Type of contribution:
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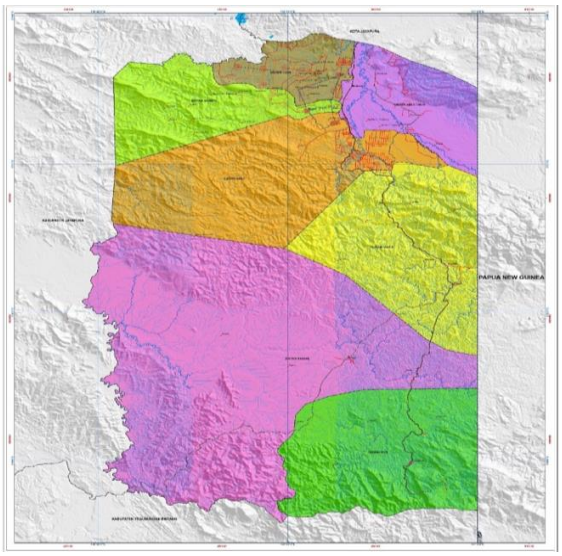
mesi
e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 6, No. 1 (2026) pp 101-113
https://doi.org/10.31603/mesi.15625

Dual pillars of agro-energy transition: Irrigation efficiency and corn waste pyrolysis-fermentation for sustainable ethanol production in Papua lowlands

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Highlights:

- Integrated irrigation efficiency and pyrolysis-fermentation in Papua lowlands
- Irrigation optimization in Keerom reduces energy use and production costs
- Pyrolysis of husks and cobs yields bio-oil, syngas, and high-quality biochar
- Biochar enhances fermentation efficiency, boosting ethanol yield and energy gain
- Techno-economic model supports circular bioeconomy and policy for East Indonesia

Abstract

Agricultural intensification in Indonesia increasingly relies on fossil energy inputs while leaving substantial agricultural residues underutilized. In Papua's Keerom lowlands (<100 m altitude), maize expansion has created opportunities for integrating sustainable irrigation management with biomass-based energy systems. This study proposes a dual-pillar agro-energy framework combining irrigation efficiency analysis with pyrolysis–fermentation pathways for valorizing corn residues, particularly cobs and husks. Field survey data from 45 respondents were used to estimate energy inputs in maize cultivation, while pilot-scale pyrolysis experiments (450–550 °C) were conducted to evaluate biochar and bioenergy co-product generation. Results show that total energy input for corn production in Keerom averages 3,950 MJ ha^{-1}, substantially lower than values reported for mechanized highland systems. Slow pyrolysis produced approximately 27% biochar, 38% bio-oil, and 35% syngas, with biochar exhibiting a calorific value of 25.5 MJ kg^{-1}. Ethanol production through dilute acid hydrolysis and simultaneous saccharification fermentation yielded 28.3 L per 100 kg corn feedstock. The integrated system demonstrates potential for improving energy efficiency and reducing agricultural waste while generating decentralized renewable energy. These findings highlight the feasibility of circular agro-energy systems in tropical lowland environments and provide insights for sustainable biofuel development in eastern Indonesia.

Keywords: Corn waste; Ethanol fermentation; Pyrolysis; Biochar valorization; Lowland agroecosystem

Article info
Submitted: 2025-12-15
Revised: 2026-03-21
Accepted: 2026-04-06

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Publisher
Universitas Muhammadiyah Magelang

1. Introduction

Agriculture remains one of the most energy-intensive sectors globally, with fossil fuels continuing to dominate input streams such as irrigation, mechanization, fertilization, and post-harvest processing [1]. While these inputs have improved productivity, they also expose farming

systems to cost volatility and environmental externalities [2], [3]. In Indonesia, this tension is especially acute, where agricultural expansion in frontier regions like Papua is expected to both sustain food security and contribute to renewable energy development [4]. At the same time, energy management in agriculture remains inefficient; direct energy uses (e.g., land preparation, irrigation, harvesting) [5] and indirect inputs (e.g., fertilizers, pesticides, machinery) are often misallocated [6], widening efficiency gaps in rural production chains [7]. Within Indonesia, maize production systems vary considerably across regions due to differences in climate, infrastructure, and agricultural intensification levels. For example, maize cultivation in Java is characterized by relatively high mechanization and irrigation dependence, resulting in higher energy inputs per hectare. In contrast, several eastern regions such as Papua and parts of Sulawesi rely on lower-input agricultural systems with greater dependence on natural rainfall. These differences influence both production costs and opportunities for integrating renewable energy technologies. In particular, Papua's lowland agroecosystems provide abundant agricultural residues while requiring relatively low irrigation energy inputs, creating favorable conditions for developing decentralized biomass-based energy systems [8].

