Integrated Exergetic and Exergoeconomic Evaluation of Teak, Matoa, and Merbau Wood Waste for Charcoal Production in a Laboratory-Scale Modified Fixed-Kiln Reactor

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ABSTRACT

This study introduced a batch-level exergy-exergoeconomic diagnostic framework for evaluating charcoal production in a laboratory-scale, modified fixed-kiln reactor. Unlike yield- based or energy-only assessments, the proposed approach, considers exergy destruction and its associated economic penalty, allowing for direct comparisons of feedstock performance under identical operating and cost conditions. Three wood residues were examined: teak (*Tectona grandis*), matoa (*Pometia pinnata*), and merbau (*Intsia spp*.). The analysis revealed that merbau is the superior feedstock, achieving the highest exergetic efficiency (43.2%) and char yield (92.3%) at the lowest peak temperature (285°C). This is in contrast to matoa, which achieved 35.0% efficiency at 429°C, and teak, which achieved 32.4% efficiency at 374°C. Economically, the study revealed that feedstock selection significantly impacts costs: Merbau exhibited the lowest specific production cost ($1.08/kg) and the lowest cost of exergy destruction ($0.47 per batch). In contrast, teak produced the highest costs ($1.91/kg; $0.64 destruction) due to substantial internal irreversibility (82.3 MJ/batch). By linking thermodynamic irreversibility directly to cost formation, this methodology shows that maximizing the reactor temperature does not guarantee efficiency. It also provides a metric that can be used to select the most suitable feedstock for small-scale biomass carbonization systems.

Keywords-charcoal production; exergy analysis; exergoeconomic assessment; fixed-kiln reactor; wood waste

I. INTRODUCTION

Traditional charcoal production is a process that converts biomass into a usable energy source, relying on wood pyrolysis, in which biomass is thermally decomposed under oxygen-deficient conditions, releasing volatile compounds and leaving behind a carbon-rich solid residue [1]. Conventional kilns typically yield only 19%–20% charcoal by mass, implying that up to 60% of wood's inherent energy content is dissipated during processing [2, 3]. Even under improved industrial conditions, reported yields are limited to 25%–37%, indicating that the inefficiency is intrinsic to the carbonization process rather than solely a function of technological simplicity. These losses intensify pressure on forest resources and accelerate forest degradation when the demand for charcoal is met by increased biomass extraction [1, 4, 5]. In addition, incomplete thermal decomposition results in the release of CO_2, CO, and CH_4, which degrade air quality while reducing charcoal yield and consistency [6, 7]. Charcoal production is dependent on energy, and the renewability of the raw materials used cannot provide sustainability. Authors in [8, 9] showed that identifying primary loss mechanisms can substantially improve biomass usage efficiency when mitigation strategies are appropriately targeted. Improving charcoal production efficiency also supports carbon-neutral energy strategies by enabling the valorization of biomass residues and reducing dependence on fossil fuels [10, 11]. Exergy-based methods offer a suitable analytical framework for addressing these challenges because they distinguish between energy quantity and quality [12]. Exergy analysis has been applied to various biomass conversion systems, such as rice husk pyrolysis, banana waste processing, and molasses-based ethanol production. In these systems, exergy analysis has proven effective in identifying irreversible losses and performance bottlenecks [13–16]. Coupling exergy analysis with an economic evaluation yields exergoeconomic analysis, which clarifies how thermodynamic irreversibility translates into monetary penalties through increased auxiliary fuel demand, reduced product recovery, or both. This combined perspective enables interpreting performance degradation as not only a physical inefficiency, but also a direct contributor to elevated production costs and environmental burden [5, 17]. However, the application of exergy and exergoeconomic analyses to traditional charcoal production is limited. Consequently, even though they are relevant to small and laboratory-scale operations, batch-level transformations occurring during a single carbonization cycle are frequently overlooked. Furthermore, comparative assessments of different wood feedstocks are often conducted under different operating or cost assumptions, which makes it difficult to attribute performance directly. The economic implications of exergy destruction, particularly its impact on the cost of charcoal production, are rarely quantified. This leaves stakeholders without a clear basis for evaluating process upgrades or feedstock selection [6, 8, 16, 18]. The present study uses batch-level exergy and exergoeconomic analyses to address the shortcomings of a laboratory-scale, modified fixed-kiln reactor that utilizes three locally sourced wood residues: teak (*Tectona grandis*), matoa (P*ometia pinnata*), and merbau (*Intsia spp*). The objectives are threefold: first, to quantify the exergy inputs, useful exergy outputs, and internal exergy destruction of individual 2.15 kg carbonization batches, second, to compare the performance of the feedstocks under identical reference states, instrumentation, and economic boundaries, ensuring that the observed differences reflect the intrinsic characteristics of the materials and processes rather than external assumptions, and third, to express the destruction of exergy as an explicit economic penalty per batch and per unit mass of charcoal. This provides metrics that are directly relevant to decisions regarding feedstock selection and the improvement of low-cost processes.

