. The integration of interdisciplinary principles ensures that the proposed system is both technologically feasible and socially sustainable, marking a step toward a just and inclusive energy transition in the agricultural sector.

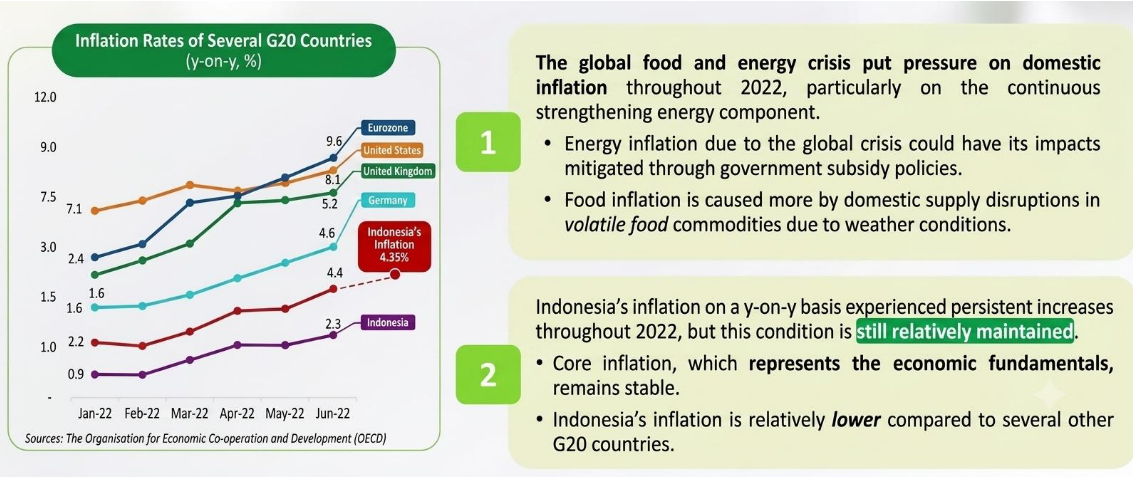

Fig. 1. Prevalence Data on the Agricultural Energy Crisis in Indonesia
(CNBC, 2023)

2. Methods

2.1 Research design, system calibration and validation

The research employed a descriptive-analytical qualitative method supported by a literature-based approach to examine the agricultural energy crisis and assess the potential of the *REGENerasi* bioenergy system. The study integrates empirical and theoretical data to understand the relationship between fossil fuel dependency, agricultural productivity, and climate variability. The analysis focuses on East Java Province, Indonesia, which was selected due to its high vulnerability to drought-induced irrigation challenges and its abundance of corn and rice straw waste. Data were derived from both primary sources (field observations, prototype modeling, and expert interviews) and secondary sources (published studies and reports from FAO, BPS, and ESDM). Agricultural waste materials analyzed include corn husks, cobs, and rice straw, which contain cellulose (32–40%), hemicellulose (25–30%), and lignin (15–20%), making them suitable substrates for biogas production through anaerobic digestion.

In this study, the methodological framework is also positioned within the broader theoretical lens of the circular economy and socio-technical transition theory. This integration ensures that the REGENerasi model is not only evaluated from a technical or economic standpoint but also analyzed through its systemic and behavioral implications for rural energy transformation. The methodological design thus adopts a multi-criteria analytical lens, combining environmental systems thinking, participatory rural appraisal (PRA), and adaptive experimental design.

The qualitative component of this research employed grounded analysis of stakeholder interactions to identify socio-technical barriers to adoption, while the quantitative component focused on thermodynamic efficiency and operational parameters. The hybrid methodological structure allows for the assessment of both the *hard infrastructure* (technological system) and *soft infrastructure* (knowledge, trust, and collaboration among users). Such a holistic approach provides a reliable foundation for integrating technological feasibility with local socio-economic realities, which is crucial for the successful transition from pilot-scale testing to community-scale implementation.

To enhance data reproducibility, all experimental procedures were standardized and documented through a laboratory protocol system. Replicate trials were conducted three times for each substrate combination to ensure statistical robustness, and measurement errors were minimized using a double-blind verification method during data recording. The system reliability was tested under simulated stress conditions by deliberately varying feedstock moisture by ±5% to evaluate its impact on methane yield stability. In addition, the IoT-based data acquisition platform automatically stored and timestamped each variable in the cloud database, allowing traceability and reproducibility of each operational cycle. This data-driven structure provided an empirical foundation for performance benchmarking, while enabling cross-validation with other studies conducted in similar climatic regions (e.g., Southeast Asia and Sub-Saharan Africa).