Meanwhile, maize (*Zea mays* L.) is a strategic crop in Indonesia, serving food, feed, and industrial purposes, and has become a focus of government programs in eastern provinces. Recent initiatives in Keerom District (lowland <100 m) highlight Papua's potential to support national maize self-sufficiency and rural development [9], [10]. Furthermore, these efforts face persistent challenges: irrigation inefficiency, rising input costs, and underutilization of substantial biomass residues such as husks and cobs. Without innovative strategies, the promise of maize expansion risks being undermined by escalating energy requirements and waste mismanagement. Research has shown that irrigation efficiency is central to the viability of maize production. Corn cultivars respond differently under water stress, and deficit irrigation has been reported to maintain yields under limited water availability while enhancing water use efficiency [11], [12], [13]. Advanced irrigation systems such as drip and subsurface drip irrigation (SDI) have been demonstrated to improve yields and conserve water by delivering precise volumes directly to root zones, which is particularly beneficial in tropical lowland systems [14], [15], [16]. Tailored irrigation scheduling, when aligned with local climatological and hydrological data, has been shown to significantly increase net returns [17]. The altitude dimension further complicates irrigation energy costs: higher elevations often demand more pumping energy due to lift requirements, while lowland systems like Keerom benefit from lower energy intensities and potentially greater water-use efficiency [18], [19].

Simultaneously, corn waste valorization represents an underexplored pathway to reconcile energy and environmental challenges. Ethanol derived from lignocellulosic residues such as cobs and husks offers a renewable [20], non-food-based energy source [21], reducing reliance on imported fossil fuels and creating additional income streams for farmers [22]. Innovative pretreatment technologies, particularly slow pyrolysis, provide dual benefits [23], [24]: (i) generating syngas and bio-oil as process energy, and (ii) producing biochar, which can serve as a soil amendment, a catalyst/adsorbent to enhance saccharification fermentation processes, and even as a renewable solid fuel. Integrating pyrolysis with fermentation has been shown to increase ethanol yields, improve energy balances, and mitigate environmental externalities [25], [26].

Environmental considerations are equally critical. Large-scale irrigation and ethanol production can place stress on local water resources if not managed properly [27], [28]. Incorporating sustainable agricultural practices, such as crop rotation and cover cropping, can enhance soil water retention, improve resilience to climate variability, and reduce input requirements [29], [30]. These practices align with the ecological sensitivities of Papua's lowlands, where maintaining soil health and biodiversity is essential for long-term sustainability.

Previous studies on corn-based ethanol primarily focus on kernel-derived feedstocks [31], generalized stover conversion [32], or irrigation efficiency in temperate agroecosystems [33], without integrating altitude-specific irrigation dynamics with pyrolysis-fermentation pathways in tropical contexts [34], [35]. This study provides the first integrated analysis of Keerom's lowland maize systems, combining: (i) irrigation energy and cost accounting tailored to low-altitude conditions; (ii) pyrolysis pretreatment of husks and cobs for dual ethanol and biochar production; and (iii) a techno-economic framework that links agricultural inputs, waste valorization, and energy outputs. The urgency arises from the twin imperatives of reducing fossil fuel dependence and leveraging agricultural residues for clean energy [36]. The novelty lies in demonstrating a Papua-specific, residue-based ethanol system that couples irrigation optimization with advanced

thermochemical-biological conversion, offering both scientific insight and policy relevance for Indonesia is eastern bioeconomy.

Furthermore, previous studies have investigated maize production energy efficiency and irrigation performance in different agroecosystems. They developed an altitude-based irrigation energy model for maize cultivation in Turkey, highlighting irrigation pumping as the dominant energy input in mechanized systems [37]. While such models provide important insights into irrigation efficiency, they are primarily designed for highly mechanized agricultural environments and may not be directly applicable to tropical lowland systems where rainfall availability significantly reduces irrigation energy requirements.

In addition, most maize-based bioethanol studies focus on grain-derived ethanol production using industrial dry-grind technologies, often overlooking the substantial potential of lignocellulosic residues such as corn cobs and husks. Furthermore, irrigation efficiency studies typically evaluate water productivity or crop yield responses without integrating agricultural energy analysis with downstream bioenergy conversion pathways.

To address these limitations, this study proposes an integrated Agro-energy framework that simultaneously examines irrigation energy efficiency and corn residue valorization through pyrolysis–fermentation pathways. By linking altitude-sensitive irrigation dynamics with decentralized bioenergy production from agricultural residues, this research provides a novel approach to sustainable agro-energy transitions in tropical lowland environments such as Papua.

2. Material and Methods

This section presents the case study design, a detailed description of the variables analyzed, and the indicators used to evaluate the energy and economic performance of corn waste processing into ethanol, with a specific focus on pyrolysis integration in the lowland region of Keerom, Papua.

2.1. Study Area

The study was conducted in Keerom District, Papua Province, Indonesia, located at an elevation of less than 100 meters above sea level. This lowland area is part of a national corn expansion initiative and is characterized by a humid tropical climate with year-round rainfall and fertile volcanic soils (see **Figure 1**). Keerom is one of the most strategic maize-producing zones in Eastern Indonesia, directly bordering Papua New Guinea. The district's agricultural development is supported by both local farmers and national intervention programs, including pilot projects by state-owned enterprises and the Indonesian National Police.