II. MATERIALS AND METHODS

The exergy and exergoeconomic assessments reported below are based on laboratory experiments conducted using a modified fixed kiln. The experimental sequence included preparing the feedstock, assembling and instrumenting the kiln, controlling the heating process (i.e., carbonization), acquiring the data, and subsequently analyzing the resulting charcoal products for exergy and economic value.

A. Feedstock and Preparation

The present study examined three wood species, as shown in Figure 1: tectona grandis (teak), pometia pinnata (matoa), and intsia spp. (merbau). The wood residues from construction were sawn into uniform 5 cm × 5 cm × 5 cm cubes. Each batch consisted of 2.15 kg of wood and was dried to an approximate moisture content of 8% to ensure consistent heat transfer characteristics. The weights of the wood and gas fuel were measured on a digital scale with a resolution of ±0.1 g, as depicted in Figure 2.


(a) (b) (c)

Fig. 1. Wood chip sample: (a) teak, (b) matoa, (c) merbau.

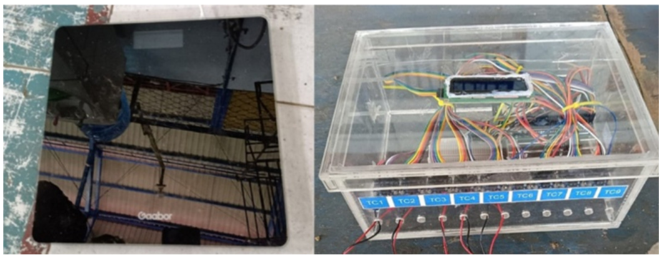

Fig. 2. Digital scale and temperature datalogger with a type K probe.

B. Fixed-Kiln Design and Instrumentation

The carbonization system consisted of a vertical, fixed-bed retort made from a modified 12-kg LPG cylinder (40 cm high by 29.5 cm in diameter) to ensure standardized control of the volume, as presented in Figure 3. Five K-type thermocouples were mounted at 15-cm intervals along the central axis of the kiln to capture the axial thermal gradient. Data acquisition was performed using an Arduino Mega microcontroller interfaced with ten Adafruit MAX6675 thermocouple amplifiers with a reported accuracy of ±1.1%. The reactor was externally heated using a commercially available LPG gas stove, and fuel consumption was monitored via a digital scale with a resolution of ±0.1 *g*. Charcoal characterization was carried out at the PUSTARHUT Integrated Laboratory in Bogor, Indonesia, in the form of proximate and elemental analysis (EDX/EDS), according to the following ASTM standards: D3173 (moisture content), D3174 (ash content), D3175 (volatile matter), and D3172 (fixed carbon).

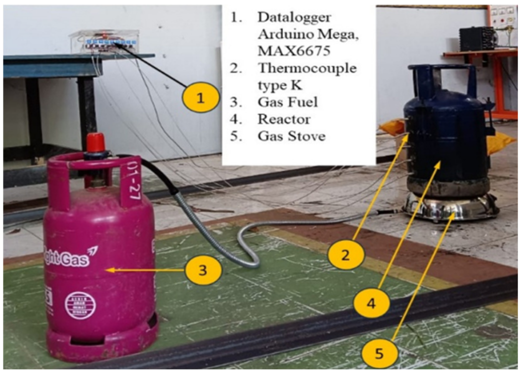

Fig. 3. Modification and arrangement of the thermocouple probes.

