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Biochar and Energy Production from Rice Husk and Corncob in Karawang: A Techno-Enviro Analysis

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ABSTRACT

The world is facing increasing challenges in sustainable energy production and waste management. This study presents a techno-environmental analysis of biochar and energy production from rice husks and corncob in Karawang, Indonesia, through co-gasification. A parametric study using Aspen Plus simulation shows that biochar yield is sensitive to temperature and equivalence ratio (ER). Specifically, corncob gasification at 450 degrees Celsius yields the highest amount of biochar. Additionally, the study finds that increases in temperature and ER lead to higher syngas and lower heating value (LHV). A life cycle assessment was conducted to evaluate three scenarios: 100% rice husk, 100% corn cob, and a 50% combination of rice husk and corncob for biochar application as carbon sequester. The findings indicate that the 50% mixing ratio has the most positive impact on global warming potential, with a carbon offset of -170,134 kg CO_2eq per 1000 kg of biochar applied to soil. The results provide valuable insights into environmental impacts of utilizing these agricultural residues for renewable energy generation and biochar production.

Keywords: Co-gasification; LCA; Aspen plus; Global Warming Potential;

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INTRODUCTION

Food, energy, and water are fundamental needs for every human being. Global projections indicate that there will be an increase in the need for the WEF (Water, Energy, Food) Nexus in the coming decades due to population growth, climate change, economic development, urbanization, international trade, and changes in culture and technology that also have an impact (FAO, 2011) . Food provision is closely linked to the agriculture industry, which is strongly related to soil. However, the FAO reports that 33% of the world's soil has been degraded, and it is estimated that by 2050, this could reach 90% (FAO & ITPS, 2015) . Soil degradation will reduce the quantity and quality of crops. This issue needs to be addressed to maintain the Nexus's resilience and solve the environmental degradation problems caused by human activities. One option that can be implemented is the use of biochar.

Biochar is a carbon-rich solid produced through the thermal decomposition of biomass under low-oxygen conditions (Lehmann & Joseph, 2009). Research on the benefits of biochar has significantly advanced recently, with scientists recognizing its vast potential. These benefits include soil conditioning, carbon storage, wastewater treatment, plant nutrition, and reducing pathogenic bacteria in the soil (Thapar Kapoor & Shah, n.d.; Y. Zhang et al., 2021) These advantages arise from biochar's characteristics, such as high porosity and surface area, as well as good cation exchange capacity and water retention ability. Additionally, the production process of biochar yields by-products such as bio-oil and non-condensable gas (NCG) or syngas. These by-products can be used for electricity or heat generation. Since the raw materials come from biomass, this energy can be considered clean energy (Kumar Mishra et al., 2023). If the biochar system is utilized effectively, it can address the WEF Nexus, improve clean water supply, generate clean energy, and maintain food security by enhancing soil conditions.

Rice is a staple food for the Asian continent, with 90% of rice being produced and consumed in this region. In Indonesia, the Central Statistics Agency recorded that 9.7 million kg of dry grain was produced in 2021 (BPS, 2021). About 20% of this dry grain is rice husk, meaning Indonesia produced 1.94 million kg of rice husk in 2021. However, in practice, most of the husk is burned directly (open combustion) by farmers (Imtiaz Anando et al., 2023; Peanparkdee & Iwamoto, 2019). This practice is considered ineffective for rice husk waste management because direct burning produces harmful particulates for the environment and releases carbon monoxide and carbon dioxide directly into the atmosphere. Therefore, an idea that can be implemented is using rice husks as a raw material for biochar. Karawang, A regency in West Java, is an area that produces rice and is close to the metropolitan area of Jakarta. In 2022, the productivity of rice paddy in Karawang is 5,675 kg/ha. The utilization of biomass as a sustainable energy resource is contingent upon its accessibility. Motivated by the prospect of employing rice husks in Karawang, it is imperative to identify other prevalent agro-industrial waste sources within the region. Corn is the second most extensively cultivated crop after rice. According to Statistic data in 2023, the production reached 74.75 tons with a harvested area of 80,000 hectares (BPS Karawang, 2016).

