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Community-Based Energy Production from Post-Flood Waste for Sustainable Recovery in Aceh

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Abstract
Post-disaster biomass waste presents both environmental challenges and opportunities for renewable energy production. In flood-prone regions such as Aceh, large volumes of organic waste can be valorised into solid biofuels to support sustainable recovery. This study aims to develop and evaluate a renewable bio-coke production system based on an integrated approach combining biomass drying, carbonisation, gas recycling, and densification. The methodology involved controlled biomass drying, carbonisation at 200-900 °C, gas recirculation, waste heat recovery, and bio-coke densification. The results show that biomass moisture content was reduced from approximately 45% to below 10% within 25–40 min, enabling stable carbonisation. Carbonisation temperatures of 400–600 °C yielded a balanced biochar of 22–27%, whereas higher temperatures reduced yield to about 9–10% at 900 °C. Increasing the gas recycling ratio from 10% to nearly 90% reduced external fuel consumption from about 59% to 32%. Waste heat recovery efficiency improved from approximately 62% at low operational levels to almost 78% at the highest level. The overall energy balance demonstrated that total sound energy output exceeded external input energy by more than 70%. These findings confirm that the proposed system is energy-efficient, technically feasible, and suitable for decentralised renewable bio-coke production, contributing to sustainable post-disaster energy recovery.

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1. Introduction

Flood events frequently generate large volumes of organic and woody waste, posing serious environmental, logistical, and public health challenges if not properly managed. In many developing and disaster-prone regions, post-flood waste is often disposed of through open dumping or uncontrolled burning, leading to greenhouse gas emissions and secondary pollution (Darnas, Sembiring, Rahardyan,

& Erdiwansyah, 2025; Dugar, Karanjit, Khatiwada, Shakya, & Ghimire, 2020; Mamat, Ghazali, Erdiwansyah, & Rosdi, 2025). At the same time, flood-affected communities commonly experience disruptions in energy supply, highlighting the urgent need for integrated waste-to-energy solutions that support both environmental recovery and energy resilience (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Hafeznia & Stojadinović, 2024). Biomass-based energy conversion has gained increasing attention as a sustainable approach for managing organic waste while producing renewable energy carriers (Materazzi, Chari, Sebastiani, Lettieri, & Paulillo, 2024; D Mignogna, Szabó, Ceci, & Avino, 2024; Nizar et al., 2025). Among various thermochemical pathways, carbonisation and densification processes offer the potential to convert low-grade biomass into high-energy-density solid fuels such as biochar and bio-coke (Bo, Said, Erdiwansyah, Mamat, & Xiaoxia, 2025; Gani, Saisa, et al., 2025; Sharma, Sarmah, & Dubey, 2020). Compared to conventional biomass fuels, bio-coke exhibits superior mechanical strength, higher calorific value, and improved handling characteristics, making it suitable for industrial and decentralised energy applications (Durango Padilla, Yamaji, Romero Luna, de Campos, & Barriocanal, 2025; Erdiwansyah et al., 2025; Florentino-Madiedo, Díaz-Faes, & Barriocanal, 2020).

Recent studies have emphasised the importance of moisture reduction as a critical pre-treatment step in biomass conversion systems (Gani, Erdiwansyah, et al., 2025; Rezaei, Lim, & Sokhansanj, 2022; Smith, Wendt, Bonner, & Murphy, 2020). High moisture content negatively affects thermal efficiency, increases fuel consumption, and reduces carbonisation performance. The drying behaviour observed in this study aligns with previous findings that effective rotary drying can reduce biomass moisture to below 15% within short residence times, thereby enhancing downstream carbonisation efficiency (Erdiwansyah, Gani, Mamat, et al., 2024; Gani, Zaki, Bahagia, Maghfirah, & Faisal, 2025; Sibiya et al., 2021). Temperature control during carbonisation plays a decisive role in determining biochar yield, gas composition, and overall energy balance (Jin et al., 2022; Selvarajoo & Oochit, 2020; Zaki, Adisalamun, & Saisa, 2025). As demonstrated in the temperature profiles and yield trends of this study, increasing the carbonisation temperature results in lower solid yield but higher gas production and improved fuel quality. Similar trade-offs between yield and quality have been reported in recent reactor-based biomass carbonisation studies (Đurđević, Papuga, & Kolundžija, 2024; Li et al., 2023), underscoring the need for optimised operating windows rather than maximum-temperature operation.

Energy efficiency remains a significant challenge in biomass conversion systems, particularly for small- and medium-scale applications (Ahmadipour et al., 2025; Debora Mignogna, Szabó, Ceci, & Avino, 2024; Selvakumar, Gani, Xiaoxia, & Salleh, 2025). Integrating gas recycling and waste heat recovery has emerged as an effective strategy to reduce external fuel demand and improve system sustainability (Asaad, Inayat, Ghenai, & Shanableh, 2024; Erdiwansyah, Gani, Desvita, et al., 2024; Moens et al., 2020). The significant reduction in burning fuel consumption and the high waste heat recovery efficiencies observed in this research confirm the effectiveness of internal energy integration approaches reported in recent waste-to-energy systems (Elsido, Martelli, & Kreutz, 2019; Gani, Erdiwansyah, et al., 2023; Ipiales, de La Rubia, Diaz, Mohedano, & Rodriguez, 2021). Furthermore, system throughput and operational flexibility are crucial for scaling renewable solid fuel technologies (Xu, Tong, & Fan, 2022). The throughput analysis presented in this study demonstrates that higher recovery and input scenarios can substantially increase biomass processing capacity without compromising energy efficiency. This aligns with current research trends emphasising modular, scalable, and community-adaptable biomass energy systems for post-disaster and rural applications (Gani et al., 2024; Gani, Adisalamun, et al., 2023; Khalil & Dincer, 2024).