C. Experimental Setup

Each test involved loading 2.15 kg of wood into the fixed-kiln, sealing it, and heating it with gas fuel burners. The gas fuel consumption per batch, measured by mass difference, was 1.6 kg for teak, 1.2 kg for matoa, and 1.3 kg for merbau. Temperature data were collected continuously for 4 h per test. After heating, the kiln was left to cool with restricted airflow to prevent spontaneous ignition. Then, the charcoal was removed, weighed, and sampled for proximate analysis.

D. Reference State and Assumptions

All thermodynamic calculations were performed using a reference environment with T_0 = 25 °C (298.15 K) and P_0 = 1 atm (101.325 kPa). The calculations were based on the following assumptions: steady-state behavior during the carbonization phase, negligible kinetic and potential exergy terms, treating pyrolysis gases as ideal gases, and adopting syngas composition and a certain Higher Heating Value (HHV) from the literature, where direct measurements were unavailable. The cost inputs (feedstock price, gas fuel price, and kiln amortization) reflect local market estimates and are explicitly stated in the exergoeconomic section. These cost parameters were based on market data: \$0.10/kg for wood, \$0.45/kg for gas fuel, and \$0.50/batch for kiln amortization. Although the fixed kiln operates in batch mode, the thermodynamic model assumes a quasi-steady thermal phase during the active carbonization window. This period is defined as the interval following the initial moisture evaporation stage (approximately 100 °C) and preceding the final cooling phase. During this period, the reactor temperature and volatile release rates remain relatively stable. This simplification enables the application of steady-flow exergy balance equations to the control volume.

E. Exergy and Exergoeconomic Analysis

The total exergy input ($E_{x,in}$) and summed chemical exergy of the wood and fuel were calculated using β = 1.047 for the conversion from HHV:

$$E_{x,in} = (m_{wood} \times HHV_{wood} \times \beta_{wood}) + (m_{fuel} \times HHV_{fuel} \times \beta_{fuel}) \quad (1)$$

where m is the fuel mass. The useful exergy output ($E_{x,out}$) comprises the chemical exergy of charcoal and exergy of syngas as:

$$E_{x,out} = (m_{char} \times HHV_{char} \times \beta_{char}) + E_{x,syngas} \quad (2)$$

The chemical exergy of the syngas was estimated using the molar fractions (H_2: 22%, CO: 35%, CH_4: 14%, CO_2: 18%, H_2O: 11%) and the standard chemical exergies of each species, as [13, 14]:

$$E_{x,syngas} = \eta_{syngas} \sum_i x_i \, ex_i^{chem} \quad (3)$$

where $\dot{n}_{syngas}$ is the total molar flow of the gas stream, x_i is the molar fraction of species i, and ex_i^{chem} the standard chemical exergy of species i. This composition was assumed to be consistent across the three feedstocks, based on average slow pyrolysis biomass values. The exergy efficiency and exergy destruction, are [19, 20]:

$$\eta_{ex} = \frac{E_{x,out}}{E_{x,in}} \quad (4)$$

$$E_D = E_{x,in} - E_{x,out} \quad (5)$$

For the exergoeconomic evaluation, monetary values were assigned to the inputs and the exergy that was destroyed. The cost of exergy destruction (C_D) is [18, 21]:

$$C_D = c_{fuel} \times E_D \quad (6)$$

where the average specific cost of the input exergy (c_{fuel}) is [22]:

$$c_{fuel} = \frac{\text{Cost}_{wood} + \text{Cost}_{fuel}}{E_{x,in}} \quad (7)$$

III. RESULTS AND DISCUSSION

A. Temperature Profiles and Carbonization Process

As illustrated in Figure 4, the measured kiln temperature profiles exhibit the expected three-stage behavior: a slow initial heating period during water vapor evaporation, a rapid volatile decomposition peak, and a slow cooling stage to prevent re-ignition. The onset of volatile decomposition occurs at approximately 274.8 °C (116.4 min) for merbau, 356.7 °C (118.6 min) for teak, and 413.6 °C (155.6 min) for matoa. Since all feedstocks were pre-dried to a standardized moisture content of approximately 8% prior to carbonization, the observed variations in thermal profiles are primarily due to the materials' intrinsic properties, such as density, thermal conductivity, and volatile-to-fixed carbon ratio, rather than to moisture content alone. For example, the onset of volatile decomposition occurred at a significantly lower temperature (274.8 °C) for merbau than for matoa (413.6 °C). This disparity suggests that merbau has superior heat transfer characteristics and a chemical composition that allows for lower activation energy for pyrolysis. In contrast, matoa requires greater thermal driving forces to overcome its internal heat transfer resistance, despite having the same initial moisture level. During the product collection stage, the kiln was cooled to prevent spontaneous ignition. The charcoal was then removed, weighed, sorted by quality, as presented in Figure 5, and packaged.