Gasification is the conversion of solid or liquid raw materials into practical gaseous fuel or chemical feedstock, which can be used for energy generation through combustion or for the production of valuable chemicals (Basu, 2010) . Pyrolysis is a thermochemical process of the thermal decomposition of materials at elevated temperatures in the absence of oxygen or any other oxidizing agent(Vikram et al., 2021). This process results in the production of biochar, bio-oil, and non-condensible gas (NCG). the factors that effect of the products of pyrolysis are reaction temperature, heating rate, and feedstock composition (Z. Zhang et al., 2019). Gasification is a thermochemical process that involves the partial oxidation of organic material at high temperatures to produce syngas, which can be used for energy production. Unlike pyrolysis, which involves the thermal decomposition of materials in the absence of oxygen, gasification requires the addition of a controlled amount of oxygen or an oxidizing agent after the initial pyrolysis step. This additional combustion step is a key distinction between the two processes.

Previous studies have highlighted the environmental benefits of biochar production using various feedstocks and technologies. For instance, Fawzy et al. demonstrated that pyrolyzing olive tree pruning residues (OTPR) can sequester approximately 2.68 tonnes of CO2 equivalent per tonne of biochar (Fawzy et al., 2022) . Similarly, Huang et al. found that co-pyrolysis of sewage sludge and sawdust reduced global warming potential (GWP) by 14-35% compared to single-feedstock pyrolysis(Huang et al., 2023). Pranolo et al. conducted experiments using palm kernel shells in a downdraft gasifier and emphasized that adjusting the equivalence ratio (ER is crucial for minimizing global warming potential during gasification (Pranolo et al., 2023). Research by Marzeddu et al. from Italy reported that biochar produced from gasification processes has the potential to reduce carbon emissions by 8.3 tonnes of CO2 equivalent per tonne of biochar produced(Marzeddu et al., 2021).

The literature indicates a lack of technical parametric studies on biochar production through the co-gasification of two agro-industrial wastes, as well as a deficiency in environmental assessments of such systems. This paper aims to conduct a parametric study of the co-gasification of rice husk and corn cob for biochar production and to perform an environmental assessment using Life Cycle Assessment to identify the scenario that offers the greatest environmental benefits. The novelty of this study lies in the absence of simulations and techno-environmental studies from mixing agro-industry waste. The impact this paper aims to deliver is the implementation of a waste-to-energy process with local communities.

RESEARCH METHOD

1, Aspen Plus Simulation of Gasification

Aspen plus simulation is built by two sections Gasification process and the Burning process. The property method used in the simulation is PR-BM(Peng-Robinson-Boston-Mathias), as mentioned in (Bhurse et al., 2024; Rosha & Ibrahim, 2022). The main assumptions for the gasification system are:

1) The gasification system model operates in a steady state.
2) The system is isobaric, with the assumption that pressure drop is negligible.
3) For density and enthalpy calculations of non-conventional components (rice husk and corn cob), the DCOALIGT and HCOALGEN models are used.

4) The inlet stream for all feed types, including air, is at 30 ºC and 1 bar.
5) The char stream consists of 100% carbon.
6) Feedstock is supplied at 100 kg/h according to the specified mixing ratio.
7) The co-gasification process is assumed to be tar-free.

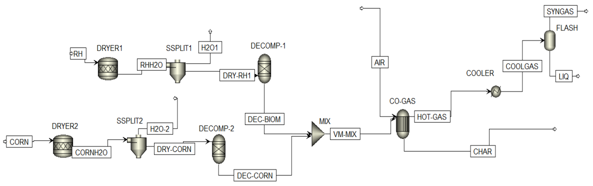

Figure 1. Aspen plus co-gasification flowsheet

1.1. Pre-treatment

Table 1. Feedstock of Co-gasification

Proximate (%wt. Dry)	Rice Husk (Pertiwi et al., 2022)	Corncob(Gani et al., 2023)
Moisture	20.5	12.44
Fixed carbon	13.3	15.4
Volatile matter	8.6	69.58
Ash	57.6	2.58
Ultimate (%wt. Dry)		
	Rice Husk	Corncob
Ash	37.42	NA
Carbon	20.5	39.88
Hydrogen	35.52	6.56
Nitrogen	0.5	0.94
Chlorine	0.12	0
Sulfur	0.14	0
Oxygen	5.8	52.62

The co-gasification process of RH (rice husk) and CC (corncob) was modeled using Aspen Plus, as illustrated in Figure 1. The pre-treatment consists of drying and decomposing. The feedstocks are initially dried in separate dryers (DRYER1 and DRYER2), where the moisture content is reduced, resulting in dry RH (DRY-RH1) and dry CC (DRY-CORN). These dried feedstocks are then subjected to a decomposition process in DECOMP-1 and DECOMP-2 units at a temperature of 100°C to break down the biomass into volatile components (DEC-BIOM for mixed volatile matter and DEC-CORN for corncob volatiles). Feeds are decomposed based on their ultimate analysis on Tabel 1. The decomposed biomass streams are subsequently mixed (VM-MIX) before entering the co-gasification reactor (CO-GAS).