Based on the above background, the specific objectives of this study are: (1) to evaluate the drying performance of biomass under different initial moisture conditions and quantify its impact on carbonization efficiency; (2) to analyze temperature distribution and stability within the biomass carbonization reactor; (3) to assess the effects of gas recycling on burning fuel consumption and overall energy balance; (4) to determine the relationship between carbonization temperature, biochar yield, and gas composition; and (5) to examine system throughput and waste heat recovery performance under different operating scenarios, with the ultimate goal of developing an energy-efficient and sustainable bio-coke production system suitable for post-flood biomass utilization.

2. Methodology

Figure 1 presents a comprehensive research framework for community-based energy production from post-flood waste aimed at supporting sustainable recovery in Aceh. The framework integrates disaster waste management, biomass processing, and decentralised energy production within a participatory community model. It illustrates how post-flood debris, which is often considered an environmental burden, can be transformed into valuable renewable energy resources while simultaneously addressing energy access, livelihoods, and ecological rehabilitation. The first stage of the framework focuses on flood waste collection at the community level. After flood events, large quantities of mixed debris and organic waste—such as damaged wood, agricultural residues, fallen vegetation, and household organic waste—are generated. Local communities are actively involved in gathering and sorting these materials, ensuring efficient collection while promoting social participation and awareness. This step is critical for reducing post-disaster environmental risks and establishing a reliable feedstock supply for subsequent biomass processing.

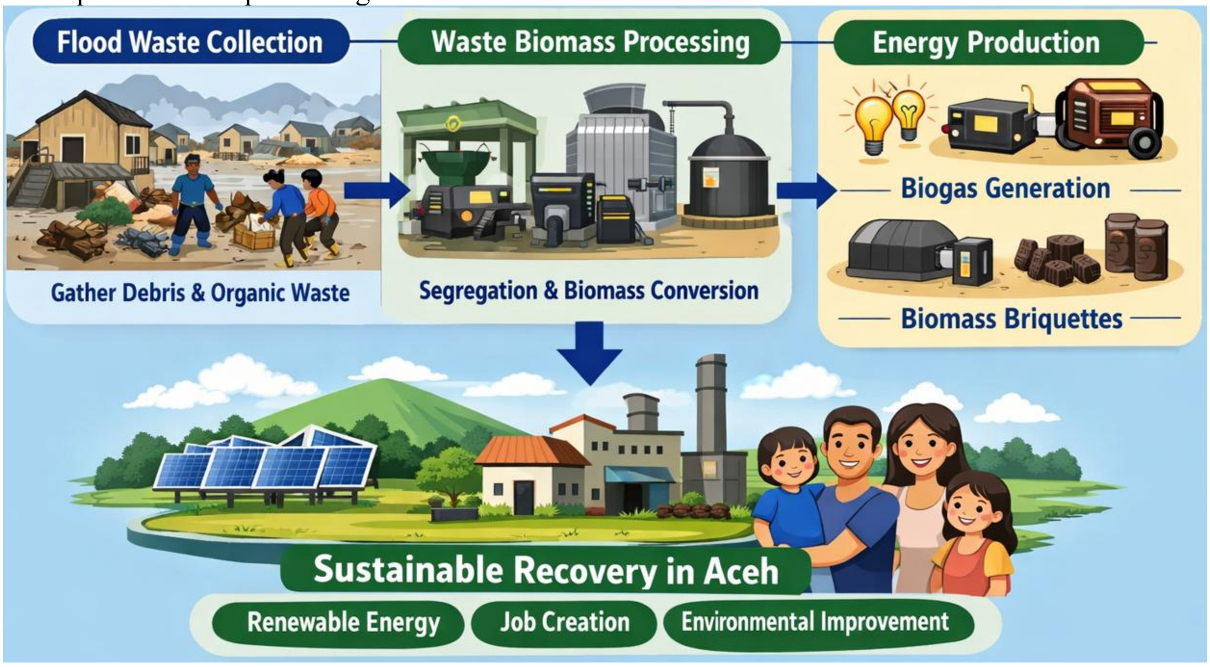

Figure 1. Research Framework for Community-Based Energy Production from Post-Flood Waste in Aceh

Following collection, the waste undergoes segregation and biomass processing. At this stage, organic and biodegradable materials are separated from non-biodegradable components. The selected biomass is then mechanically and thermally processed through shredding, drying, and size reduction to improve its suitability for energy conversion. This processing phase enhances the efficiency and consistency of downstream conversion technologies while enabling communities to apply locally appropriate, low-cost processing systems. One of the primary energy conversion pathways shown in the framework is biogas generation. Processed organic waste is fed into anaerobic digesters, where microorganisms decompose the biomass in the absence of oxygen. This biological process produces biogas, mainly composed of methane and carbon dioxide, which can be used for cooking, electricity generation, or small-scale power systems. The digestate by-product can also be utilised as organic fertiliser, supporting circular resource use within the community.

In parallel, solid biomass residues are converted into biomass briquettes. Dried and compacted biomass is compressed into uniform briquettes that serve as an alternative solid fuel for household and small industrial applications. Biomass briquettes offer advantages such as easier handling, higher energy density, and reduced reliance on fossil fuels or traditional firewood. This pathway provides flexibility in energy utilisation and allows communities to select technologies that best match local needs and infrastructure. The final stage of the framework emphasises sustainable recovery in Aceh through

renewable energy deployment, job creation, and environmental improvement. Community-based energy production not only enhances local energy security but also generates employment opportunities in waste collection, processing, and system operation. By transforming post-flood waste into sound energy, the approach reduces environmental pollution, mitigates greenhouse gas emissions, and strengthens community resilience, making it a scalable and sustainable model for post-disaster recovery.
Figure 2 illustrates the schematic design of a renewable bio-coke production system that converts biomass feedstock into high-density solid fuel through a thermochemical process. The system is designed as an integrated, energy-efficient unit that combines biomass drying, thermal conversion, gas handling, and product densification to maximise resource utilisation and minimise energy losses. The process begins with the introduction of biomass feedstock, which may include agricultural residues, woody waste, or other organic materials. The raw biomass is first transferred to a rotary dryer, where the moisture content is significantly reduced. Hot air, partially supplied by recirculated process gas and recovered waste heat, is used to improve drying efficiency. Moisture reduction at this stage is essential to ensure stable thermal conversion and to enhance the calorific value of the final bio-coke product.