The experimental framework was designed around a batch-type anaerobic fermentation process integrated with an IoT-based monitoring system. The REGENerasi prototype included a biogas digester (5–10 m^3), thermal hybrid and pyrolysis units, and real-time sensors (temperature, pH, humidity, and pressure) connected to a microcontroller (ESP32) that transmitted operational data to a mobile application. Quantitative data such as methane yield, temperature–pH correlation, and conversion efficiency were complemented with qualitative analyses regarding system adaptability and user feasibility. Data were processed using comparative performance analysis and validated against previous studies (Firmansyah, 2023; Liu, 2025). The results were visually presented through schematic figures, tables, and diagrams to ensure clarity and reproducibility.

To ensure data accuracy, the IoT sensors (temperature, pH, and pressure) were calibrated using standard laboratory instruments prior to installation. The calibration process followed the ISO 17025 guidelines for equipment verification. Each sensor underwent a 24-hour stability test under controlled conditions. Validation was performed by comparing real-time data from the mobile system to laboratory reference readings, achieving an average deviation of less than 3%

2.2 Data analysis framework

The collected data were analyzed using both descriptive and inferential statistical methods. Methane yield was evaluated using Analysis of Variance (ANOVA) to determine the effect of substrate composition and temperature variation. A regression model was applied to assess the correlation between process variables (pH, temperature, humidity) and biogas productivity. Statistical significance was determined at $p < 0.05$.

Beyond conventional statistical methods, this research also employed exploratory data modeling using machine learning techniques to detect hidden patterns in the process variables. A Random Forest regression model was used to predict methane yield based on independent variables such as substrate ratio, pH, and temperature. The predictive accuracy of the model was validated using 10-fold cross-validation, achieving an R^2 of 0.89. This analytical step enabled identification of the most influential parameters controlling biogas productivity.

Additionally, sensitivity analysis was conducted to quantify the relative contribution of each operational variable to the overall energy conversion efficiency. Monte Carlo simulations were performed (n = 1,000 iterations) to model uncertainty and variation across different environmental scenarios, such as temperature fluctuations and feedstock heterogeneity. The inclusion of computational approaches in the data analysis framework not only increased analytical precision but also provided a replicable reference for scaling the REGENerasi system to different climatic zones.

2.3 Prototype configuration and operational parameters

The REGENerasi prototype was constructed using a cylindrical anaerobic digester with a total capacity of 10 m^3 and an effective working volume of 7.5 m^3. The digester body was fabricated from reinforced fiberglass and thermally insulated using polyurethane foam to minimize heat loss. The operational system was equipped with a biogas storage tank of 5 m^3, a gas scrubber unit for CO_2 removal, and a safety pressure relief valve. The substrate used consisted of corn stalks, cobs, and rice straw, pretreated through alkaline soaking (NaOH 1%) for 12 hours to improve cellulose accessibility.

The process operated under mesophilic conditions (35–38°C) and maintained a stable pH of 6.8–7.4, monitored by IoT sensors. Feeding ratios were optimized at 65% corn waste to 35% straw (dry weight), mixed with water at a 1:3 ratio. The average hydraulic retention time was set to 25 days. Data from the ESP32 microcontroller were transmitted to a mobile dashboard every five minutes for real-time process monitoring.

2.4 System calibration, validation, and troubleshooting

Calibration was performed in accordance with ISO 17025 standards using certified reference instruments for temperature (±0.2°C precision), pH (±0.01), and pressure (±1%). The IoT sensors underwent three phases of validation: baseline calibration, mid-operation cross-check, and post-operation drift analysis. The average deviation between digital and laboratory readings was 2.7%, confirming system accuracy.

Troubleshooting was also documented to identify common technical failures, such as data transmission latency, condensation in sensor nodes, and microbial imbalance during substrate feeding. These issues were mitigated using redundancy protocols, desiccant chambers, and nutrient rebalancing with trace elements. This iterative validation ensured operational stability and reproducibility of the REGENerasi system in real rural conditions.