1.2. Co-gasification Process

After the pre-treatment process, the feedstocks are directed to the gasification stage. Since Aspen Plus does not include a specific reactor model for gasification, an equilibrium Gibbs reactor (RGIBBS) was used to simulate the gasification process. The temperature during gasification varies between 450°C and 700°C.

Tabel 2. Reaction for co-gasification in RGibbs ("CO-GAS") (Turns, 2001)

No.	Reaction name	Reaction	Entalphy (kJ/mol)
R1	Partial combustion	$\boxed{C + 0.5\, O_2 \rightarrow CO}$	-111
R2	Carbon monoxide combustion	$\boxed{CO + 0.5\, O_2 \rightarrow CO_2}$	-283
R3	Hydrogen oxidation	$\boxed{H_2 + 0.5\, O_2 \rightarrow H_2O}$	-242
R4	Steam - Carbon	$\boxed{C + H_2O \leftrightarrow H_2 + CO}$	+131
R5	Boudard	$\boxed{C + CO_2 \leftrightarrow 2CO}$	+172
R6	Water – gas shift	$\boxed{CO + H_2O \leftrightarrow H_2 + CO_2}$	-41
R7	Hydrogasification	$\boxed{C + 2\, H_2 \leftrightarrow CH_4}$	-75
R8	Methanation	$\boxed{CH_4 + H_2O \leftrightarrow CO + 3H_2}$	+206

Tabel 3. Aspen plus models for co-gasification flowsheet

Block Name	Model	Function
DRYER	RStoic	Dry feedstocks
SSPLIT	SSPLIT	Separate moisture from dryer
DECOMP	RYield	Decompose unconventional feeds into volatiles
CO-GAS	RGibbs	Gasification Process
COOLER	Exchanger	Reducing syngas temperature before flash separation
FLASH	Flash	Separate liquid and Syngas

1.3. Power generation

The co-gasification system produces syngas as a co-product, which can be utilized as a fuel in a gas turbine. In this study, an RSTOIC reactor model within Aspen Plus is employed to simulate the burner. The model in this section follows Lan et. al. models (Lan et al., 2018). The syngas is compressed to 25 bars before being mixed with compressed air. The power generated by this system is calculated by subtracting the work required by the compressors for syngas and air from the work produced by the gas turbine. The lower Heating Value (LHV) of syngas is calculated by applying the equation (e.1) the value of LHV in syngas as fuel is determined by the composition of CO, H_2, and CH_4. The stream labeled 'SYNGAS' in Fig. 1 represents the stream where the LHV is calculated. LHV CO, LHV H_2, and LHV CH4 are 13.1, 37.1, and 11.2, respectively.

$$\boxed{LHV(MJ/(Nm^3)) = x_{CO} \times LHV_{CO} + x_{H_2} \times LHV_{H_2} + x_{CH_4} \times LHV_{CH_4}\ (eq.1)}$$

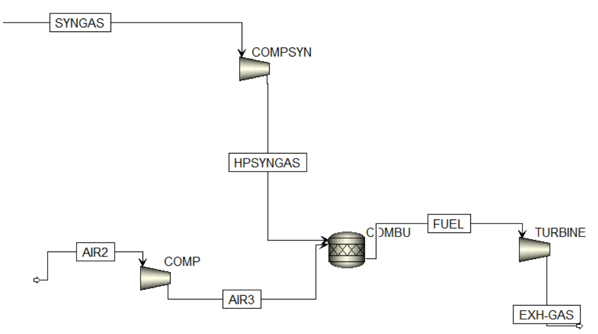

Figure 2. Flowsheet Syngas Burner for Gas Turbine in Aspen Plus

Syngas is compressed to 25 bars after the condensing process of co-gasification. AIR2, initially at 30°C and 1 bar, is compressed to 25 bars. The air excess is set to be 10% of the syngas mass outlet. Both compressors operate with an isentropic efficiency of 0.85. The air and syngas are mixed and combusted in the reactor (COMBU) with an assumed pressure drop of 0.2 bar. After combustion, the fuel is used as input in a gas turbine, which has a mechanical efficiency of 0.98 and an isothermal efficiency of 0.85. The discharge pressure of the gas turbine is set to 1 bar. Power generation is calculated by determining the output of the gas turbine and subtracting the work needed for the air and syngas compressors.

