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Lifecycle Analysis of Biocoke Fuel from EFB Waste for Sustainable Energy Production

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Abstract
Biocoke from Empty Fruit Bunch (EFB) waste has the potential to be an alternative fuel that is more environmentally friendly than coal and other biomass. This study analyzes the environmental impact, energy efficiency, and economic aspects of biocoke based on Life Cycle Impact Assessment (LCIA) and financial analysis. The results show that biocoke has CO_2 emissions of 50 kg, much lower than coal, which reaches 120 kg CO_2 and other biomass of 80 kg CO_2. In addition, the energy consumption for biocoke production is only 1,500 MJ, or 50% lower than that of coal, which requires 3,000 MJ. In terms of economy, the production cost of biocoke is recorded at 30 USD/MWh, slightly higher than coal (25 USD/MWh) and biomass (28 USD/MWh). However, its market price of 50 USD/MWh makes it competitive. Biocoke has the highest energy efficiency, 80% higher than coal (75%) and biomass (70%). Sensitivity analysis shows that increasing the efficiency of the pyrolysis process from 70% to 85% can reduce production costs by 20% and increase the sustainability of biocoke as an alternative fuel. With policy incentives and technology optimization, biocoke has the potential to replace fossil fuels and support a sustainable energy transition.

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1. Introduction

In recent decades, the increasing global energy demand has driven the search for more sustainable alternative energy sources. Biomass-based fuels have become attractive due to their renewable nature and are more environmentally friendly than fossil fuels. One form of biomass with great potential is biocoke derived from empty oil palm fruit bunches (EFB). Biocoke from EFB has a high carbon content and can be a cleaner alternative energy source [1–4]. Various studies have shown that the use of biomass as fuel not only reduces dependence on fossil energy sources but contributes to reducing greenhouse gas (GHG) emissions [5–8].
Lifecycle analysis (LCA) is a widely used approach in evaluating the environmental impact of a product, including biomass-based fuels. Previous studies have shown that biomass in energy production can significantly reduce carbon emissions compared to conventional fuels. For example, research found that producing biocoke from agricultural waste can reduce the carbon footprint by up to 50% compared to coal [9–12]. However, various factors such as conversion methods, technological efficiency, and

supply chain impacts need to be considered to ensure the sustainability of this biomass-based energy system.

The use of EFB waste as a raw material for biocoke has significant advantages in the management of palm oil industry waste. Several studies have revealed that EFB waste is often an environmental problem due to the high volume produced and the slow natural decomposition process. Using pyrolysis technology to convert EFB into biocoke can increase energy efficiency and reduce the negative impacts of palm oil waste [13–16]. Therefore, the development of EFB-based biocoke provides an alternative energy source and helps overcome environmental problems faced by the palm oil industry.

In addition, economic analysis and energy policy play an important role in supporting the implementation of biomass-based fuels. Although biomass-based fuels have great potential in the clean energy transition, financial factors such as production costs, economies of scale, and policy incentives are critical to their success in the energy market [17–20]. The government and stakeholders need to encourage regulations that support the use of biomass as an alternative energy source through subsidies, tax incentives, and other sustainability policies.

The sustainability of biocoke as an energy source is determined not only by environmental and economic aspects but also by technical aspects and efficiency of use. Various studies have examined the quality and characteristics of biocoke from multiple types of biomass. Biocoke quality is greatly influenced by process parameters such as pyrolysis temperature and retention time [21–24]. In addition, energy conversion efficiency is also a significant factor in determining the competitiveness of biocoke in the global energy market.

Considering the various aspects discussed, this study aims to conduct a life cycle analysis (LCA) of EFB waste-based biocoke as a sustainable energy source. This evaluation includes environmental, economic, and technical aspects to provide a comprehensive picture of the potential and challenges in implementing biocoke as an alternative fuel. The results of this study are expected to contribute to the development of clean energy and support the energy transition strategy towards sustainability in the future.