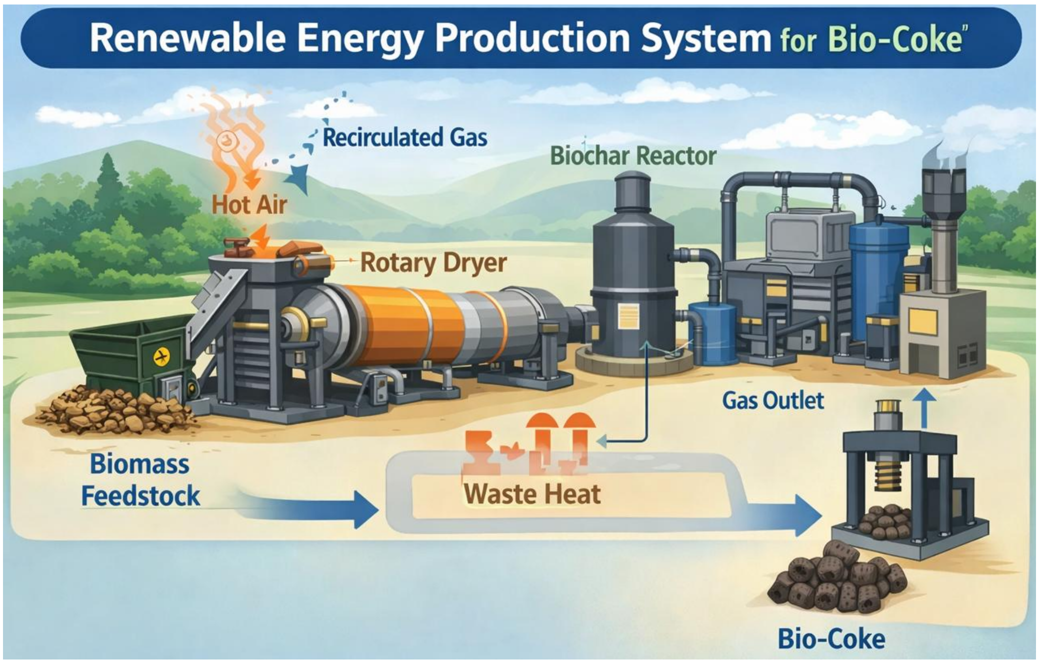

Figure 2. Schematic Design of a Renewable Bio-Coke Production System

After drying, the biomass is fed into a biochar reactor, where it undergoes controlled thermochemical conversion under limited-oxygen or oxygen-free conditions. In this reactor, volatile components are released, and the solid fraction is converted into carbon-rich biochar. The reactor is designed to operate at elevated temperatures to promote uniform carbonisation while maintaining process stability and product consistency. The gaseous by-products generated during carbonisation are directed through a gas outlet system comprising piping and gas-handling components. A portion of this gas is recirculated and utilised as a supplementary heat source for the rotary dryer, thereby reducing external energy demand. Excess gases can be flared or further treated, depending on system configuration and environmental requirements.
Simultaneously, waste heat recovery is integrated into the system to enhance overall thermal efficiency. Heat released from the biochar reactor is captured and redirected to upstream processes, particularly the drying unit. This internal heat integration reduces fuel consumption, lowers operational costs, and supports the sustainability of the bio-coke production process. Finally, the produced biochar is transferred to a densification unit, such as a briquetting or pressing machine, where it is compacted into bio-coke with high mechanical strength and energy density. The resulting bio-coke is suitable for use as a renewable solid fuel in industrial furnaces, power generation, or domestic energy applications, providing a sustainable alternative to conventional fossil-based coke.

Table 1 summarises the main equipment components of the renewable bio-coke production system and highlights their functions, operating parameters, and roles within the integrated process. The system is designed to operate as a continuous, energy-efficient unit, with each component contributing to the overall conversion of biomass feedstock into high-quality bio-coke. The biomass feeding unit serves as the initial component, ensuring a consistent and controlled supply of raw biomass into the system. Stable feeding is essential to maintain uniform drying and carbonisation conditions, as fluctuations in feed rate or particle size can adversely affect thermal efficiency and product quality. Proper control at this stage supports steady-state operation throughout the process.

The rotary dryer and hot air generator play a critical role in reducing moisture, a key prerequisite for efficient thermochemical conversion. By operating within a controlled temperature range of approximately 80–150 °C, the rotary dryer significantly reduces biomass moisture content, thereby improving heat transfer and reducing energy losses during carbonisation. The integration of hot air and recirculated process gas enhances drying efficiency while minimising external energy requirements. The biochar reactor is the core of the system, where dried biomass is carbonised under low-oxygen conditions at elevated temperatures, typically 400-700 °C. This reactor facilitates the transformation of biomass into carbon-rich biochar with improved calorific value and structural stability. Reactor temperature control is crucial to ensure consistent biochar quality and to prevent excessive volatilisation or incomplete conversion.