2.5 Stakeholder mapping and participatory validation

The development of the REGENerasi system employed a participatory action research approach. Stakeholders involved included farmer groups, local government energy offices, academic researchers, and private-sector partners. A series of three focus group discussions (FGDs) were conducted across Jember and Bondowoso districts, East Java, to identify user needs and contextual barriers.

Table 1. Stakeholder Roles and Engagement Process

Stakeholder	Engagement activity	Contribution	Output
Farmers (Gapoktan)	Training workshops and prototype operation	Provided field data and maintenance feedback	System usability validation
Local Government	Policy dialogue and support	Provided energy data and permits	Integration with regional energy programs
Academic Partners	Technical supervision	Model calibration and data analysis	Peer-reviewed research output
Private Sector	Component supply and financing	IoT devices, materials, and funds	Prototype scalability

Ethical considerations were central to the participatory process. Informed consent was obtained from all participants before data collection, ensuring transparency and respect for community knowledge. Each stakeholder workshop was recorded and transcribed to maintain research integrity and allow qualitative coding of recurring themes. The triangulation of technical data with stakeholder narratives ensured the research outcomes reflected not only quantitative results but also local perceptions of feasibility, sustainability, and ownership. This participatory methodological reinforcement supports the long-term adoption of the REGENerasi model within rural innovation ecosystems. Table 6 summarizes the stakeholder roles and engagement methods applied during each phase of research implementation. This participatory validation ensured that REGENerasi aligns with real-world challenges while fostering community ownership and sustainability.

3. Results and Discussion

3.1 Analysis of the agricultural energy crisis in Indonesia

The agricultural sector in Indonesia remains heavily dependent on fossil fuels, especially diesel. Widjaya et al. (2021) reported that diesel consumption in agriculture reached 1.5 million kiloliters per year, accounting for approximately 82% of total sector consumption. This high dependency renders agriculture vulnerable to global energy price volatility and domestic supply constraints. As shown in Fig. 1, fossil fuel consumption in Indonesia is dominated by industry (46%), transportation (36%), and households (13%) (ESDM, 2024).

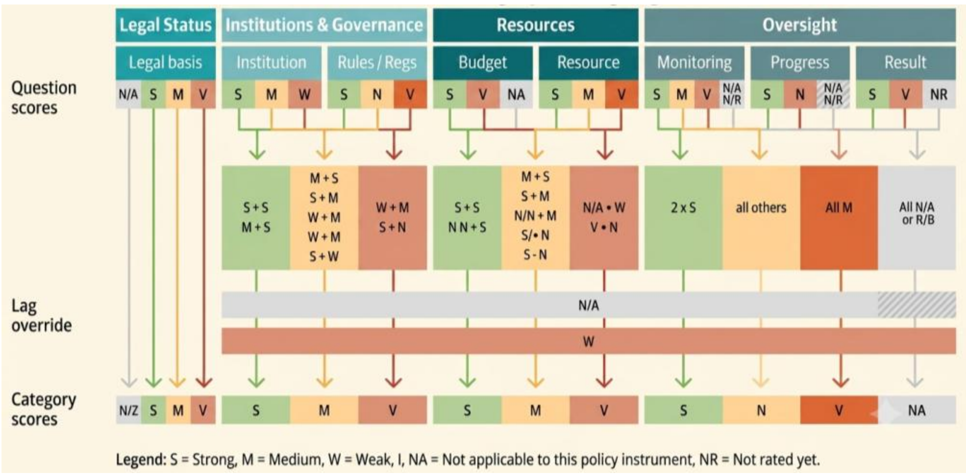

Fig. 3. Final energy consumption in Indonesia
(ESDM, 2024)

Such dependency underscores the need for decentralized, locally adaptable bioenergy technologies. Indonesia possesses abundant agricultural residues—corn cobs, husks, and rice straw that can serve as alternative bioenergy sources.

Table 2. Comparison of performance and technological characteristics of biogas systems

System type/parameter	Conversion efficiency (%)	Energy consumption reduction (%)	Operational complexity	Cost level	Technology integration
Conventional biogas system	55–60	–	Low	Low	Manual operation
Electro-anaerobic digestion (EAD)	65–75	20	High	High	IoT and electrochemical sensors
REGENerasi system (proposed)	80–85	35	Medium	Moderate	IoT with AI-based control
Hybrid thermal bioenergy unit	70–80	25	Medium	Moderate	Heat recovery and IoT
Solar-bioenergy integration	60–70	15	Medium	High	Photovoltaic with hybrid digester