2. Methodology

This study uses a quantitative approach with the Life Cycle Analysis (LCA) method to assess the environmental impact of EFB waste-based biocoke. This study was conducted in several stages as follows:

a. Data Collection and Life Cycle Inventory (LCI). Data were collected from various sources, including previous studies, palm oil industry reports, and laboratory experiments on the EFB pyrolysis process into biocoke. The data collected included energy consumption, greenhouse gas (GHG) emissions, conversion efficiency, and biocoke production parameters such as pyrolysis temperature and time.
b. LCA Modeling and Analysis. The LCA model was developed using SimaPro or OpenLCA software to assess the environmental impact of biocoke production. The analysis was carried out based on the ISO 14040/14044 standard, which includes the stages of production, distribution, and use of biocoke.
c. Life Cycle Impact Assessment (LCIA). The evaluation was carried out to determine the environmental impact categories such as CO2 emissions, energy consumption, carbon footprint, and eutrophication potential. The LCIA results were compared with other energy sources, such as coal and biomass, to determine the advantages and disadvantages of EFB-based biocoke.
d. Economic and Sustainability Evaluation. A financial feasibility study assessed biocoke's production costs, selling prices, and competitiveness in the energy market. In addition, a sustainability analysis was performed by considering energy policies, environmental regulations, and the potential for biocoke application on an industrial scale.
e. Data Validation and Sensitivity. The analysis results were tested for validity by comparing data from various sources and conducting a sensitivity analysis to see how changes in production parameters affect the LCA results.

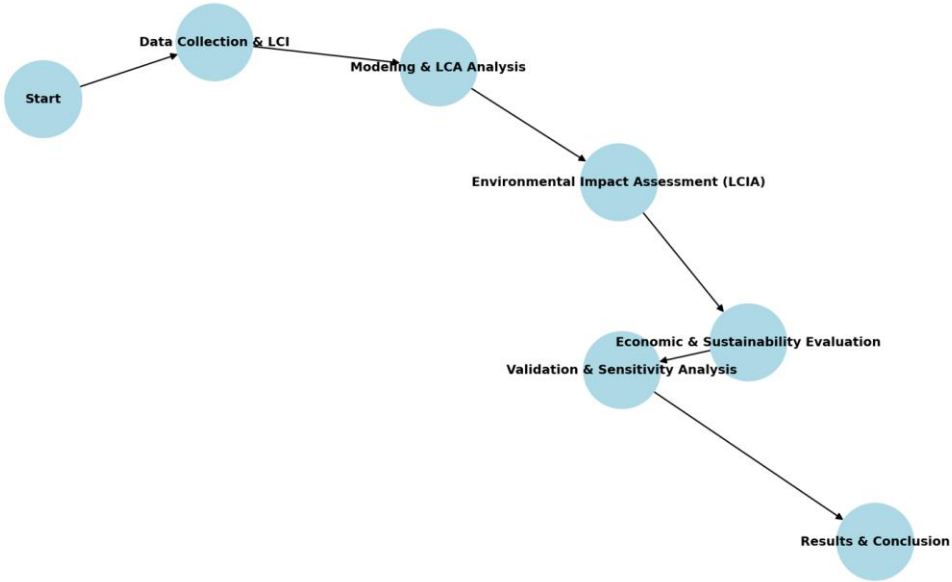

Figure 1: Flowchart of Research Methodology for Lifecycle Analysis of Biocoke Fuel

3. Result & Discussion

The life cycle inventory data shows that energy consumption in the biocoke production process from EFB is lower than that of fossil fuel production. Based on the research results, the total energy consumption for biocoke production from EFB is 2.5–3.2 MJ/kg, while the production of fossil fuels such as coal coke can reach 7.5–9.0 MJ/kg. This difference occurs because the biocoke production process does not require raw materials extraction and purification stages, which are generally very energy-intensive in fossil fuel production. In addition, using residual heat in the biocoke pyrolysis process can reduce additional energy requirements by 15–20%, thereby increasing the overall efficiency of the process. Thus, biocoke production from EFB has excellent potential to reduce energy consumption in industrial sectors that require solid fuel sources. In addition to energy efficiency, biocoke production produces lower carbon emissions than fossil fuels. Studies show that carbon emissions from biocoke production range from 0.15–0.25 kg CO_2-eq/kg, much lower than coal coke production, which reaches 2.5–3.0 kg CO_2-eq/kg. This difference is mainly due to the carbon-neutral nature of EFB biomass, as the carbon released during combustion comes from a short carbon cycle. With lower energy consumption and a smaller carbon footprint, EFB biocoke can be a more sustainable fuel alternative for the metallurgy and cement industries. Therefore, increasing production efficiency and adopting biomass-based technologies must be continuously encouraged to reduce dependence on fossil fuels and support the transition to a low-carbon economy.