1.2. Life Cycle Assessment

The environmental impact of biochar production via gasification from biomass waste, such as rice husk or coconut shell, is evaluated using Life Cycle Assessment (LCA). This methodology is based on ISO 14040:2006, which provides a framework for LCA and outlines four main phases: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment, and Interpretation. For the purposes of this study, three stages are emphasized in the next section.

1.2.1. Goal and Scope Definition

The goal of LCA is to:

1.) Quantifying the environmental impacts of biochar production through gasification technology.
2.) Identifying hotspots in the entire life cycle of biochar based on simulating gasification results.

By focusing on these elements, the LCA aims to provide a comprehensive overview of the environmental performance of biochar production through gasification to its end application, highlighting areas where improvements can be made to reduce the overall environmental footprint. Quantifying a process requires measurement, which is why LCA introduces a functional unit. For this study, the functional unit in each scenario will be the production of 1000 kg of biochar applied to the soil. The goal of this LCA study is to evaluate the environmental impacts associated with the co-gasification of rice husk and corncob to produce biochar and syngas. The LCA scope of this system is from cradle to grave, which means the analysis considers the impacts from raw material extraction to the application of the final products. OpenLCA is used to calculate the input of inventory and estimate the impact assessment.

1.2.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase involves the detailed collection and analysis of data related to all inputs and outputs associated with the biochar production process. The Ecoinvent ver. 3.9.1, Agribalyse ver. 3.01 databases are used as secondary inventory data. The whole input and output are listed and calculated by OpenLCA, an open-source LCA software. 5 processes, from the acquisition of biomass feedstocks to the application use of biochar, are drawn in Figure 3. The comprehensive LCI data is presented in the supplementary material to provide transparency and allow for a thorough understanding of the underlying data used in the study.

1) Feed acquisition

This stage includes the cultivation, harvesting, transportation, and pre-treatment processes for obtaining rice husk (RH) and corncob (CC) biomass feedstocks. Rice husks are cultivated from paddy fields, harvested, and then milled at the farming facility to separate the rice grain from the husk and straw residues, with a 3% loss assumed during milling. After milling, the rice husks are prepared for transport. Inventory data on rice cultivation and drying are sourced from Shafie et. al. (Shafie et al., 2012).

For corncobs, corn is ground and dried after harvesting from farms. Losses occur during processing before the corncob waste is ready for transport to the co-gasification facility. Inventory data for corncobs is sourced from the reference (Giusti et al., 2023; Santolini et al., 2022).

2) Feed transportation

   The feedstocks were transported by lorries weighing 16-32 tons over an assumed distance of 50 km from each source to the gasification plant. Inventory data for transportation were obtained from ecoinvent.

3) Gasification and Power Generation

   Gasification with power generation using a gas turbine for this LCA study obtains data from the simulation study in the previous section. The biochar amount from the co-gasification model is set to 1000 kg. Emissions from combusting syngas are obtained from the 'FLUE GAS' stream, and the results are input into openLCA.

4) Biochar Quenching and packaging and transportation

   Afterwards, the biochar is introduced to the quenching process with water. It is assumed that the water required is one-third of the biochar inlet. The biochar is packaged in big bags made of polypropylene material. The required amount is approximately 5 kg per 1000 kg of biochar, as in Marzeddu et. al. study (Marzeddu et al., 2021)

5) Applied to soil biochar

   The carbon stability of biochar was assumed to be 80%, with 20% losses due to factors such as wind and rain. The potential for carbon sequestration in this study is calculated using the following equation: First, the fixed carbon content in biochar must be determined as per the equation below.