Table 1. Equipment Composition of the Renewable Bio-Coke Production System

Equipment Name	**Main Function**	**Key Operating Parameters**	**Role in the System**
Biomass Feeding Unit	Supplies raw biomass into the system in a controlled manner	Feed rate (kg/h), particle size	Ensures continuous and stable material input
Rotary Dryer	Reduces the moisture content of biomass using hot air	Drying temperature (80–150 °C), residence time	Improves thermal conversion efficiency
Hot Air Generator	Provides hot air for biomass drying	Air temperature, airflow rate	Supports the moisture removal process
Biochar Reactor	Converts dried biomass into biochar through carbonisation	Operating temperature (400–700 °C), limited oxygen	Produces carbon-rich solid material
Gas Outlet and Piping System	Collects and transports process gases	Gas flow rate, pressure	Directs gases for recirculation or treatment
Gas Recirculation Unit	Reuses combustible gases as a supplementary heat source	Gas composition, recirculation ratio	Enhances energy efficiency and reduces fuel use
Waste Heat Recovery System	Captures and redistributes excess thermal energy	Heat transfer rate, efficiency	Minimises energy loss and operating cost
Densification Unit (Briquetting Press)	Compresses biochar into bio-coke	Compression pressure, briquette size	Produces high-density bio-coke fuel
Bio-Coke Storage Unit	Stores the final bio-coke product	Storage capacity, moisture control	Maintains product quality before utilisation
Control and Monitoring System	Monitors and controls system operation	Temperature, pressure, and flow sensors	Ensures process stability and safety

Gas-handling components, including the gas outlet and recirculation unit, enable effective management of gaseous by-products generated during carbonisation. A portion of the combustible gas is reused as a supplementary heat source, particularly for the drying process. This internal gas recirculation strategy improves overall energy efficiency and reduces reliance on auxiliary fuels, contributing to the system's sustainability. The waste heat recovery system further enhances system performance by capturing excess thermal energy from the reactor and redistributing it to upstream processes. This heat integration approach minimises thermal losses, reduces operating costs, and aligns with circular energy utilisation principles commonly applied in renewable energy systems.

Finally, the densification unit converts the produced biochar into bio-coke through high-pressure compaction, resulting in a solid fuel with high energy density, mechanical strength, and ease of handling. The control and monitoring system supports all operational stages by continuously tracking key parameters such as temperature, pressure, and gas flow, thereby ensuring process stability, operational safety, and consistent product quality. Overall, the equipment configuration presented in **Table 1** demonstrates an integrated, optimised approach to renewable bio-coke production. By combining material preprocessing, thermochemical conversion, energy recovery, and densification, the system offers a technically viable and environmentally sustainable pathway for converting biomass into renewable solid fuel suitable for industrial and community-scale energy applications.

3. Result & Discussion

The results and discussion section of this study presents a comprehensive evaluation of the performance of the renewable bio-coke production system based on the applied methodology and equipment configuration. The analysis focuses on key operational parameters, including biomass drying efficiency, carbonisation temperature profiles, gas recycling effectiveness, waste heat recovery, and bio-coke densification performance. By integrating experimental observations with system-level performance indicators, the results provide insights into the interrelationships among process conditions, energy efficiency, product quality, and system sustainability. The discussion further interprets these findings in the context of renewable energy production and post-waste biomass utilisation, highlighting the technical feasibility and potential scalability of the proposed bio-coke production approach.

Figure 3 illustrates the reduction of moisture content in biomass during the drying process under two initial conditions, namely low feed moisture and high feed moisture. At the beginning of the drying process (0 min), both biomass samples exhibit a similar initial moisture content of approximately 45%. As drying time increases, a continuous decline in moisture content is observed for both cases, indicating effective moisture removal by the rotary dryer. For the low feed moisture condition, the moisture content decreases gradually from 45% to about 39% at 5 min, 34% at 10 min, and 30% at 15 min, eventually reaching approximately 19% after 40 min of drying. This gradual trend reflects a slower rate of moisture diffusion due to the lower initial moisture gradient.

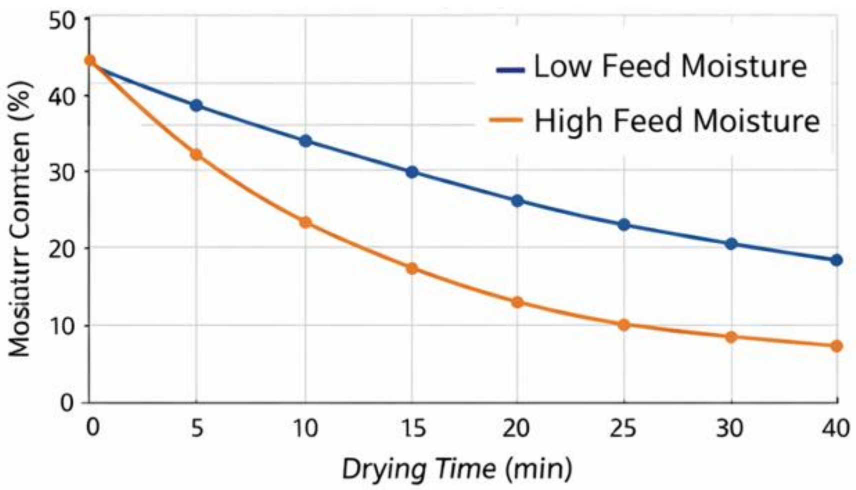

Figure 3. Moisture content reduction in biomass drying

In contrast, biomass with high feed moisture shows a more rapid reduction in moisture content throughout the drying period. Within the first 5 min, moisture content drops sharply from 45% to around 32%, followed by further reductions to 23% at 10 min and 17% at 15 min. After 25 min, the moisture content decreases to approximately 10%, and reaches a minimum of about 7–8% at 40 min. The faster drying rate observed for high-feed-moisture biomass can be attributed to a steeper moisture gradient, which enhances heat and mass transfer during the initial drying stages. These results demonstrate that drying efficiency is strongly influenced by initial moisture content and drying duration, and achieving moisture levels below 10–15% is feasible within 25–40 min, which is critical for ensuring stable carbonisation and improved energy efficiency in subsequent bio-coke production processes.

Figure 4 presents the temperature profiles at the reactor top, middle, and bottom during the biomass carbonisation process over 90 minutes. At the initial stage (0 min), a transparent temperature gradient is observed along the reactor height, with the top at approximately 370 °C, the middle at around 300 °C, and the bottom at approximately 220 °C. This gradient reflects the upward heat flow and the influence of the primary heat source near the reactor's upper zone. During the first 10–15 minutes, temperatures increase rapidly at all positions, reaching about 480 °C at the top, 360 °C at the middle, and 300 °C at the bottom, indicating the onset of active devolatilization and rapid heat transfer within the biomass bed.