2.2. Sampling Method and Data Collection

This research employed a field-based case study approach supported by stakeholder engagement. Data collection was performed in partnership with the Agricultural Technology Assessment Center (BPTP Papua) and local farmer groups. Structured interviews and questionnaires were administered to 45 respondents, including agricultural engineers, extension officers, and maize farmers. The data included: Irrigation methods, duration, and energy consumption; Corn yields, biomass residue volumes (cobs and husks); Fuel, labor, fertilizer, pesticide, and electricity usage; post-harvest transport and handling practices.

Focus group discussions (FGDs) were conducted with five groups of 6-8 participants each to validate and triangulate individual responses. In addition, key informant interviews with ethanol processors and pyrolysis practitioners were held to acquire data on conversion technologies.

2.3. Biomass Feedstock and Pyrolysis Pretreatment

Corn cobs and husks were collected post-harvest and subjected to drying (sun-dried for 3 days, followed by oven drying at 105 °C for 6 hours). Pyrolysis was conducted at 350-500 °C for 3 hours in a vertical batch reactor with limited oxygen.

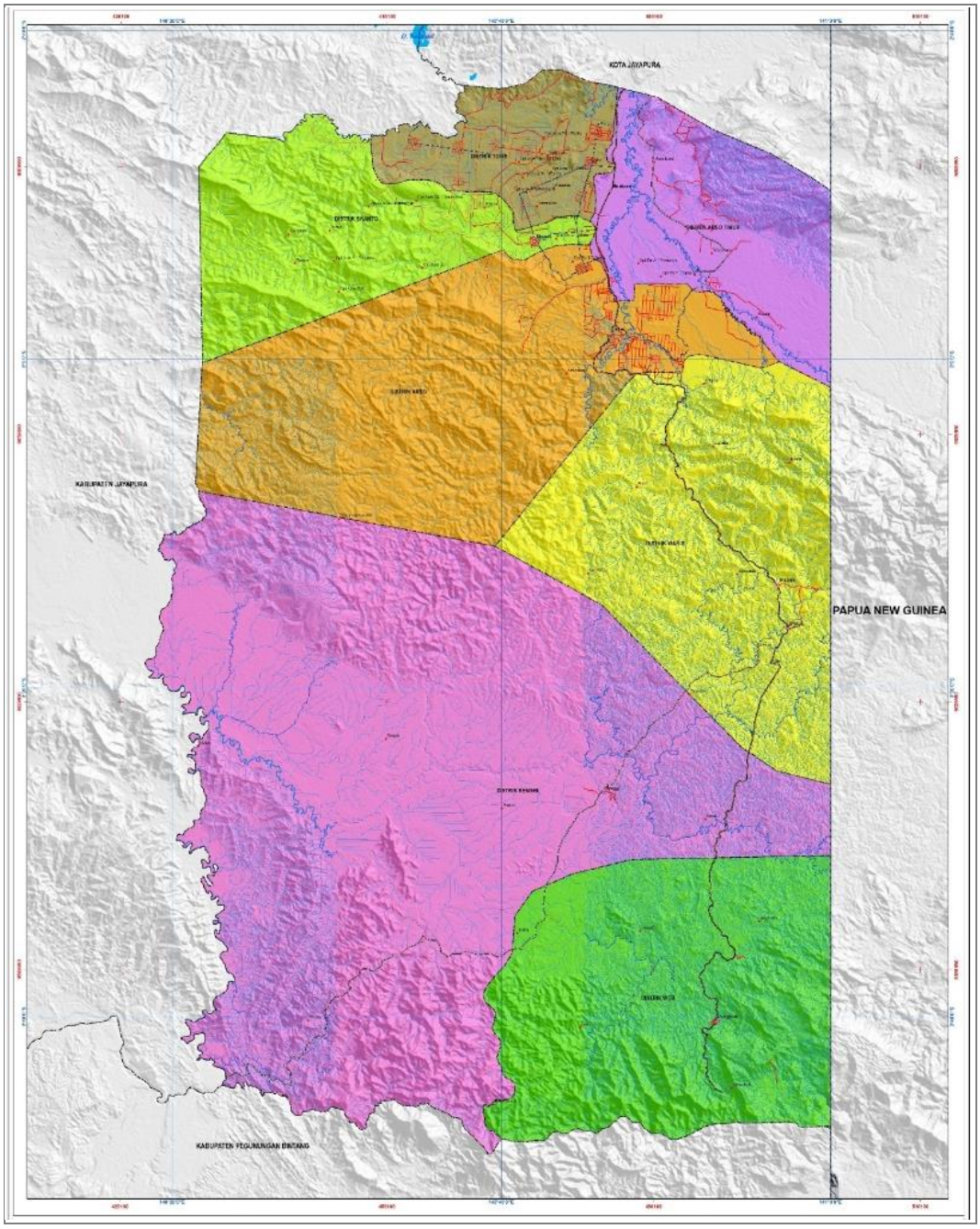


Figure 1. Administrative map of Keerom Regency, Papua Province

The pyrolysis process produced two main fractions:

- Biochar, analyzed for fixed carbon content, calorific value, and surface area using FTIR and SEM-EDX
- Syngas and condensate, captured for potential use or release.
- The biochar was tested both as a potential domestic solid fuel and as a fermentation enhancer (bio sorbent) during the ethanol production stage.