$$FC\ (\%) = 0.037 \times T + 55.86 \qquad (eq.2)$$

$$CO_2\ sequestartion = 1000\ kg \times 80\% \times FC(\%) \qquad (eq.3)$$

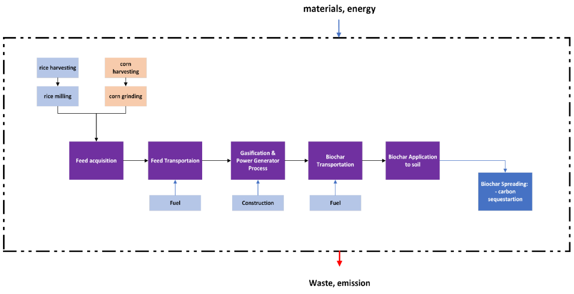

Figure 3. LCA Boundary system of biochar production

1.2.3. Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment is a phase of the LCA process that connects the inventory data to the results and interpretation. The LCIA step involves choosing a method to calculate the impact categories. The method used in this research is the CML IA baseline approach. the categories of CML IA baseline include abiotic depletion, global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication (OpenLCA, 2016). The selected categories in this study are global warming potential, as well as other relevant environmental impact categories such as eutrophication potential, acidification potential, and fossil fuel depletion. The reason for focusing on global warming potential is that biochar is closely related to carbon sequestration, and the application of biochar to soil is usually targeted to mitigate carbon dioxide emissions.

RESULT AND DISCUSSION

Gasification Simulation

1. Effect of Temperature on biochar yield

Figure 4 illustrates the relationship between gasification temperature and biochar yield for different feedstock mixtures of Rice Husk (RH) and Corncob (CC). The graph shows a clear decreasing trend in biochar yield as the temperature increases from 450°C to 700°C. This behavior is consistent across all feedstock combinations, with the yield starting high at lower temperatures and gradually declining to nearly zero at the highest temperature. Specifically, the 100% RH feedstock yields the lowest biochar across the temperature range, while the 100% CC feedstock results in the highest biochar yield at lower temperatures. Mixed feedstocks (RH 75% & CC 25%, RH 50% & CC 50%, and RH 25% & CC

75%) exhibit intermediate yields that decline at rates dependent on the proportion of RH and CC. The observed trend aligns with conventional gasification principles where higher temperatures enhance the conversion of biomass into syngas rather than biochar. This simulation result suggests that lower gasification temperatures are more favorable for maximizing biochar yield, with corncob proving to be the most efficient feedstock for biochar production, especially at these lower temperatures. It underscores the importance of selecting appropriate feedstock mixtures and maintaining optimal gasification temperatures to achieve desired biochar yields

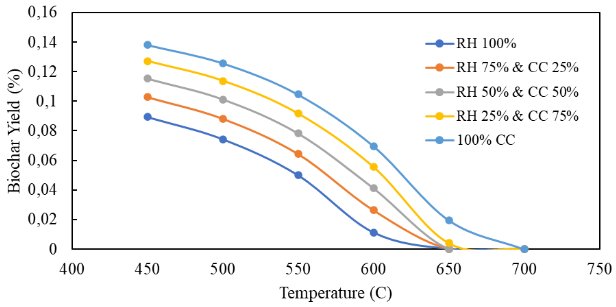

Figure 4. Temperature effect of biochar yield in ER=0,1

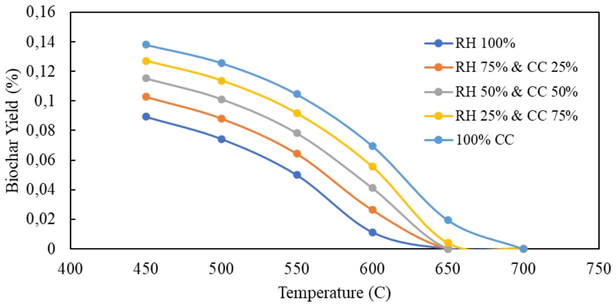

Figure 5. Temperature effect of biochar yield in ER=0,2

Similar to Figure 4, Figure 5 illustrates a clear downward trend in biochar yield as the temperature increases from 450°C to 700°C. This decline is observed across all feedstock combinations, with biochar yield starting at higher values at lower temperatures and gradually diminishing to near zero at the highest temperature. However, compared to Figure 3, the biochar yields are consistently lower at each temperature, indicating that a higher ER (0.2) results in a reduced yield of biochar. This higher ER means more oxygen is present, promoting biomass conversion into syngas rather than biochar. The 100% RH feedstock consistently produces the lowest biochar yield, while the 100% CC feedstock results in the highest yield at lower temperatures. Mixed feedstocks exhibit intermediate yields that decrease at varying rates based on their RH and CC proportions. This trend reinforces the importance of controlling the ER and temperature to optimize biochar production, with lower temperatures and a lower ER favoring higher biochar yields. Corncob remains the most efficient feedstock for biochar production, especially at lower temperatures and lower ER values.