B. Exergy Performance

Table I summarizes the exergy inputs and outputs. Merbau emerged as the thermodynamically superior feedstock, achieving an exergetic efficiency of 43.2%. Matoa followed with 35.0%, and teak trailed behind with 32.4%. Exergy destruction was the dominant term in the energy balance for all species, ranging from 60,369 kJ to 82,269 kJ. This indicates that most of the input energy was dissipated through heat loss and chemical irreversibility rather than stored in the product. The calculated exergy efficiencies were 43.2% for merbau, 35.0% for matoa, and 32.4% for teak. Since the combined instrumental uncertainty is minimal (mass precision ±0.1 g and temperature accuracy ±1.1%), the 10.8% differential significantly exceeds the margin of error, confirming that merbau's superior performance is due to its intrinsic properties rather than measurement variability. Exergy destruction was the largest term in all cases (60,368.5 kJ–82,269.3 kJ), indicating substantial irreversibility of heat loss, incomplete recovery of volatile exergy, and chemical irreversibility during pyrolysis. Merbau's superior performance resulted in higher useful exergy and lower destruction, which is due to the favorable combination of fixed carbon and a lower moisture/volatile ratio, reducing external heat and thermal gradients. Conversely, teak was the least profitable feedstock based on the results of this study due to higher fuel gas consumption and greater exergy destruction.

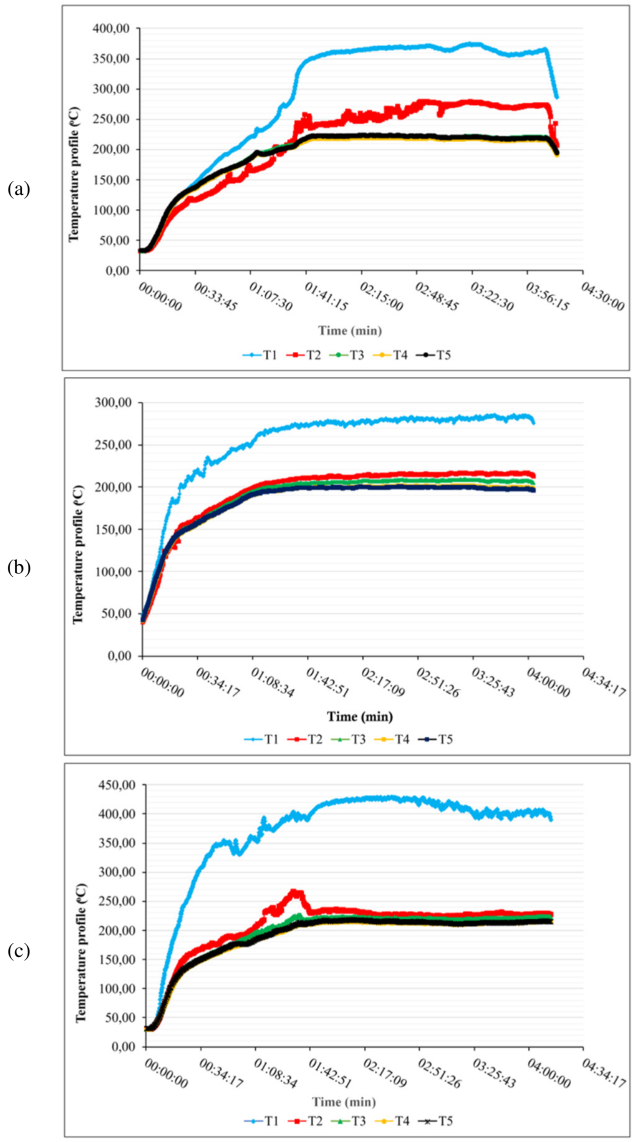

Fig. 4. Temperature profile carbonization fixed-kiln: (a) teak wood, (b) merbau wood, and c) matoa wood.