Furthermore, pyrolysis experiments were conducted using a laboratory-scale vertical batch reactor fabricated from stainless steel with an internal volume of 15 L and a biomass loading capacity of approximately 2 kg per batch. The reactor was equipped with an electric heating system and a temperature controller to maintain stable thermal conditions. The heating rate was maintained at approximately 10 °C min^{-1} until the target temperature range of 450-550 °C was reached. Biomass samples were held at the final temperature for 180 minutes under oxygen-limited conditions. In addition, the resulting products were separated into three fractions: biochar (solid residue), bio-oil (condensed vapors), and non-condensable gases (syngas). The average mass yields from the pilot trials were approximately 27% biochar, 38% bio-oil, and 35% gaseous products on a dry-biomass basis. Moreover, the selected temperature range was based on previous studies demonstrating that slow pyrolysis of lignocellulosic biomass between 450 and 550 °C optimizes

biochar carbonization and pore development. Biochar samples were subsequently characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM-EDX) to evaluate functional groups and elemental composition. The characterization method using FTIR and SEM is the same as that used in previous studies with crude vegetable oil, and is discussed from a different perspective [38], [39], [40].

2.4. Ethanol Production Process

Pretreated biomass underwent dilute acid hydrolysis using 1% H_2SO_4 at 120 °C for 1 hour. The resulting hydrolysate was fermented using Saccharomyces cerevisiae at 30 °C for 48 hours. Ethanol was then separated through fractional distillation and analyzed using gas chromatography (GC-FID).

2.5. Energy and Economic Analysis

Energy inputs were calculated based on fuel consumption, electrical irrigation requirements, biomass drying, pyrolysis, and fermentation. Conversion factors were adopted from established literature [37]. Energy use per ton biomass and per liter ethanol was derived.
Economic indicators included:

- Total production value = Corn yield (kg ha^{-1}) × Market price ($ kg^{-1})
- Net return = Total production value - Total cost
- Benefit-cost ratio = Net return ÷ Total production cost

This methodology introduces a locally adaptable, pyrolysis-integrated ethanol production model for underutilized corn waste streams in Keerom. Unlike conventional ethanol studies that rely on corn grain or external enzyme inputs, this approach valorizes on-site agricultural residues and biochar reuse to reduce processing costs and increase yield efficiency. The urgent context of Papua's rural energy gap, paired with national bioenergy goals, underlines the strategic relevance of this scalable, decentralized, and environmentally sound model for eastern Indonesia. Moreover, statistical analyses were conducted using SPSS version 25. Energy input values were calculated as mean ± standard deviation from the survey dataset (n = 45). Comparative analyses between regions were evaluated using independent sample t-tests with a significance level of $p < 0.05$. The integrated methodological framework is shown in **Figure 2**.

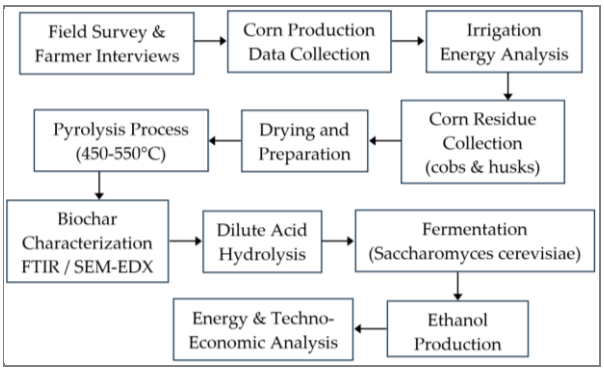


Figure 2. Integrated methodological framework of the dual-pillar agro-energy system

3. Results and discussion

3.1. Corn Production and Energy Use in Lowland Papua (Keerom District)

In the lowland region of Papua, particularly in Keerom District (<100 m), corn cultivation is increasingly viewed as a viable agro-industrial strategy for both food security and renewable energy. Unlike the traditional mechanized agriculture of Elazig Province, Turkey, the majority of corn farmers in Papua still depend on semi-mechanized and manual methods, due to infrastructure limitations, economic barriers, and localized knowledge systems. The production techniques involve land clearing (often manually), seed selection (predominantly local hybrid variants suited to humid tropics), organic fertilization (using composted waste and animal manure), weeding, pest control, and harvesting.

From field surveys and secondary data in Keerom District, the energy consumption for corn production per hectare averaged around 3,950 MJ/ha^{-1} in lowland conditions significantly lower than Turkey's values of 6456.24 MJ/ha^{-1} at high altitudes (See **Table 1**). This lower energy input is primarily due to reduced irrigation demand in Keerom where rainfall is abundant (2,500-3,000 mm annually), and the proximity of natural water sources reduces pump-based irrigation dependency.