2. *Effect of Temperature on LHV Syngas*

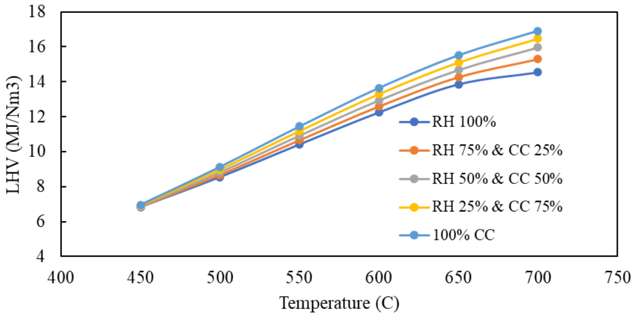

Figure 6. Temperature effect of LHV Syngas in ER=0,1

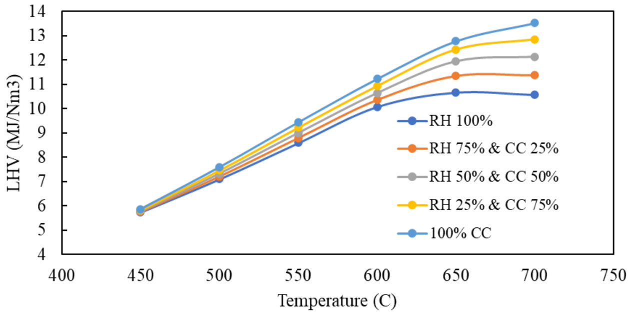

Figure 7. Temperature effect of LHV Syngas in ER=0,2

Figure 6 illustrates the trend in the lower heating value (LHV) of syngas as a function of temperature for different mixtures of RH (rice husk) and CC (corncob) as feedstock in a gasification simulation. As the temperature increases from 450°C to 700°C, the LHV of syngas consistently rises for all feedstock combinations. This indicates that higher temperatures enhance the gasification process, leading to a more efficient conversion of biomass into syngas with higher energy content. Additionally, mixing the feedstocks shows a relatively minor effect on LHV compared to the impact of temperature. Pure RH tends to produce syngas with the highest LHV across all temperatures, while pure CC generally results in the lowest LHV. Intermediate mixtures (RH 75% & CC 25%, RH 50% & CC 50%, RH 25% & CC 75%) produce LHV values that lie between these extremes.

The trend remains consistent for an ER of 0.2, with the LHV increasing as the temperature rises (Figure 7). Similar to the previous figure, the LHV of syngas increases with rising temperature from 450°C to 700°C for all feedstock combinations. This trend indicates that higher temperatures improve the efficiency of the gasification process, leading to syngas with higher energy content. Pure RH (RH 100%) consistently produces syngas with the highest LHV across all temperatures, while pure CC (CC 100%) results in the lowest LHV. However, the impact of temperature is more pronounced, with all feedstock mixtures displaying a similar upward trend in LHV as temperature increases. This emphasizes the dominant role of temperature in enhancing syngas quality, regardless of the feedstock blend. In Figure 6, where a lower ER is considered, the LHV values are generally lower compared to Figure 7. The increased ER in Figure 6 leads to higher LHV values across all feedstock combinations, suggesting that additional oxygen enhances gasification. This improvement is likely due to more complete combustion reactions occurring at higher ER, resulting in a higher proportion of energy-rich syngas components such as hydrogen and carbon monoxide. Consequently, while both temperature and ER significantly influence the LHV of the produced syngas, a higher ER contributes to a notable increase in LHV by optimizing the oxygen supply and enhancing the overall gasification efficiency.