(a) (b) (c)

Fig. 5. Carbonized wood products: (a) teak, (b) matoa, and (c) merbau.

TABLE I. EXERGY PERFORMANCE OF CHARCOAL PRODUCTION

Parameter	Teak	Matoa	Merbau
Initial weight (kg)	2.15	2.15	2.15
Final charcoal weight (kg)	0.75	0.85	1.2
Fuel gas consumption (kg)	1.6	1.2	1.3
Maximum temperature (°C)	374.07	428.77	284.89
Char yield (%)	46.88	70.83	92.31
HHV charcoal (MJ/kg)	32.00	25.03	29.57
Exergy input (wood) (kJ)	38,566.5	38,566.5	38,566.5
Exergy input (gas fuel) (kJ)	83,160	62,370	67,695
Total exergy input (kJ)	121,726.5	100,936.5	106,261.5
Exergy output (charcoal) (kJ)	25,128	22,251	37,100
Exergy output (syngas) (kJ)	14,329.2	13,122	8,793
Total useful exergy output (kJ)	39,457.2	35,373	45,893
Exergetic efficiency (%)	32.4	35.0	43.2
Exergy destruction (kJ)	82,269.3	65,563.5	60,368.5

Figure 6 shows the energy flows of the three feedstocks within a fixed clinal configuration. The chemical exergy of the biomass remained constant at 38,566.5 kJ for all tests. However, the exergy contribution of the gaseous fuel varied from 62,370 kJ to 83,160 kJ. Therefore, the total exergy input differed based on the feedstock input. Quantitatively, the partitioning of input exergy differed significantly by species. Teak wood had a total input of 121,726.5 kJ, of which 25,128 kJ and 14,329 kJ appeared as charcoal and syngas, respectively. This left 82,269 kJ wasted, accounting for 67.6% of the total input. Matoa wood used less gas fuel (a total of 100,936.5 kJ) and produced 22,251 kJ of charcoal and 13,122 kJ of syngas. In this case, 65,563.5 kJ (65.0%) of the input exergy was wasted. Merbau wood had the best performance with a total input of 106,261.5 kJ, useful outputs of 37,100 kJ (charcoal) and 8,793 kJ (syngas), and 60,368.5 kJ (56.8%) of exergy destruction, yielding the highest useful exergy fraction among the three species.

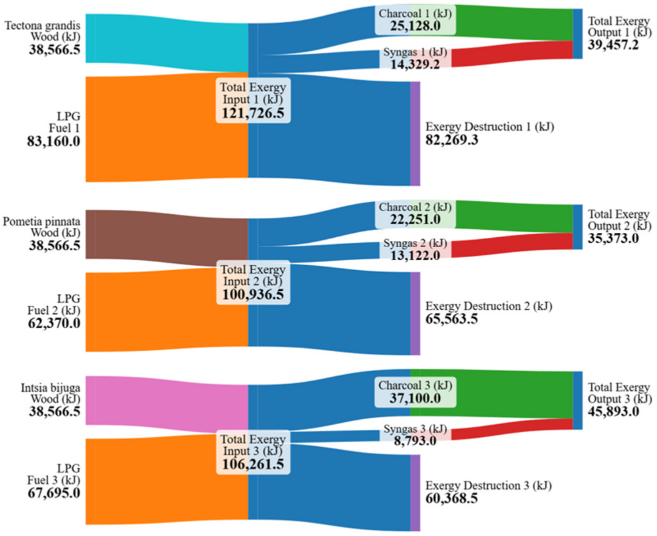

Fig. 6. Carbonization exergy flow.