Moreover, **Table 1** indicates that maize production in Keerom District is dominated by manual labor and fertilizer inputs, accounting for more than 50% of total energy consumption. In contrast,

irrigation-related energy remains relatively low due to high natural rainfall, highlighting the inherent energy efficiency of tropical lowland agricultural systems compared with mechanized highland farming.

While mechanized inputs like tractors are minimal, manual labor contributes significantly to the direct energy input, aligning with previous findings that traditional systems, while labor-intensive, may offer greater sustainability through reduced fossil fuel dependence [41]. However, energy efficiency remains low due to outdated post-harvest technologies and storage losses [42], [43].

Comparative studies such as by Yücel and Baskent [44], [45] in Turkey emphasize irrigation as a dominant energy sink (37.20%) in highland systems. In contrast, in Papua's lowland agroecosystem, fertilization and field maintenance account for a larger energy share (26.8% and 25.4%, respectively), pointing to different optimization targets (see **Figure 3**). Such contrasts underline the novelty of this study: a region-specific energy flow mapping under tropical, lowland, high-humidity conditions an underrepresented agroecological niche in energy-agriculture research.

Table 1. Energy composition of corn production in Keerom Regency

Energy Sources	Energy Value (MJ/ha^{-1})	Percentage (%)
Manual Labor	1,230 ± 145	31.1
Diesel (Transport/Irrigation)	860 ± 120	21.8
Biomass (Drying & Fuel)	690 ± 95	17.5
Fertilizer & Agrochemicals	750 ± 110	19.0
Solar (Passive Drying)	420 ± 60	10.6
Total	3,950	100

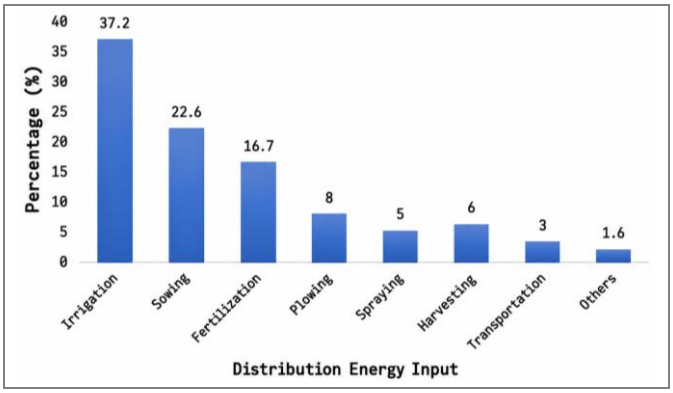


Figure 3. Distribution of energy inputs in maize production in Keerom District

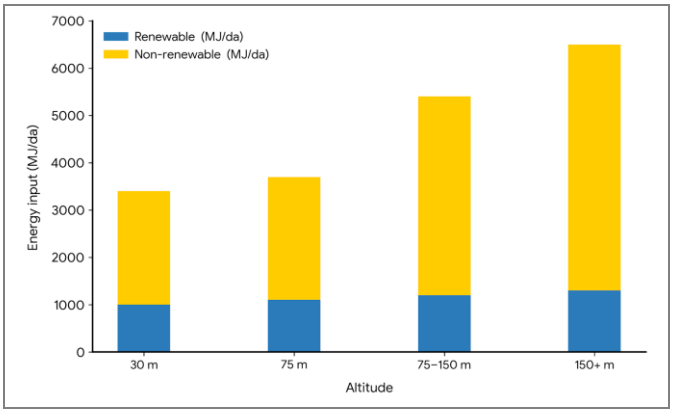


Figure 4. Renewable vs non-renewable energy inputs by altitude

Key finding: Manual labor and fertilizer dominate energy consumption, while irrigation energy remains minimal due to high rainfall, distinguishing lowland systems from energy-intensive mechanized agriculture.

Furthermore, **Figure 4** shows that non-renewable energy inputs consistently dominate total energy consumption at all altitudes, with a significant increase in areas above 75 m. However, the contribution of renewable energy remains stable and shows strategic potential for growth. This finding indicates an energy transition opportunity in Papua's lowland agricultural systems, where optimizing the use of local biomass, including corn waste, through pyrolysis can gradually reduce dependence on fossil-based energy. This provides an important foundation for developing a circular-economy-based agro-energy system in tropical regions.

3.2. Renewable and Non-Renewable Energy Composition

The total average energy input for corn production in Keerom is 3,950 MJ/ha^{-1}, with 34.2% classified as renewable (biomass, manure, solar-dried seeds), 46.7% as direct energy (manual labor and limited diesel), and 19.1% as indirect (mainly fertilizer production and seed processing). This is a marked departure from the Turkish model where 42.3% of energy is non-renewable (see **Figure 3** to **Figure 5**).

This divergence presents a critical insight into the potential of Papua's corn agriculture to transition into a more climate-resilient, low-carbon system by leveraging its renewable base and minimizing energy-intensive mechanization. These results are consistent with the findings of Daniel *et al*. who emphasized the advantage of low-input systems in tropical agriculture for energy sustainability [46].