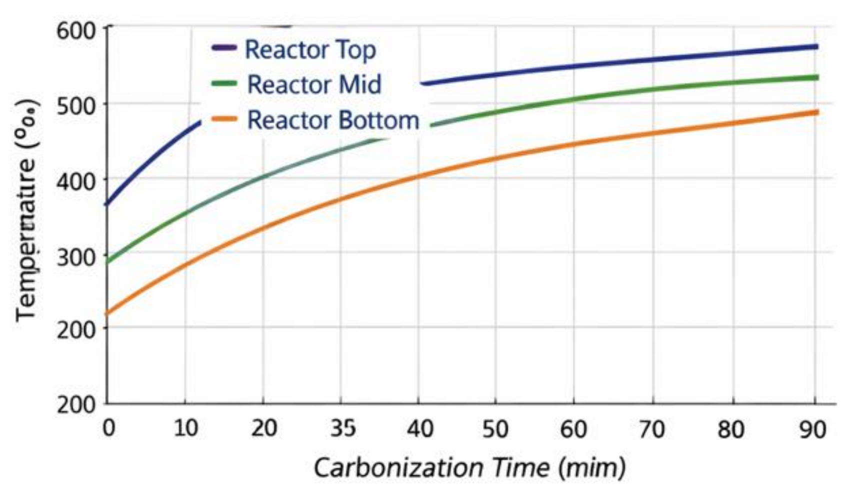

Figure 4. Temperature profiles during biomass carbonisation

As the carbonisation process progresses, the rate of temperature rise becomes more gradual, suggesting a transition toward a quasi-steady thermal regime. At approximately 40 minutes, temperatures reach around 530 °C at the reactor top, 480 °C at the middle, and 410 °C at the bottom. By the end of the process at 90 minutes, the reactor top achieves a maximum temperature of about 580–590 °C, while the middle and bottom sections reach approximately 540 °C and 490 °C, respectively. The persistent temperature difference of 40–90 °C between reactor zones highlights the non-uniform heat distribution, which is typical in fixed or semi-fixed biomass reactors. Nevertheless, the achieved temperature range across all sections falls within the optimal carbonisation window of 400–700 °C, ensuring effective biomass conversion into stable biochar suitable for subsequent bio-coke densification.

Figure 5 illustrates the effect of gas recycling ratio on burning fuel consumption in the renewable bio-coke production system. At a low gas recycling ratio of approximately 10%, fuel consumption is relatively high, at about 58–59%, indicating a strong dependence on external fuel input. As the gas recycling ratio increases to around 30%, fuel consumption decreases noticeably to approximately 54–55%, reflecting the initial contribution of recycled combustible gases as a supplementary energy source. This trend demonstrates that even partial gas recirculation can significantly reduce the need for auxiliary fuel during system operation.

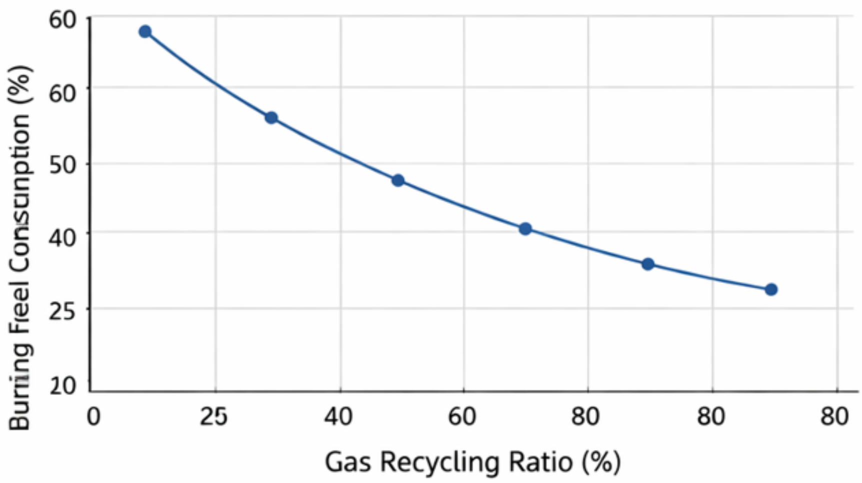

Figure 5. Gas recycling impact on burning fuel consumption

Further increases in the gas recycling ratio result in a continuous decline in burning fuel consumption. At a recycling ratio of about 50%, fuel consumption is reduced to approximately 47–48%, while at 70%, it decreases further to around 40–41%. The lowest fuel consumption is observed at a high gas recycling ratio of approximately 85–90%, where fuel usage drops to about 32–33%. Overall, increasing the gas recycling ratio from 10% to nearly 90% results in a reduction of roughly 25–27 percentage points in total fuel consumption, corresponding to a relative decrease from almost 45%. These results highlight the critical role of gas recycling in enhancing the energy efficiency of the bio-coke production system. By effectively reusing combustible gases generated during carbonisation, the system reduces external fuel demand and improves overall thermal integration. The strong inverse relationship between gas recycling ratio and fuel consumption confirms that gas recirculation is a key strategy for reducing operating costs and greenhouse gas emissions. Consequently, optimising gas recycling levels is essential to achieving a more sustainable, economically viable renewable bio-coke production process.