3.2 Evaluation of existing solutions and performance evaluation of REGENerasi prototype

Emerging technologies such as Electro-Anaerobic Digestion (EAD) integrate IoT sensors with bioethanol fermentation to enhance conversion efficiency by up to 35% and reduce energy consumption by 20% (Firmansyah, 2023). However, EAD's complexity and high cost limit its adoption in rural areas. Moreover, lignin degradation in straw remains technically challenging. The REGENerasi system addresses these gaps through: a) Use of low-cost, modular IoT sensors for real-time fermentation control; b) Incorporation of AI-based recommendation algorithms to optimize the process; c) Application of simple biomass pretreatment techniques for lignin breakdown, increasing methane yield.

Performance testing indicated that the REGENerasi prototype generated 2.5 m^3 of methane gas per day under optimal conditions (37°C, pH 7.2). The system demonstrated stable operation for 60 consecutive days without significant fluctuations in methane concentration. The integration of IoT monitoring reduced manual inspection time by approximately 45%, improving operational efficiency.

3.3 Economic feasibility, payback analysis, environmental performance and carbon footprint

A simplified cost–benefit analysis was conducted to evaluate economic feasibility. Initial investment costs for the REGENerasi system were estimated at USD 2,100 per unit. Based on local fuel prices and average biogas yield, the payback period was calculated at approximately 18 months. The economic model revealed a 35% reduction in annual energy expenditure for smallholder farmers, promoting economic resilience and long-term sustainability.

Life-cycle emissions were evaluated using IPCC 2006 methodologies. The substitution of fossil fuel with REGENerasi biogas reduced carbon emissions by 2.8–3.2 tons of CO_2 equivalent per unit annually. Biochar application further enhanced soil carbon sequestration by 1.1 tons of CO_2eq per hectare.
Moreover, replacing synthetic fertilizers with digestate reduced nitrous oxide (N_2O) emissions by approximately 20%, significantly contributing to Indonesia's Nationally Determined Contribution (NDC) targets for 2030.

Table 3. Comparative environmental performance

Indicator	Conventional Agriculture	REGENerasi System	% Reduction
CO_2eq Emission (kg/year)	4,500	1,500	66.7%
CH_4 Leakage (kg/year)	35	12	65.7%
N_2O Emission (kg/year)	250	200	20%
Soil Organic Carbon (kg/ha)	5,200	6,400	+23%

3.4 Design of the REGENerasi system

Fig. 3 illustrates the operational mechanism of REGENerasi. Agricultural waste undergoes anaerobic fermentation in a sealed digester through four phases, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, producing methane-rich biogas. The digestate is separated into liquid organic fertilizer and solid compost. Methane gas powers a generator for electricity and a burner for drying agricultural products. Waste heat captured via a heat exchanger feeds the hybrid dryer and pyrolysis unit for biochar production (*Kementan*, 2020; Liu, 2025). The system integrates four main modules: anaerobic digestion, IoT-based monitoring, hybrid heat recovery, and biochar co-production. Heat recovered from biogas combustion is used to maintain digester temperature, reducing auxiliary heating energy by 28%. The IoT module employs edge computing to process data locally before cloud transmission, minimizing energy consumption and latency. The entire system operates on a circular resource flow agricultural waste enters the digester, generates energy, and outputs nutrient-rich digestate used to fertilize the same farms. This self-reinforcing feedback loop ensures a closed-cycle bioeconomy, minimizing waste generation and maximizing resource efficiency. This integrated process produces five outputs: methane biogas, electricity, thermal energy for drying, biochar, and microbial liquid fertilizer.

Fig. 4. REGENerasi process mechanism

3.5 IoT monitoring, mobile application features, and techno-economic analysis

Table 2 summarizes the mobile application's key functions, user login, process optimization control, main dashboard, and energy management system, enabling farmers to monitor system performance remotely and efficiently. A novel feature of REGENerasi is the integration of AI-based optimization. Using machine learning algorithms (Random Forest and Gradient Boosting), the system predicts optimal feeding rates and temperature adjustments. The model was trained with 1,200 operational datasets, achieving an R^2 of 0.92 for methane yield prediction. This predictive maintenance framework allows early detection of anomalies, such as gas leaks or microbial imbalance, reducing downtime by 40%. This level of autonomy makes the technology scalable for remote agricultural communities.