3. *Syngas Burning*

The co-production of biochar and syngas will bring value if both products are utilized properly. For the syngas product of the gasifier system, the composition of CO, H_2, CH_4, and CO_2 are different for each temperature and mixing feedstock. Burning syngas to generate power with the gas turbine results in different electricity capacities but still produces constant biochar for 1000 kg. Besides electricity, the heat from cooling syngas can also be used to heat the system. The power generated from the gas turbine is increasing as the equivalence ratio (ER) rises. As the ER increases, the amount of oxygen available for the gasification process also increases, allowing for more complete combustion of the feedstock.

Tabel 5. Power generated by the syngas burning for ER 0.1

Run	RH(%)	CC (%)	Turbine Work (kW)	Power Generated (kW)
450	100	0	4866	2178
650	100	0	51932	26401
450	50	50	4263	2086
650	50	50	12866	6253
450	0	100	3562	1704
700	0	100	31500	15302

Tabel 6. Power generated by the syngas burning for ER 0.2

Run	RH	CC	Turbine Work (kW)	Power Generated (kW)
450	100	0	8477	2703
600	100	0	110918	55828
450	50	50	7201	2862
600	50	50	29758	15149
450	0	100	6639	3115
600	0	100	65723	33009

4. *Global Warming Potential Reduction*

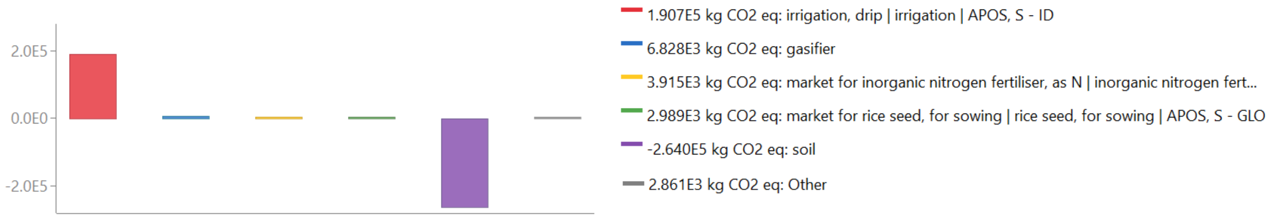

Figure 8. For feedstock 100% RH

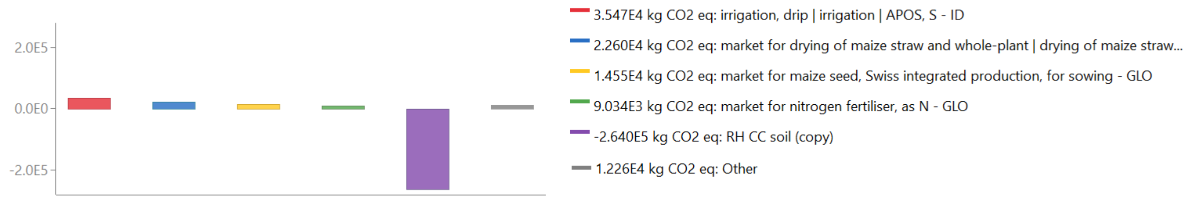

Figure 9. For feedstock 50% RH & 50% CC

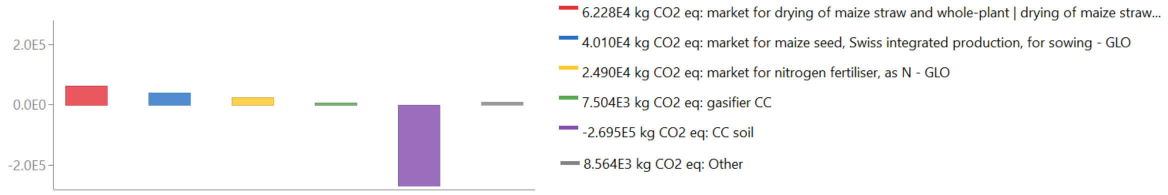

Figure 10. For feedstock 100% CC

LCA results for the 100% rice husk (RH) scenario are depicted in Figure X. The data highlights that irrigation is the most significant contributor to the Global Warming Potential (GWP), with an impact of 1.9075 × 10^5 kg CO_2 equivalent per ton biochar applied. This is substantially higher compared to other processes, such as gasification (6.8283 × 10^3 kg CO_2 equivalent), the market for inorganic nitrogen fertilizer (3.9153 × 10^3 kg CO_2 equivalent), and the market for rice seed for sowing (2.9983 × 10^3 kg CO_2 equivalent). This indicates that the GWP impact in the entire life cycle of biochar is predominantly influenced by upstream processes, particularly irrigation. Irrigation practices