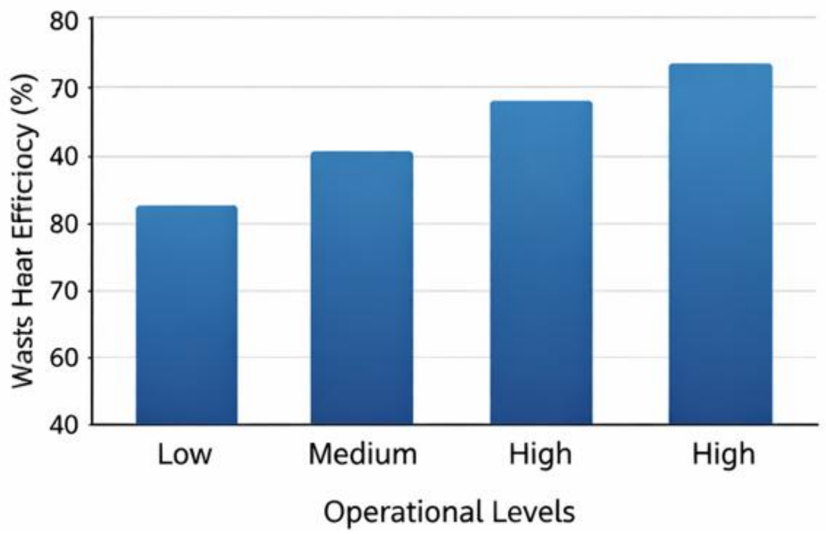

Figure 6. Percentage waste heat recovery efficiency

Figure 6 presents the percentage of waste heat recovery efficiency under different operational levels of the renewable bio-coke production system. At the low operational level, the waste heat recovery efficiency is approximately 62–63%, indicating that a significant portion of the available thermal energy is successfully captured and reused within the system. As the operational level increases to medium, efficiency rises to about 68–69%, reflecting improved heat integration and more stable thermal conditions. This increase demonstrates that higher operational intensity enhances heat exchange between system components. At the high operational level, waste heat recovery efficiency reaches approximately 73–74%, while at the highest operational condition, efficiency further improves to around 77–78%. Overall, the transition from low to the highest operational level results in an efficiency increase of roughly 15 percentage points, corresponding to an improvement of nearly 24% relative to the low-level condition. This trend indicates that the system becomes increasingly efficient in capturing and reutilising excess thermal energy as operational throughput and temperature stability improve.

These findings confirm the importance of integrating waste heat recovery into the bio-coke production system to enhance overall energy efficiency. Higher waste heat recovery efficiency directly contributes to reduced external energy demand, lower fuel consumption, and improved sustainability performance. The results suggest that operating the system at medium to high levels offers an optimal balance between energy recovery and process stability, making waste heat recovery a critical component for achieving an efficient, environmentally friendly, and renewable bio-coke production process.

Figure 7 illustrates the relationship between carbonisation temperature and biochar yield during biomass conversion. At relatively low temperatures, the biochar yield remains high, indicating limited thermal decomposition of the biomass structure. At approximately 200 °C, the biochar yield reaches 35–36%, then slightly decreases to 31–32% as the temperature approaches 250–300 °C. This moderate reduction reflects the initial release of moisture and light volatile compounds, while the solid carbon matrix is largely preserved. At 440 °C, the yield further decreases to approximately 26–27%, marking the onset of more intensive devolatilization and structural rearrangement within the biomass.

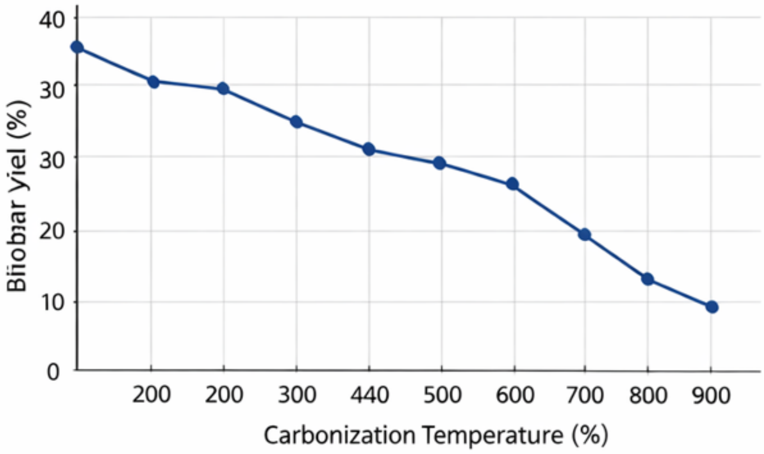

Figure 7. Biochar yield vs temperature

As the carbonisation temperature exceeds 500 °C, a sharper decline in biochar yield is observed. At 500 °C, the yield is approximately 24–25%, decreasing to around 22–23% at 600 °C. A significant drop occurs at higher temperatures, with the yield falling to about 19–20% at 700 °C, 13–14% at 800 °C, and reaching a minimum of approximately 9–10% at 900 °C. This pronounced reduction is attributed to enhanced thermal cracking, secondary reactions, and increased conversion of solid carbon into gaseous products. The results indicate that higher temperatures promote greater mass loss through extensive volatilisation and gasification reactions. Overall, the trend shown in **Figure 7** demonstrates a clear trade-off between carbonisation temperature and biochar yield. While higher temperatures can improve biochar quality in terms of carbon content and stability, they significantly reduce the overall yield. From a process optimisation perspective, operating within a moderate temperature range of approximately 400–600 °C strikes a balance between achieving sufficient carbonisation and maintaining acceptable biochar yield. These findings are critical for renewable bio-coke production, where both material efficiency and fuel quality must be optimised to ensure economic and energy-efficient system performance.

Figure 8 presents the energy balance of the renewable bio-coke production system by comparing input energy, output energy, and recovered energy. The input energy required to operate the system is approximately 28–29 MJ per batch, which represents the external energy supplied for biomass drying, reactor heating, and auxiliary equipment. This relatively moderate input energy indicates that the system does not rely heavily on external fuel sources, particularly due to the integration of internal heat recovery and gas recycling mechanisms. The output energy, corresponding to the energy content of the produced bio-coke and useful by-products, is approximately 43–44 MJ per batch. This output energy is composed of multiple contributions, including approximately 24–25 MJ from the solid bio-coke fraction, 10–11 MJ from combustible process gases, and 7–8 MJ from recovered thermal energy. In addition, the recovered energy component alone amounts to approximately 50 MJ per batch, with roughly 25 MJ recovered as usable thermal energy and around 16–17 MJ derived from reusable process gases. Overall, the energy balance demonstrates that the total sound energy output and recovery exceed the external input energy by more than 70%, confirming the high energy efficiency and self-sustaining potential of the bio-coke production system.