Merbau wood exhibited high carbonization efficiency (92.31%), but much lower exergy efficiency (43.2%), suggesting differences in energy quantity and quality. It also exhibited the least exergy destruction (60,368.5 kJ) and the greatest useful exergy recovery and char yield (1.20 kg) at a lower temperature (284.9 °C). In contrast, teak wood exhibited the greatest exergy destruction (82,269.3 kJ) and the lowest exergy efficiency (32.4%), partly due to the increased use of gaseous fuel (1.6 kg per batch). The main contributors to exergy destruction in a fixed furnace are irreversible chemical processes during pyrolysis, heat loss to the environment, and unrecovered exergy in volatile gases. In contrast, an integrated conversion system yields much higher exergy efficiency [23, 24]. Across combustion, heat loss, and carbonization, many basic charcoal technologies demonstrate poor exergetic performance. Earth-pit kilns typically report efficiencies ranging from 15% to 35%, while more advanced brick or metal retort designs generally perform better. Field and experimental reports indicate that, under favorable conditions, improved designs can approach the 35%-45% range. Therefore, targeted upgrades can reduce energy waste and emissions [4, 6, 25-30]. In the context of global charcoal production technologies, as displayed in Table II, the modified fixed-kiln is a significant intermediate upgrade. Traditional earth-pit and brick kilns operate at low exergetic efficiencies of 15%-30% due to uncontrolled heat dissipation and air leaks. In contrast, the reactor in this study achieved efficiencies of 32.4%-43.2%. This aligns with the best-case "improved" retort designs reported in recent literature (26%-35%), confirming that modest capital interventions, such as insulation and batch control, can significantly reduce thermodynamic waste. However, the system still falls short of engineered pyrolysis or gasification plants, which reach efficiencies of 57%-85% by fully recovering syngas for cogeneration [4, 17, 18, 23, 31]. Thus, the modified kiln is a pragmatic, scalable solution for decentralized producers who cannot afford industrial pyrolysis units but require a higher efficiency than that of traditional mounds.

TABLE II. COMPARATIVE EXERGETIC EFFICIENCY OF THE CHARCOAL SYSTEMS

Technology	Exergetic efficiency (%)	Remarks	Ref.
Earth-pit charcoal kiln	15–30	Traditional, low control, and high heat loss	[25, 32]
Brick charcoal kiln	15–34	Semi-enclosed with moderate insulation	[26–28]
Metal/retort kiln	26–35	Improved kiln and improved airflow control	[28–30]
Improved charcoal kilns (best cases reported)	35–50	Optimization of operation and insulation	[25, 32]
The fixed-kiln charcoal system (this study)	32.4–43.2	Laboratory-scale, gas fuel-assisted	This study
Biomass pyrolysis reactors	57–85	Engineered systems under controlled conditions	[18, 23, 31]

These comparisons suggest that the fixed kiln approach behaves like an "upgraded" traditional system, improving useful exergy recovery significantly, though it does not match the performance of pyrolysis or gasification platforms. Targeted, low-cost modifications, such as insulation, combustion control, and syngas capture, are promising ways for small-to-medium producers to improve energy recovery, reduce hidden costs, and lessen environmental impact.

C. Exergoeconomic Performance

Table III presents the exergoeconomic analysis results for the three feedstocks, including unit-batch cost details and irreversible economy quantification. The cost of the raw material (0.215 $ per batch) and the capital cost (0.50 $ per batch) remained consistent across all cases, reflecting the cost of biomass inputs and kiln investment. However, gas fuel consumption varied: 1.6 kg for teak, 1.2 kg for matoa, and 1.3 kg for merbau, producing fuel costs of $0.72, $0.54, and $0.59 per batch, respectively. The exergoeconomic results showed total production costs of approximately $1.255 (matoa wood), $1.435 (teak wood), and $1.30 (merbau wood) per batch. Charcoal weight yielded specific costs of approximately 1.91 USD/kg (teak), 1.48 USD/kg (matoa), and 1.08 USD/kg (merbau). Merbau wood had the lowest unit cost, mainly due to its superior charcoal yield. Teak had the highest cost of exergy destruction (0.642 $ per batch), while merbau wood had the lowest (0.468 $ per batch). From an industrial perspective, exergoeconomic analysis transforms abstract thermodynamic losses into concrete financial metrics. Although the capital and raw material costs were fixed, the specific exergy cost of the final product varied significantly: $1.08/kg for merbau versus $1.91/kg for teak. This shows that producing charcoal from thermodynamically inefficient feedstocks, such as teak, nearly doubles the unit production cost. Furthermore, the cost of exergy destruction, representing the financial penalty of waste, ranged from $0.47 (merbau) to $0.64 (teak) per batch, accounting for approximately 35%-45% of the total production cost. For Small-to-Medium Enterprises (SMEs), these metrics demonstrate that "waste" is an economic liability as well as an environmental issue, justifying investment in improved feedstock selection and reactor insulation.