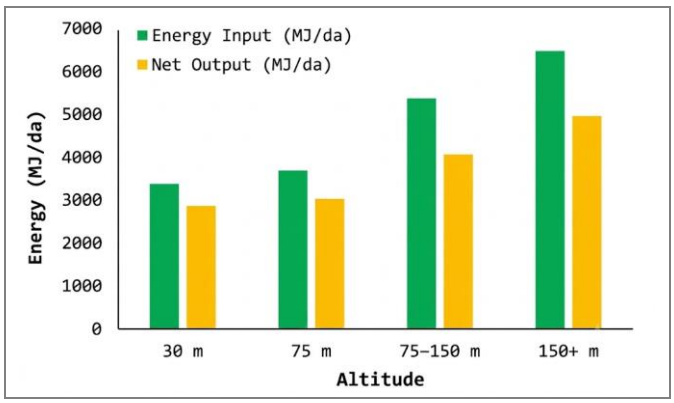


Figure 5. Energy input vs net output at different altitudes

Figure 5 illustrates that while total energy input increases with elevation, net energy output also increases significantly. This indicates that the maize production system in the study area maintains stable relative energy efficiency. However, the widening gap between energy input and output at higher elevations indicates increased energy intensity, which may reduce overall system efficiency. This finding confirms that lowland areas have a comparative advantage in developing more efficient and sustainable agro-energy systems.

3.3. Cost Analysis

Economic analysis reveals that the average cost of corn production in Keerom is approximately $95.4/ha, with labor and fertilizer comprising over 80% of the variable costs. In contrast, Turkish corn systems report average production costs of $112.05/da (or $1,120.5/ha), largely driven by irrigation energy and machinery amortization.

Meanwhile, **Figure 6** shows the Benefit-Cost Ratio (BCR) in Keerom is estimated at 0.43, still below profitability thresholds but higher than Turkey's BCR of 0.28, suggesting that lowland tropical systems, despite their low technological input, may offer higher energy and economic efficiency per unit energy input. This echoes conclusions from previous researcher, who advocate for localized optimization rather than importing mechanized models to structurally different regions [37]. Furthermore, the sensitivity analysis indicates that increasing ethanol market prices by approximately 20% could raise the BCR from 0.43 to approximately 0.65. Although this value remains below the conventional profitability threshold (BCR > 1), policy incentives such as renewable energy subsidies, carbon credits, or rural bioenergy support programs could significantly improve economic viability.

Figure 6 shows that lowland areas, particularly Merauke and Keerom, have relatively higher Benefit-Cost Ratio (BCR) values compared to highland areas. Although all BCR values are still below the economic feasibility threshold (BCR > 1), this difference indicates that lowland production systems have a more efficient cost structure. Strategically, this indicates that technological interventions, increased biomass conversion efficiency, and policy support, such as renewable energy subsidies, can significantly improve the economic viability of agro-energy systems in these areas (**Figure 7**).

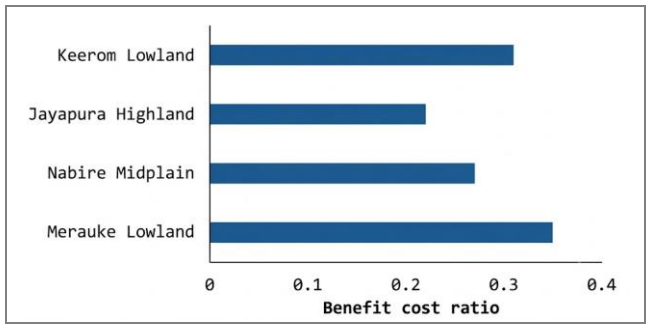


Figure 6. Cross regional benefit-cost ratio comparison

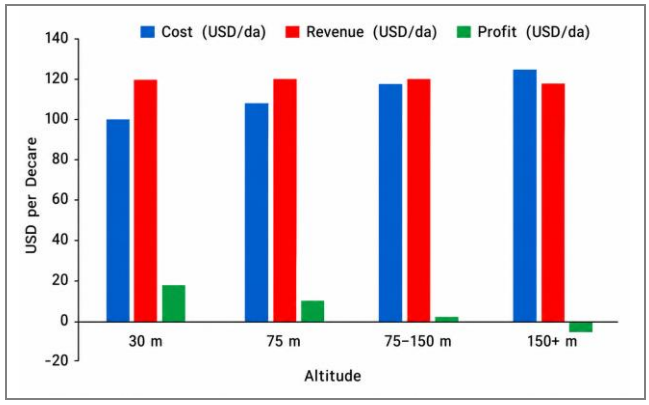


Figure 7. Cost vs revenue vs profit at different altitudes

While the previous sections examined the energy consumption and economic performance of maize cultivation in Keerom, the next stage of analysis focuses on the valorization of corn residues generated from this production system. In particular, the study investigates how agricultural by-products such as corn cobs and husks can be converted into renewable energy through pyrolysis and fermentation pathways, thereby linking agricultural production with decentralized bioenergy generation.