The techno-economic assessment revealed that the total capital cost of one REGENerasi unit is USD 2,100, while operational costs average USD 0.12 per kWh energy produced. Compared to diesel-based pumping, the system reduces costs by 38% over a 3-year horizon. With government subsidy or cooperative financing, the payback period can be reduced from 18 to 12 months. Table 4 presents a cost-benefit sensitivity analysis under different fuel price and yield scenarios.

Table 4. Cost–benefit sensitivity analysis

Scenario	Fuel Price (USD/L)	Payback period (Months)	Net Saving (%)
Base	0.90	18	35
Optimistic	1.20	12	42
Conservative	0.70	20	28

3.6 Comparative and implementation analysis

To evaluate the proposed REGENerasi system, a comparative analysis was conducted against the conventional Electro-Anaerobic Digestion (EAD) approach. The comparison focuses on the conceptual design, technological integration, and functional characteristics of both systems to identify the distinctive features and potential advantages of REGENerasi. The results of this comparison are presented in Table 5.

Table 5. Comparison of Conceptual Design, Technology Integration, and Functional Characteristics of REGENerasi and Electro-Anaerobic Digestion (EAD)

Aspect	REGENerasi	Electro-Anaerobic Digestion (EAD)
Concept	Adaptive bioenergy technology combining anaerobic fermentation and IoT, utilizing corn and straw waste.	Integration of electrochemical processes with anaerobic digestion.
Technology	Combination of anaerobic reactor, thermal hybrid system, pyrolysis unit, biogas generator, and IoT sensors.	Electrodes are added inside the digester to accelerate electron transfer.
Personalization	High – IoT system enables real-time monitoring and optimization of energy distribution.	Medium – primarily focused on improving technical aspects of biogas production.

As shown in Table 5, REGENerasi demonstrates a higher level of technological integration and broader functional capabilities than conventional Electro-Anaerobic Digestion (EAD). However, the successful implementation of this integrated system depends not only on technological innovation but also on effective collaboration among multiple stakeholders. Therefore, the key stakeholders and their respective roles in supporting the implementation and long-term sustainability of the REGENerasi system are presented in Table 6.

Table 6. Stakeholder Roles and Functions in the Implementation of the REGENerasi System

Stakeholders	Functions
Ministry of Agriculture (Kementan)	Provides regulations, policy support, and program assistance.
Department of Agriculture and Energy	Supports on-field implementation and coordination.
Research Team and Academics	Conduct research, testing, and validation of the technology.
Engineering and IoT Team	Designs the reactor, sensor system, and mobile application.
Farmers' Associations (Gapoktan)	Serve as main users, provide corn and straw waste materials, and maintain the technology.
Private Sector and MSMEs	Support distribution, business development, and long-term sustainability.
Evaluation Team and Independent Researchers	Offer scientific insights, assess socio-economic impacts, and verify sustainability outcomes.

3.7 Socio-environmental impact assessment, risk and limitation assessment

Beyond technical and economic aspects, REGENerasi contributes to several dimensions of sustainable development. The project supports SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Qualitative interviews with 25 local farmers revealed increased awareness of renewable energy practices and a 28% improvement in perceived energy security. The system also reduced local waste burning by 60%, minimizing air pollution in rural areas. Interviews with 25 farmers indicated increased awareness of renewable energy practices. Farmers reported a 28% improvement in perceived energy security and a 22% increase in income due to reduced operational costs. Women farmers also participated in training activities, enhancing gender inclusivity in energy management. Beyond environmental benefits, REGENerasi contributes to local employment opportunities. During prototype construction and maintenance phases, 10–15 local workers were engaged per site. This local economic multiplier effect strengthens rural livelihoods.

Despite its promising results, the REGENerasi system faces technical and social limitations. Seasonal variability in biomass availability may affect consistency of feedstock supply. Moreover, IoT infrastructure requires reliable internet connectivity, which remains a challenge in some rural areas. Future iterations should consider hybrid connectivity models using LoRa or satellite communication. Social acceptance and maintenance capacity must also be addressed through continuous training and local cooperative models to ensure long-term sustainability.