TABLE III. EXERGOECONOMIC PERFORMANCE (PER BATCH)

Parameter	*Teak*	*Matoa*	*Merbau*
Cost of wood per batch ($)	0.215	0.215	0.215
Cost of gas fuel per batch ($)	0.72	0.54	0.585
Capital cost per batch ($)	0.5	0.5	0.5
Total production cost per batch ($)	1.435	1.255	1.30
Cost of exergy destruction ($)	0.642	0.501	0.468
Specific exergy cost of charcoal ($/kg)	1.913	1.476	1.083

The choice of wood species dictates the cost formation mechanism due to its intrinsic thermodynamic properties. Merbau wood has the most favorable exergoeconomic profile, demonstrating the highest carbonization efficiency (92.31%), the lowest exergy destruction (60,369 kJ), and the lowest specific exergy cost ($1.08/kg). These results are directly linked to its proximate composition. With moderate volatile matter content (31.43%) and fixed carbon content (67.79%), Merbau wood achieved optimal carbonization at a relatively low peak temperature (284.9°C). This minimized the thermal exergy destruction associated with high-temperature gradients. In contrast, teak exhibited a "high-quality, high-cost" paradox. Although it generated charcoal with the highest fixed carbon content (79.02%), the process incurred the highest specific cost ($1.91/kg) and cost of exergy destruction ($0.64/batch). This confirms that the cost of producing teak charcoal is driven not by the price of the raw material (which was fixed), but by the high fuel demand (1.6 kg) required to drive the reaction. This results in excessive thermodynamic irreversibility. Meanwhile, matoa exhibited an intermediate performance; its high peak temperature (428.8 °C) did not translate into economic efficiency, resulting in a specific cost of $1.48/kg due to a lower fixed carbon yield (44.56%) and substantial heat loss. These comparisons validate that minimizing exergy destruction via feedstock selection is a more important economic lever than simply maximizing reactor temperature. Analysis of traditional charcoal production methods reveals significant operational and exergetic deficiencies. Unlike improved retort systems, traditional earth-pit kilns have low biomass-to-charcoal conversion efficiencies of 15%-30%, mainly due to heat dissipation and incomplete combustion [25, 32, 33]. Additionally, the absence of process control in traditional methods leads to prolonged production cycles of 7–14 days and inconsistent calorific values of 25–32 MJ/kg. This contrasts with the consistent quality and shorter production cycles of 3–5 days in modern kilns. These operational inefficiencies increase labor costs and intensify greenhouse gas emissions. Thus, minimizing irreversibility through better insulation and kiln design is essential for economic and environmental sustainability [25, 32]. Additionally, traditional methods lack process control, resulting in inconsistent product quality. For example, charcoal produced in earth pit kilns showed significant variability in calorific value (25–32 MJ/kg), compared to controlled systems like retort kilns, which achieved a narrower range (28–30 MJ/kg) [28, 32]. Another identified inefficiency was the prolonged production cycle of traditional kilns, which lasted 7–14 days compared to improved methods that can achieve carbonization in 3–5 days [32]. The extended duration increases labor costs and contributes to higher greenhouse gas emissions, particularly methane (CH_4) and carbon dioxide (CO_2). The economic evaluation of traditional methods requires minimal investment, typically less than $50 per kiln [34]. However, long-term operational inefficiencies impact overall costs. For instance, the cost of raw materials per ton of charcoal produced may increase by 20-30% due to incomplete carbonization and biomass waste [18].