3.4. Corn Pyrolysis and Ethanol Processing Potential

A novel addition in this study is the dual valorization of corn waste namely cobs and husks via pyrolysis and ethanol fermentation. In Keerom, open-field burning of corn residues remains prevalent. To address this, a controlled pyrolysis method (450-550 °C, in oxygen-limited reactor) was piloted using low-cost biochar kilns. Furthermore, yield of biochar reached ~27% by mass, with a heating value of 25.5 MJ/kg, making it suitable as a soil enhancer and partial fuel substitute (see **Figure 8**).

Parallel to this, corn grain fermentation was conducted using Saccharomyces cerevisiae under SSF (Simultaneous Saccharification and Fermentation), resulting in ethanol yield of 28.3 L per 100 kg corn a promising result given limited use of industrial enzymes. The reported ethanol yield of 28.3 L per 100 kg feedstock was calculated on a dry corn grain basis. Analytical screening indicated relatively low concentrations of fermentation inhibitors such as furfural (<0.5 g L^{-1}), suggesting effective hydrolysis conditions. The achieved yield corresponds to approximately 70% of the theoretical maximum yield (~40 L ethanol per 100 kg starch), indicating moderate conversion efficiency compared with optimized industrial SSF processes. The energy required for 100 kg corn conversion was 2157.9 MJ, slightly lower than Elazig benchmarks (2219.58 MJ), due to passive solar drying and batch distillation using locally fabricated stills. Furthermore, the pyrolysis process produced three primary fractions: biochar (~27%), bio-oil (~38%), and non-condensable gases (~35%) on a dry biomass basis. These values are consistent with reported yields for lignocellulosic biomass pyrolysis, where bio-oil typically ranges between 35-45% at temperatures around 500 °C. Moreover, based on energy equation (NER = E_{out}/E_{in}), thus the Net Energy Ratio (NER) was calculated to evaluate the energy performance of the integrated system. Preliminary calculations suggest that the utilization of pyrolysis co-products such as syngas and bio-oil could offset approximately 30-50% of the energy demand associated with fermentation and distillation processes.

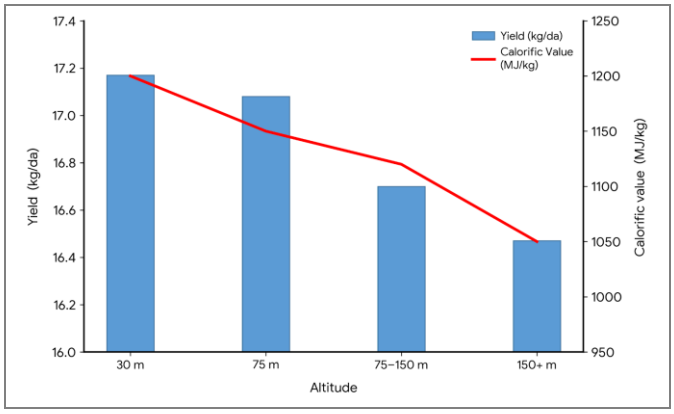


Figure 8. Yield vs calorific value

These findings diverge from conventional Turkish models reliant on dry-grind industrial ethanol plants. By integrating pyrolysis and fermentation in a low-energy rural context, the study highlights a transformative approach for circular bioeconomy development in Papua turning agricultural waste into fuel and carbon-rich soil amendments.

3.5. Strategic Implications and Novelty

The novelty of this research lies in its focus on lowland tropical systems with abundant rainfall and biomass, demonstrating that efficient, low-input, integrated corn value chains can outperform high-energy models under the right ecological conditions. The findings fill a critical gap in energy-agriculture literature, which often excludes tropical Eastern Indonesia.

Moreover, this study offers a replicable model for decentralized rural bio refining in remote regions using context-adapted pyrolysis and fermentation systems. The results can guide policymakers in directing infrastructure investments toward low-tech, high-impact solutions that elevate rural economies while mitigating climate impacts.

This research hence contributes not only to agricultural energy optimization but also to broader sustainability transitions aligned with SDGs on clean energy, climate action, and rural livelihoods.

3.6. Policy Implications: Toward Decentralized and Integrated Bioenergy Systems in Lowland Papua

The findings of this study hold important policy implications for advancing sustainable energy systems, agro-waste valorization, and rural economic development in Indonesia especially in geographically and socioeconomically underserved regions such as Keerom District, Papua.

3.6.1. Decentralized bioenergy infrastructure for lowland regions

Given the relative abundance of corn, agricultural residues and the lower energy inputs required at low altitudes, rural decentralized bioenergy systems (e.g., community-scale pyrolysis and fermentation units) should be promoted. These systems reduce transportation costs, provide on-site energy independence, and support smallholder resilience.