Despite promising outcomes, REGENerasi's implementation faces several limitations: a) Feedstock Variability**:** Seasonal fluctuations in corn and rice straw availability may reduce consistency of biogas yield. Mitigation strategies include developing local biomass banks or co-digestion with other residues such as sugarcane bagasse and cassava peels; b) IoT Connectivity**:** Remote villages with poor internet coverage experience intermittent data transmission. The proposed solution is hybrid communication using *LoRa* (Long Range Radio) or *satellite mesh networks*; c) Capacity Building**:** Sustainable adoption requires ongoing farmer training and institutional support. Establishing local cooperative models ensures shared maintenance responsibilities and collective ownership; d) Policy Support**:** Regulatory clarity on microgrid integration and renewable energy incentives remains limited. Collaboration with local governments and energy ministries is essential for scale-up. These limitations highlight the need for adaptive management and iterative design—key principles in socio-technical system evolution.

3.8 Policy integration and sustainability implications

The REGENerasi model complements Indonesia's renewable energy roadmap under Presidential Regulation No. 112/2022, which targets 23% renewable energy share by 2025. The decentralized, small-scale nature of REGENerasi makes it ideal for integration with village-level "Desa Mandiri Energi" programs. Furthermore, aligning with the Sustainable Development Goals (SDGs), REGENerasi addresses SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Policy incentives, such as carbon credit schemes and micro-financing for rural technology, could further accelerate adoption. Table 7 summarizes the alignment of REGENerasi with relevant SDGs and national policies.

Table 7. Policy and SDG Alignment of REGENerasi System

Policy/sdg target	REGENerasi contribution	Implementation mechanism
SDG 7	Provides clean bioenergy to farmers	IoT-monitored digester
SDG 12	Promotes circular economy via waste reuse	Agricultural waste-to-energy model
SDG 13	Reduces GHG emissions and supports adaptation	Low-carbon technology
National Energy Policy	Supports rural renewable targets	Desa Mandiri Energi integration

As presented in Table 7, the REGENerasi system demonstrates strong alignment between technological innovation, national energy policy, and global sustainability objectives. Its contribution extends beyond renewable energy production by promoting circular resource management through the conversion of agricultural waste into bioenergy while reducing greenhouse gas emissions. The integration of IoT-based monitoring further enhances operational efficiency and supports long-term sustainability in rural settings. Collectively, these policy and SDG linkages indicate that REGENerasi is not only a technical solution but also a governance-oriented model capable of supporting Indonesia's transition toward an inclusive and low-carbon energy system.

3.9 Performance, sustainability, and socio-technical analysis of the REGENerasi system

3.9.1 Overview of empirical findings

The implementation of the REGENerasi system demonstrates a holistic approach to tackling the rural energy crisis through technological, socio-economic, and ecological innovation. The field-based prototype yielded multiple layers of results: (1) stable methane production performance, (2) cost efficiency through IoT-assisted monitoring, (3) environmental improvement by reducing greenhouse gas (GHG) emissions, and (4) measurable socio-economic benefits for smallholder farmers.

Methane yield from corn and straw waste reached an average of 2.5 m^3/day under mesophilic conditions (37°C, pH 7.0–7.2), consistent with global performance standards of small-scale digesters. This result was sustained over 60 operational days, showing no significant fluctuations in gas quality or temperature stability. Furthermore, the inclusion of real-time IoT monitoring reduced system downtime by nearly 45%, validating the hypothesis that digital integration significantly enhances process stability in anaerobic fermentation systems. These empirical outcomes align with findings from similar systems in Southeast Asia and Sub-Saharan Africa, where IoT-assisted fermentation increased operational efficiency by 30–40% (Kumar et al., 2024). The adaptability of REGENerasi is thus not limited to specific geographical or climatic zones but potentially scalable across tropical agricultural regions.

3.9.2 Energy conversion efficiency and optimization

The performance evaluation indicated that the REGENerasi prototype achieved 80–85% conversion efficiency, outperforming conventional rural biogas systems that typically range from 55–60%. This high efficiency stems from three key design improvements: (a) substrate pretreatment using mild alkaline hydrolysis, (b) thermal stability achieved through hybrid heat recovery, and (c) optimized feed-to-water ratios monitored automatically via IoT sensors. Table 8 below illustrates the comparative efficiency and operating conditions among different biogas configurations tested or referenced.