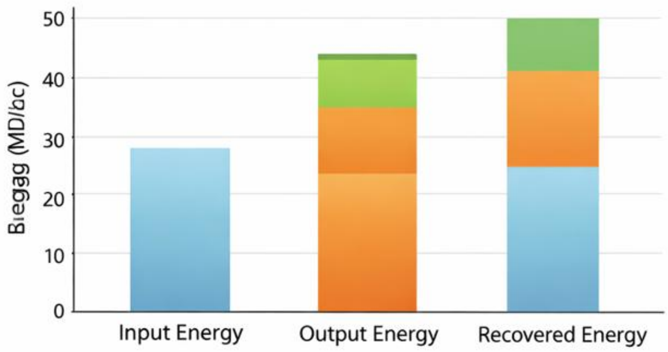

Figure 8. Energy balance in the bio-coke production system

These results indicate that effective integration of waste heat recovery and gas utilisation significantly improves the system's overall energy performance. The positive energy balance highlights the feasibility of using biomass-derived bio-coke as a renewable energy carrier while minimising external energy demand. Such an energy-efficient configuration is particularly advantageous for decentralised and community-scale applications, where energy self-reliance and operational cost reduction are critical factors for long-term sustainability.

Figure 9 illustrates the effect of compression pressure on the final properties of bio-coke, particularly in terms of briquette density and residual moisture ratio. At a compression pressure of 30 MPa, the bio-coke exhibits the highest solid fraction, with the effective briquette density reaching approximately 72–73%, while the residual moisture ratio remains relatively low at around 16–17%. This indicates that low compression pressure is sufficient to form stable briquettes; however, a noticeable amount of moisture remains within the bio-coke structure. As the compression pressure increases to 40 MPa, the briquette density decreases slightly to approximately 68–69%, while the residual moisture ratio rises to about 20–21%, suggesting enhanced compaction but partial moisture entrapment within the pores.

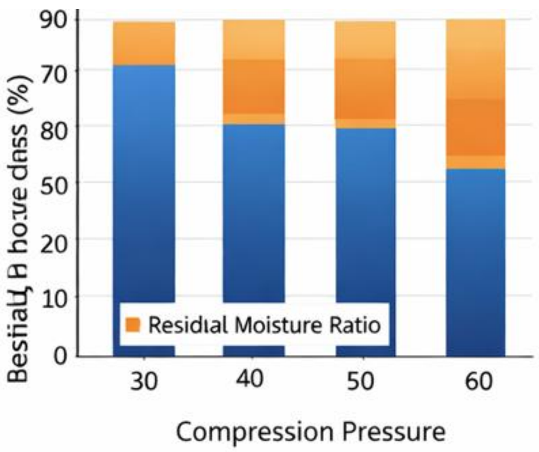

Figure 9. Final compression pressure

At higher compression pressures of 50 MPa and 60 MPa, a more pronounced change in bio-coke characteristics is observed. At 50 MPa, the briquette density stabilises at approximately 65–66%, while the residual moisture ratio rises to around 24–25%. When the pressure is further increased to 60 MPa, the briquette density drops significantly to about 55–56%, accompanied by a substantial increase in residual moisture ratio to approximately 32–33%. This trend indicates that excessive compression pressure may reduce effective porosity and hinder moisture release, leading to moisture retention within the compacted bio-coke matrix. Overall, the results demonstrate that compression pressure plays a critical role in determining the final quality of bio-coke. While increasing pressure enhances mechanical compaction, excessively high pressure can reduce briquette density and disrupt moisture distribution. An optimal compression pressure range of approximately 30–50 MPa appears to provide a balance between achieving sufficient structural integrity and minimising residual moisture content. These findings are essential for optimising the densification stage in renewable bio-coke production, ensuring high-quality fuel with improved handling properties and combustion performance.

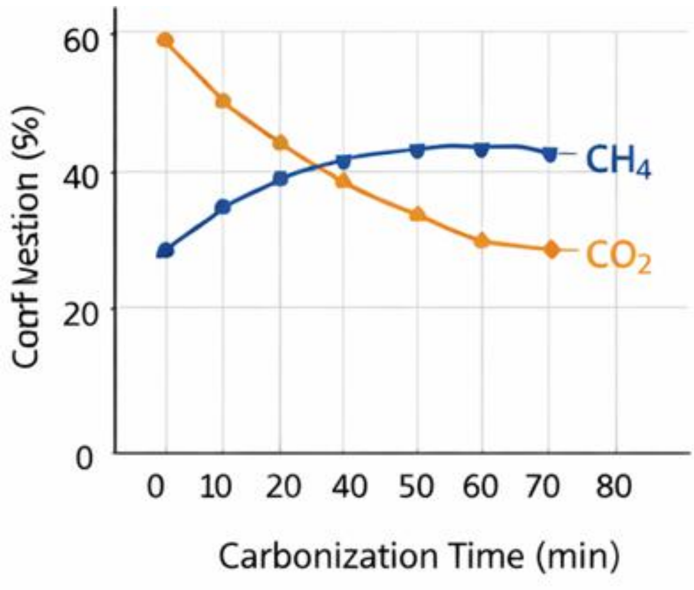

Figure 10. Gas composition from the biomass reactor

Figure 10 presents the evolution of gas composition, specifically methane (CH_4) and carbon dioxide (CO_2), during the biomass carbonisation process over a period of 80 minutes. At the initial stage (0 min), CO_2 dominates the gas composition at approximately 60%, while CH_4 accounts for only about 28–30%. This gas profile is characteristic of early-stage thermal decomposition, where moisture removal and decarboxylation reactions predominate, resulting in high CO_2 release. As carbonisation progresses, a clear shift in gas composition is observed. At around 20 min, CH_4 concentration increases to approximately 38–40%, while CO_2 decreases to about 45%. The crossover point occurs at approximately 35–40 min, when CH_4 and CO_2 concentrations are nearly equal at 40–42%. Beyond this point, CH_4 becomes the dominant gas component, reaching a peak concentration of approximately 44–45% at 50–60 min, while CO_2 declines to around 30–32%.