100% CC feedstock is assessed for the same method and same functional unit. The analysis reveals that the market for drying maize straw and whole-plant is the largest contributor to the Global Warming Potential (GWP), with an impact of 6.2284 × 10^4 kg CO_2 equivalent. This is followed by the market for maize seed, which contributes 4.0104 × 10^4 kg CO_2 equivalent, and the market for nitrogen fertilizer, with an impact of 2.4904 × 10^4 kg CO_2 equivalent. The gasification process itself accounts for 7.504 × 10^3 kg CO_2 equivalent. The analysis indicates that drying corn cob is the main contributor to the global warming potential in the 100% corncob scenario. However, the overall life cycle assessment of the 100% corncob scenario still shows a net benefit due to the carbon sequestration potential of the biochar produced.

For a mixing ratio of 50% RH and 50% CC scenario, the most significant positive CO_2 contributor is irrigation (drip irrigation), which accounts for 3.547 × 10^4 kg CO_2 eq (fig. This highlights the energy and water resources required for cultivating either rice or corn. Drip irrigation, while efficient in water use, can still be energy-intensive depending on the water source and infrastructure. The drying of maize straw and the whole plant contributes 2.260 × 10^4 kg CO_2 eq, indicating that the energy consumed in mechanical drying, or the indirect emissions associated with this process is substantial. Additionally, the production of maize seed contributes 1.455 × 10^4 kg CO_2 eq, reflecting the emissions from agricultural practices such as the use of fertilizers, machinery, and land management.

The analysis shows that for each scenario assessed, the inventory includes the calculation of electricity and heat generated from the syngas produced. The 100% rice husk (RH) scenario generates the highest amount of electricity from burning the syngas, even though the lower heating value (LHV) of the syngas is lower than the other two scenarios. This is because the amount of syngas produced from the 100% RH stream is the highest. The electricity generated in each scenario is fed into the grid, but the low renewable energy portfolio in Indonesia results in no distinct benefits from the renewable energy production.

To further enhance the environmental benefits, recommendations include optimizing water use through alternative irrigation methods or improved efficiency of drip irrigation systems, shifting technology into efficient energy.

CONCLUSION

This paper aims to fill the gaps in co-gasification life cycle assessment in agro-industry waste. based on the findings presented in the journal paper, several conclusions can be drawn regarding the co-gasification of rice husk (RH) and corn cob (CC) to produce biochar and syngas. Firstly, it is evident that temperature plays a critical role in the process, as higher temperatures lead to decreased biochar yield but increased production of syngas. This sensitivity underscores the need for precise control and optimization of temperature conditions in co-gasification processes to balance biochar production with syngas yields effectively.

Moreover, the optimal equivalence ratio (ER) is highlighted as crucial for achieving desired outcomes: a lower ER favors higher biochar yields, whereas a higher ER enhances the production of hydrogen and methane within the syngas. The composition of the feedstock mixture (CC and RH) also significantly influences the outputs, influencing both the composition of syngas and the overall biochar yield. Specifically, higher temperatures in the co-gasification reactor intensify syngas production, further emphasizing the temperature dependency observed throughout the study.

Additionally, the life cycle assessment (LCA) reveals specific environmental hotspots associated with each feedstock's biochar production process. For rice husk, irrigation in paddy fields emerges as a critical hotspot, whereas for corn cob, the drying of maize grain stands out. These insights are pivotal for designing more sustainable biochar production processes that mitigate environmental impacts effectively.

Lastly, the co-gasification scenario presents promising environmental benefits, particularly in reducing Global Warming Potential (GWP), which underscores its potential as a viable approach for sustainable waste utilization and energy production. These conclusions collectively advocate for further research and development efforts aimed at optimizing co-gasification technologies to enhance both environmental sustainability and process efficiency in biomass utilization for biochar production.

Declaration of generative ai and ai-assisted technologies in the writing process

The authors utilized ChatGPT to enhance the readability and grammar of the manuscript during the preparation process. After employing the tool, the authors reviewed and revised the content as necessary and assume full accountability for the publication's content.

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