D. Policy and Practical Recommendations

Improving the sustainability and efficiency of traditional charcoal production requires coordinated technical upgrades and supportive policy frameworks that utilize small- and medium-scale biomass. This study's findings indicate that substantial exergetic losses persist in conventional fixed-kiln systems due to uncontrolled heat transfer, inefficient combustion, and suboptimal use of feedstock [35]. Addressing these weaknesses does not require radical technological shifts. Instead, small, targeted interventions can yield meaningful gains. From a technical perspective, transitioning from rudimentary methods to improved kiln design is the most effective immediate measure. While traditional earth-pit kilns operate at low exergetic efficiencies of 15%-30%, the modified fixed-kiln in this study achieved efficiencies of 32.4%-43.2%, effectively bridging the gap to industrial pyrolysis reactors (57%-85%). Subsidizing improved kilns is supported by the measurement of exergy destruction, which remains the largest term in the energy balance (60,368–82,269 kJ per batch). Since this destruction is primarily driven by thermal loss and unrecovered volatiles, policies that promote kilns with insulation and basic airflow control can mitigate the dominant source of thermodynamic inefficiency directly [4, 32, 33]. Practical strategies must prioritize feedstock quality because moisture content and density significantly impact performance. A specific comparison between species supports this recommendation: teak incurred 36% higher exergy destruction (82,269 kJ) than merbau (60,368 kJ) due to the higher fuel demands required for carbonization. Consequently, policies should encourage pre-drying biomass and selecting high-density residues, such as merbau. This is an economic necessity as well as a technical preference, as shown by the exergoeconomic analysis. Using inefficient feedstocks nearly doubles the specific production cost (1.91 $/kg for teak versus 1.08 $/kg for merbau). Routine application of exergetic analysis should be standard for technology assessment programs. By quantifying the cost of exergy destruction, which was found to be between 0.47 and 0.64 dollars per batch in this study, practitioners can identify "hidden" economic losses that mass-yield metrics miss. Capacity-building initiatives should train local producers to use these metrics to audit their operations and ensure that efficiency upgrades offer a clear Return on Investment (ROI) [16, 17, 21]. Capacity-building initiatives are crucial at the policy level. Training programs that familiarize local producers with improved kiln operations, basic process controls, and feedstock selection can accelerate technological uptake and reduce resistance to change. Evidence from improved charcoal programs in sub-Saharan Africa suggests that, when paired with modest financial incentives, knowledge transfer significantly improves adoption rates and long-term performance outcomes [36]. Such approaches tend to be more effective than regulatory enforcement in informal and semi-formal production sectors. Charcoal production policies must also integrate sustainable biomass sourcing. Encouraging the use of wood waste, construction residues, and non-merchantable biomass reduces pressure on natural forests while maintaining feedstock availability [1, 2, 17]. Aligning charcoal production with local land-use practices stabilizes supply chains and improves outcomes through community-managed plantations and residue-based initiatives. Finally, incorporating charcoal production into broader national energy and climate strategies can help legitimize investments in efficiency improvements. While traditional charcoal systems are unlikely to achieve high exergetic efficiencies for advanced gasification or combined-cycle technologies, well-designed improved kilns can achieve efficiencies of 57%-85% [4, 17, 18, 23]. Therefore, supporting gradual innovation in this sector is a practical way to transition to cleaner energy in regions where charcoal is used for household and industrial purposes.

IV. CONCLUSIONS

This study showed that charcoal production performance is primarily dictated by feedstock-dependent exergy destruction rather than nominal energy input or peak operating temperature. Under identical operational and economic conditions, merbau (*Intsia spp.*) exhibited the lowest irreversibility. This resulted in the highest exergetic efficiency (43.2%) and the lowest specific production cost ($1.08/kg), despite merbau operating at a lower peak carbonization temperature than matoa (*Pometia pinnata*) or teak (*Tectona grandis*). Beyond laboratory metrics, these findings have significant economic implications for small-scale and rural charcoal enterprises. The results confirm that prioritizing thermodynamically efficient wood species is a zero-capital strategy that can reduce production costs by nearly 43% (compared to 1.91 $/kg for teak). Decentralized producers who cannot afford advanced pyrolysis reactors can enhance economic viability and reduce environmental waste by selecting feedstocks with favorable exergy-density properties rather than simply increasing the kiln temperature. While this study establishes a robust diagnostic framework, future work should expand beyond current assumptions about volatile composition. Integrating direct syngas characterization (e.g., via gas chromatography) is crucial to reducing uncertainty in chemical exergy cost allocation and allowing for more precise by-product valuation. Though currently limited to laboratory-scale data, this exergoeconomic approach can be fully transferred to industrial settings, offering a rigorous tool for auditing process efficiency in larger commercial operations.

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