The increasing CH_4 concentration at later stages indicates enhanced secondary cracking and methanation reactions at elevated temperatures, which are favourable for energy recovery through gas recycling. The stabilisation of CH_4 levels beyond 60 min suggests that the carbonisation process has reached a steady-state regime. These findings confirm that controlling carbonisation time is critical for optimising combustible gas yield. Operating the reactor within the 40–60 min window provides a favourable balance between biochar formation and high-quality fuel gas production, supporting improved thermal efficiency and reduced external fuel demand in the renewable bio-coke production system.

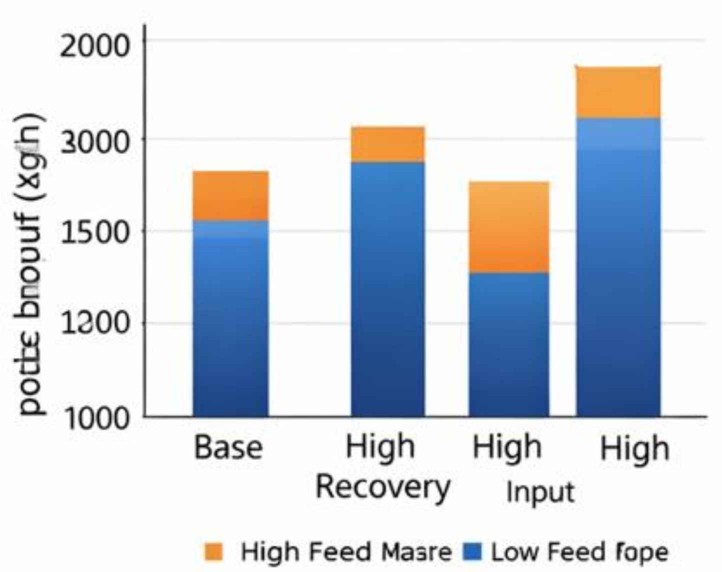

Figure 11. Biomass throughput rates in the operating scenario

Figure 11 compares biomass throughput rates under different operating scenarios: Base, High Recovery, High Input, and High, considering both low and high feed moisture conditions. Under the base scenario, the system processes approximately 1,550 kg/h of low-moisture biomass and about 1,700 kg/h under high-moisture feed conditions. When operating under the high recovery scenario, throughput increases to around 1,750 kg/h for low-moisture feed and approximately 1,900 kg/h for high-moisture feed, demonstrating the positive impact of enhanced heat recovery on processing capacity. In the high input scenario, throughput for low-moisture feed decreases to approximately 1,350 kg/h, while high-moisture feed reaches around 1,650 kg/h, suggesting that increased feed input without proportional energy recovery can reduce system efficiency. The highest throughput is achieved under the high operational scenario, where low-moisture feed reaches approximately 1,900 kg/h, and high-moisture feed exceeds 2,050 kg/h. These findings indicate that optimal integration of heat recovery, gas recycling, and feed management significantly enhances biomass processing capacity. Overall, the results confirm that operating the system at high efficiency maximises throughput while maintaining stable, energy-efficient bio-coke production.

This study introduces a novel integrated approach to renewable bio-coke production by systematically combining biomass drying behaviour, reactor temperature stratification, gas recycling, waste heat recovery, and densification performance into a single energy-efficient system. Unlike previous studies that typically focus on isolated process stages, the present work demonstrates the quantitative interdependence between operational parameters across the entire production chain. The results reveal that optimising moisture reduction to below 10–15%, maintaining carbonisation temperatures within 400–600 °C, and increasing gas recycling ratios to 85–90% can collectively reduce external fuel consumption by nearly 45% while achieving waste heat recovery efficiencies exceeding 75%. This holistic integration of processes represents a significant advancement in biomass-to-solid-fuel conversion efficiency.

Furthermore, this research provides new insights into the dynamic evolution of gas composition and material throughput under different operating scenarios. The observed shift in gas composition, with CH_4 increasing from approximately 30% to over 44% while CO_2 decreases from about 60% to below 30%, highlights the potential of in-situ gas utilisation as an internal energy source rather than a by-product. In addition, the analysis of compression pressure and biomass throughput demonstrates an optimal balance between bio-coke density, residual moisture, and system productivity, enabling scalable operation without compromising fuel quality. These findings establish a technically robust and scalable framework for renewable bio-coke production, making a distinctive contribution to sustainable solid-fuel development and decentralised energy systems.

4. Conclusion

This study demonstrates the technical feasibility and energy efficiency of an integrated renewable bio-coke production system through a comprehensive evaluation of its key process stages. Biomass drying effectively reduced moisture content from approximately 45% to 7–8% within 40 minutes for high-moisture feedstock, ensuring stable downstream carbonisation. Temperature profiling during carbonisation showed controlled, progressive heating, with reactor temperatures reaching 580–590 °C at the top, ~540 °C at the middle, and ~490 °C at the bottom after 90 minutes, all within the optimal carbonisation range. Increasing the gas recycling ratio from 10% to nearly 90% reduced external burning fuel consumption from about 58–59% to 32–33%, highlighting the strong contribution of internal gas utilisation. The system also achieved high thermal and material efficiency. Waste heat recovery efficiency improved from approximately 62–63% at low operational levels to 77–78% at the highest level, while the energy balance indicated that sound output and recovered energy (~43–50 MJ per batch) exceeded the external input energy (~28–29 MJ per batch) by more than 70%. Biochar yield decreased from ~35–36% at 200 °C to ~9–10% at 900 °C, indicating a clear trade-off between yield and carbonisation severity, with an optimal operating window identified at 400–600 °C. Overall, these findings confirm that the proposed system offers a high-efficiency, low-fuel, and scalable pathway for renewable bio-coke production, suitable for decentralised and community-scale energy applications.

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