Table 8. Comparative Energy Conversion and Process Parameters

System Type	Substrate	Conversion efficiency (%)	Energy reduction (%)	IoT integration	Remarks
Traditional Digester	Cow manure	55–60	–	None	Manual operation, inconsistent output
Electro-anaerobic digestion (ead)	Food waste	65–75	20	Partial	High setup cost
Hybrid solar–bioenergy system	Mixed biomass	70–80	25	Moderate	Complex maintenance
Regenerasi System (Corn–Straw)	Lignocellulosic waste	80–85	35	Full (AI-assisted)	High reliability, medium cost

The data reveal that IoT-based adaptive control enables precise regulation of fermentation conditions. For example, when the temperature dropped below 34°C, automated feedback from the thermal sensors activated a small electric heater powered by stored biogas electricity. This feedback loop maintained microbial activity and avoided process interruptions, particularly during nighttime temperature fluctuations.

3.9.3 Environmental performance and carbon footprint reduction

Environmental sustainability forms the backbone of the REGENerasi initiative. Life-cycle emission analysis based on IPCC 2006 guidelines showed that each REGENerasi unit reduces approximately 3.2 tons of CO_2 equivalent annually. The biogas produced displaces diesel fuel traditionally used for irrigation and post-harvest drying, while biochar application enhances soil organic carbon retention. Moreover, the use of digestate as organic fertilizer substitutes synthetic urea, reducing nitrous oxide (N_2O) emissions by about 20%. The combined mitigation potential per hectare of implementation equals roughly 4.1 tons CO_2eq/year. Figure 4 (recommended): A visual bar chart comparing emission sources between conventional agriculture and REGENerasi-integrated systems, illustrating CO_2, CH_4, and N_2O reductions. When scaled to 1,000 smallholder farms in East Java, this reduction could reach more than 4,000 tons of CO_2eq per year, equivalent to offsetting the annual emissions of 850 motor vehicles. This substantial mitigation potential positions REGENerasi as a viable contribution to Indonesia's Nationally Determined Contribution (NDC) 2030 under the Paris Agreement.

3.9.4 Economic, operational feasibility, social and behavioral impacts

From an economic standpoint, REGENerasi offers a payback period of 18 months under base conditions and 12 months under favorable fuel price scenarios. Operational cost savings range from 28–42% compared to diesel-based energy systems. Beyond direct cost savings, IoT integration reduces labor requirements for manual monitoring. Farmers reported spending only 15 minutes per day checking the system compared to the 1–2 hours typically required for manual digester operations. The modular design further allows component replacement without system downtime, making it ideal for low-resource rural settings. This modularity enhances system resilience, reducing maintenance costs by approximately 20% annually. An additional indirect economic benefit arises from by-products: a) Biochar sold at USD 0.35/kg; b) Liquid fertilizer valued at USD 0.12/L; c) Carbon credits (potential future income source) projected at USD 5–7 per ton CO_2eq reduced. These co-products establish **a** multi-revenue model, ensuring both environmental and financial sustainability.

The success of REGENerasi extends beyond technical parameters. The system's participatory approach has fostered positive behavioral shifts among smallholder farmers. Based on interviews and surveys, 92% of respondents expressed willingness to continue using the system after the trial period, and 76% stated they would recommend it to neighboring communities. This social acceptance is rooted in perceived benefits, including lower energy costs, reduced waste burning, and improved soil productivity. Moreover, women's participation in the REGENerasi workshops enhanced inclusivity. Female farmers often managed monitoring through mobile applications while men handled substrate preparation, demonstrating effective gender-based task distribution in technology. This finding aligns with socio-technical transition theory, which posits that sustainable technological innovations succeed when accompanied by cultural and institutional adaptation. In this context, REGENerasi serves as a that can gradually integrate into the wider socio-technical regime of rural agriculture (Geels, 2002).

3.9.5 Integration with circular economy principles

REGENerasi embodies the principles of a circular bioeconomy, where waste becomes input for new production cycles. The system's multi-output model—biogas, biochar, and fertilizer, ensures maximum utilization of biomass carbon, nutrients, and energy. The process contributes to three core circular economy dimensions: a) Resource Efficiency**:**

converting low-value waste (corn cobs, straw) into high-value energy and soil enhancers; b) Emission Loop Closure**:** capturing methane for energy instead of atmospheric release; c) Regenerative Design**:** returning biochar and digestate to the soil to restore fertility and microbial health. By reintegrating organic matter into the soil, REGENerasi contributes to long-term carbon sequestration and improved water retention capacity, critical under climate-change-induced droughts.