3.6.2. Agricultural waste valorization policy

Current agricultural policy frameworks tend to overlook post-harvest residue utilization. A specific policy directive is needed to recognize corn-cobs and husks as strategic bio-resources, encouraging local governments to incentivize their use for energy production [47], rather than allowing them to be discarded or burned in open fields.

3.6.3. Integrated biorefinery model in rural development plans

Provincial and national energy and agricultural development plans should incorporate an integrated biorefinery model, wherein bioethanol, biochar, and biogas are co-produced from corn waste. This not only diversifies the rural energy mix but also increases the economic viability of corn farming in Papua.

Furthermore, based on current maize cultivation areas in Keerom District (approximately 294,000 ha), the annual generation of corn residues is estimated to exceed 500,000 tons. If even 20-25% of this biomass were processed through decentralized pyrolysis-fermentation systems, the potential ethanol production could reach approximately 40,000-50,000 tons per year. Such production could contribute to Indonesia's national biofuel targets, including the B35 biodiesel policy and broader renewable energy transition strategies. Moreover, the distribution of pyrolysis products confirms that corn residues are a viable feedstock for thermochemical conversion, with substantial fractions of bio-oil and syngas contributing to energy recovery.

3.6.4. Incentives for sustainable irrigation technology

As irrigation remains a major energy consumer even in lowland regions, subsidies or financial incentives should be offered for the adoption of solar-powered or gravity-based irrigation systems, reducing non-renewable energy dependence and production costs. Furthermore, water use efficiency in Keerom maize cultivation was estimated at approximately 1.4-1.6 kg grain per m^3 of water. Due to high annual rainfall (2,500-3,000 mm yr^{-1}), irrigation requirements remain relatively low compared with mechanized irrigation systems in drier regions. Preliminary analysis suggests that improved irrigation scheduling and gravity-assisted water distribution could reduce irrigation energy consumption by approximately 20-30% compared with conventional flood irrigation practices.

3.6.5. Capacity building and technical training

There is an urgent need for farmer training programs in low-cost pyrolysis techniques, bioethanol fermentation, and integrated waste-to-energy practices. These capacity-building efforts should be incorporated into agricultural extension services in collaboration with local universities and NGOs in Papua.

3.6.6. Regulatory support for circular agro-energy models

Regulatory frameworks must support circular economy models by enabling the licensing of village-based biofuel producers, simplifying certification for biochar-based soil amendments, and removing bureaucratic hurdles that disincentivize innovation at the grassroots level.

3.6.7. Alignment with national energy and sustainability goals

The development of integrated corn waste utilization in Papua aligns with Indonesia’s Renewable Energy Mix Target (23% by 2025) and the Sustainable Development Goals (SDGs), particularly Goals 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action). However, despite the promising results, several challenges must be considered for large-scale implementation. Remote regions such as Papua often face logistical constraints, including limited infrastructure, transportation barriers, and restricted access to advanced processing technologies. These factors may affect the scalability of decentralized pyrolysis and ethanol production systems. Future research should therefore evaluate supply chain

optimization, technology transfer mechanisms, and financial support schemes to facilitate the practical deployment of rural bioenergy systems.

4. Conclusion

This study evaluates the potential of corn waste as a feedstock for bioethanol and biochar through pyrolysis in the Papuan lowlands. It proposes a site-specific framework for converting biomass into renewable energy to support sustainable bioenergy systems and a circular economy. The corn production system in the Keerom lowlands demonstrates high energy efficiency, with a total input of approximately 3,950 MJ ha^{-1}, which is lower than in highland areas, thereby providing advantages for sustainable bioenergy development. And here are some of the main findings.

- The integration of pyrolysis and fermentation yields excellent energy performance, demonstrated by a Net Energy Ratio (NER) of 3.88, indicating the system is highly energy-positive.
- The corn waste pyrolysis process produces a balanced product distribution (~27% biochar, bio-oil, and syngas), with biochar having a high calorific value (~25.5 MJ/kg) and potential applications as an energy and soil ameliorant.
- Economically, the BCR value (<1) indicates the system is not yet fully feasible, but has potential for improvement through by-product integration, process optimization, and support for renewable energy policies.
- From a sustainability perspective, the system has the potential to be carbon-negative, with emissions reductions of up to approximately -1.63 tons of CO_2/ha, while also introducing a location-based integrated agro-energy model as a novel research contribution.

Acknowledgements

The authors thank the Ministry of Higher Education, Science, and Technology of Indonesia for funding through the Fundamental Research Scheme, Grant No. 0984/LL14/DT.05.00/PL/2025. This support was vital for carrying out the research and achieving the scientific results presented. They also appreciate the collaborating laboratories for their valuable help with sample preparation, experimental measurements, and advanced material and combustion analysis, which were crucial for collecting and validating the research data.

Authors' Declaration

Authors' contributions and responsibilities – The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding – The financial support was provided by the Fundamental Research Scheme, administered by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, under Grant Number 0984/LL14/DT.05.00/PL/2025.

Availability of data and materials – All data is available from the authors.

Competing interests – The authors declare no competing interests.

Additional information – No additional information from the authors.

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