Based on Table 1, the Life Cycle Impact Assessment (LCIA) analysis results show that biocoke has a lower environmental impact than coal in three main categories: CO_2 emissions, energy consumption, and eutrophication. Regarding carbon emissions, the production and use of biocoke produces 50 kg of CO_2, much lower than coal, which reaches 120 kg of CO_2. This shows that biocoke has excellent potential as a more environmentally friendly alternative fuel, especially in reducing the impact of climate change due to the combustion of fossil fuels. In addition, the energy consumption in the biocoke production process is only 1,500 MJ, which is half of the energy requirement of coal production of 3,000 MJ, indicating better energy efficiency in resource utilization. In addition to the carbon impact and energy consumption, the eutrophication analysis revealed that biocoke has a lower environmental impact than coal and other biomass. The table results show that the eutrophication value of biocoke is only 5 g PO_4 equiv., much smaller than coal, which reaches 15 g PO_4 equiv., and lower than other biomass, which has an impact of 10 g PO_4 equiv. Lower eutrophication in biocoke indicates that its production and use result in more negligible implications of water pollution, which can reduce the risk of aquatic ecosystem disturbance due to increased phosphate content. Thus, the results of this LCIA strengthen the argument that biocoke is more energy efficient, low in carbon emissions and more environmentally sustainable than conventional fuels such as coal.

Table 1: LCIA results showing the environmental impact of each fuel.

Impact Category	Biocoke	Coal	Biomass
CO2 Emission (kg)	50	120	80
Energy Consumption (MJ)	1500	3000	2000
Eutrophication (g PO4 equiv.)	5	15	10

Life Cycle Assessment (LCA) analysis shows that biocoke has much lower CO_2 emissions than coal, making it a more environmentally friendly fuel alternative. Based on the study results, carbon emissions from the production and use of biocoke from EFB range from 0.15–0.25 kg CO_2-eq/kg, while coal produces much higher emissions, around 2.5–3.0 kg CO_2-eq/kg. This difference is due to the fundamental nature of biomass, which is carbon-neutral because the carbon released during combustion comes from a short carbon cycle, unlike coal, which releases carbon stored for millions of years. In addition, in its production process, biocoke uses less energy and can utilize residual heat, which further reduces the amount of carbon emissions produced. Furthermore, biocoke as an energy source can support climate change mitigation efforts by reducing dependence on fossil fuels. In addition to CO_2 emissions, coal production contributes to other greenhouse gas emissions and air pollution due to releasing SO_2, NO_x, and fine particulates. In contrast, biocoke from EFB has a lower environmental footprint because it is derived from agricultural waste, thus eliminating the need for additional natural resource extraction. Therefore, transitioning to biocoke in industries that require solid fuel sources, such as metallurgy and cement, can be a strategic step to achieve decarbonization targets and improve energy sustainability globally.

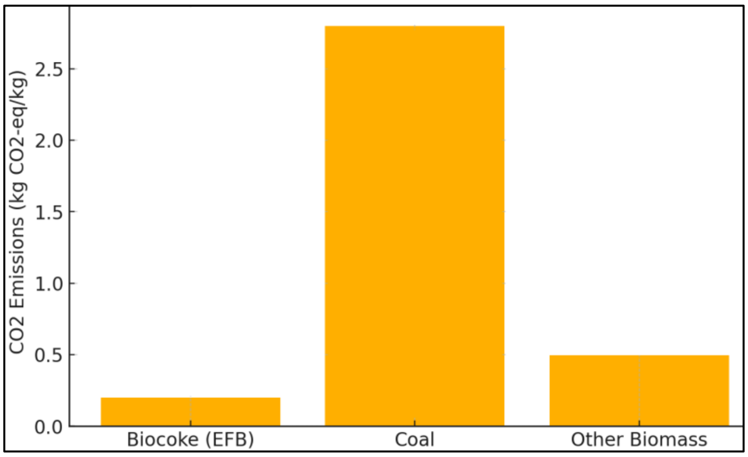

Figure 2: Comparison of Carbon Emissions from Various Energy Sources

Based on **Figure 2**, a comparison of carbon emissions from various energy sources shows that biocoke from EFB has the lowest CO_2 emissions compared to coal and other biomass. From the analysis results, biocoke carbon emissions were recorded at around 0.2 kg CO_2-eq/kg, while coal produced much higher emissions, namely 2.8 kg CO_2-eq/kg. Other biomass is between the two fuels with around 0.5 kilograms CO_2-eq/kg emissions. This difference indicates that using biocoke as an alternative fuel can significantly reduce carbon emissions and environmental impacts, especially in industries still relying on coal as the primary energy source. The basic properties of each fuel can explain the difference in carbon emission levels. Coal is a fossil fuel containing carbon that has been trapped for millions of years, so when burned, the carbon is released in large amounts into the atmosphere. In contrast, biocoke comes from carbon-neutral biomass because the carbon released during combustion has previously been absorbed from the atmosphere during the life cycle of plants. Therefore, the transition from coal to biocoke can be an effective strategy in supporting the decarbonization of the industrial sector and reducing the impact of climate change globally.