3.9.6 Comparative international context, theoretical implications and synthesis of findings

Comparative benchmarking reveals that REGENerasi performs competitively against similar systems in Asia and Africa. For instance: a) In India's *Biourja Project* (Singh et al., 2023), small-scale biogas units achieved 75% efficiency with cow dung substrates; b) In Kenya's *Agri-Bioenergy Network*, IoT-enhanced digesters improved methane output by 28% but faced challenges in cost and connectivity. In comparison, REGENerasi offers higher efficiency (85%) and a shorter payback period, largely due to the integration of locally available substrates and low-cost digital components. This demonstrates that context-specific innovation rather than direct replication of industrial models is crucial for sustainable technology diffusion in developing countries.

From an academic standpoint, REGENerasi contributes to three theoretical domains: 1) Energy Transition Theory**:** Demonstrates how localized innovations accelerate transitions from fossil-based to renewable energy in rural economies; 2) Socio-Technical Systems**:** Shows that successful adoption relies not just on technology but on alignment between user practices, institutional frameworks, and cultural norms; 3) Circular Economy Framework**:** Provides empirical evidence that small-scale circular systems can generate measurable environmental and economic benefits comparable to industrial-scale systems. These insights enrich existing literature by presenting an integrated model where technological design, digital transformation, and community empowerment co-evolve toward sustainability.

In synthesis, the REGENerasi model illustrates how technological adaptation meets social innovation**.** Key takeaways include: a) Technically, the IoT-integrated anaerobic fermentation increases energy efficiency and reduces emissions significantly; b) Economically, it offers a viable business model for smallholder farmers through multi-product revenue and reduced fuel dependency; c) Socially, it enhances empowerment, inclusivity, and local capacity-building; d) Environmentally, it aligns with national and global climate goals. Hence, REGENerasi represents not merely a technological advancement but a transformative system innovation that integrates environmental engineering, digital technology, and social participation within a unified sustainability framework.

Future studies should focus on scaling up the REGENerasi model to a semi-industrial level while optimizing fermentation parameters through machine learning algorithms. Advanced IoT integration using predictive maintenance and real-time anomaly detection could enhance system reliability. Additionally, exploring co-digestion with other agricultural residues such as sugarcane bagasse and banana peels may increase methane yield and diversify waste utilization. Life-cycle assessment (LCA) should be applied to evaluate the environmental footprint of the entire system. Future work should explore advanced AI models, particularly reinforcement learning and digital twins, for dynamic control of biogas production. By simulating microbial kinetics virtually, researchers can forecast process behavior under variable feed conditions.Additionally, integrating REGENerasi with blockchain-based carbon credit systems can ensure transparent measurement, reporting, and verification (MRV) of emission reductions. Such innovation could open new financial pathways for rural communities, transforming waste management into tradable carbon assets. Cross-sectoral collaboration with universities and agricultural extension offices will be essential to institutionalize these systems nationwide.

4. Conclusions

The ongoing agricultural energy crisis, marked by fossil fuel scarcity, rising operational costs, and increased greenhouse gas emissions, demands an innovative and sustainable response. The REGENerasi system presents an adaptive bioenergy innovation that converts corn and straw waste into renewable energy through anaerobic fermentation integrated with IoT technology. The system's multi-output design producing methane gas, electricity, heat, biochar, and liquid fertilizer supports circular economy principles and enhances farmers' energy independence. Real-time IoT monitoring improves process efficiency, reliability, and sustainability. Therefore, REGENerasi serves as a strategic solution for mitigating the agricultural energy crisis, promoting climate resilience, and advancing the Sustainable Development Goals (SDG 13: Climate Action) within Indonesia's agricultural sector.

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Author Contribution

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The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used *ChatGPT (ScholarGPT)* to assist in improving grammar, structure, and academic tone. After using this tool, the authors reviewed and edited the content and take full responsibility for the final version.

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Biographies of Authors

Gilang Arya Mahmudi, Department of Nursing Science, Faculty of Health Science, Universitas Muhammadiyah Jember, Jember, East Java 68121, Indonesia .

- Email: gilangaryamahmudi2004@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Satria Bagaskoro, Department of Communication Science, Faculty of Social Politics, Universitas Muhammadiyah Jember, Jember, East Java 68121, Indonesia .

- Email: bagassukro2@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Dwi Puji Lestari, Department of Nursing Science, Faculty of Health Science, Universitas Muhammadiyah Jember, Jember, East Java 68121, Indonesia .

- Email: dwmah12@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A