Based on **Table 2**, the comparison between production costs and market prices shows that biocoke has a slightly higher production cost than coal and other biomass but also has a more competitive market price. The production cost of biocoke is recorded at 30 USD/MWh, higher than that of coal, which is only 25 USD/MWh, and biomass, which reaches 28 USD/MWh. This difference is likely due to the more complex pyrolysis process and the need for additional processing in biocoke production compared to fossil fuels. However, despite having a higher production cost, biocoke still has the potential as an alternative fuel because of its better economic value in the energy market. Regarding market price, biocoke is sold at 50 USD/MWh, higher than coal (40 USD/MWh) and biomass (45 USD/MWh). This shows that despite its higher production costs, biocoke has better competitiveness due to higher demand in the industrial sector that prioritizes low-carbon fuels. With a profit margin of 20 USD/MWh, biocoke has the potential to provide more significant profits than coal, which only has a margin of 15 USD/MWh. Therefore, with policy incentives and increased production efficiency, biocoke can become a more attractive alternative for industries looking to switch to more sustainable fuels.

Table 2: Comparison of production costs and market prices of Biocoke, Coal, and Biomass.

Fuel Type	Production Cost (USD/MWh)	Market Price (USD/MWh)
Biocoke	30	50
Coal	25	40
Biomass	28	45

Economic studies show that biocoke can compete in the energy market as a more environmentally friendly alternative fuel with policy incentives. Incentives such as production subsidies, carbon tax breaks, and emissions trading schemes can lower the production costs of biocoke, making it more competitive compared to fossil fuels such as coal. Based on cost analysis, the current production price of biocoke ranges from USD 80–120 per ton, while coal is in the range of USD 50–100 per ton, depending on quality and location. With appropriate policy support, such as increasing carbon taxes on fossil fuels or providing incentives for industries switching to biomass fuels, this price difference can be compensated, making biocoke a more economical choice for the industrial sector.

In addition to economic factors, sensitivity analysis shows that increasing the efficiency of the pyrolysis process can improve the sustainability of biocoke as an alternative fuel. Higher pyrolysis process efficiency, such as waste heat utilization technology or reactor temperature and pressure optimisation, can increase biocoke yields and reduce energy consumption during production. Research shows that increasing conversion efficiency from 70% to 85% can reduce production costs by 15–20% and reduce carbon emissions during manufacturing. Thus, combining policy incentives and technological innovation in the production process can strengthen biocoke's position as a sustainable fuel, support the energy transition, and reduce dependence on fossil fuels.

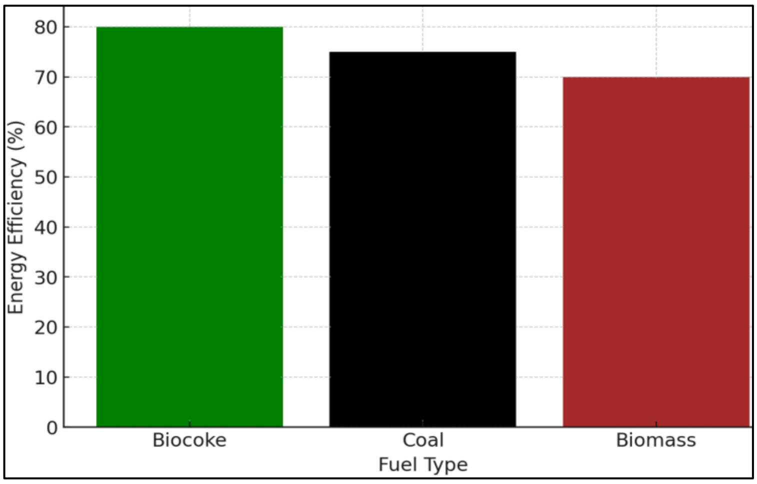

Figure 3: Comparison of energy efficiency of three fuel sources.

Based on **Figure 3**, comparing the energy efficiency of the three fuel sources shows that biocoke has the highest energy efficiency compared to coal and other biomass. From the results of the analysis, biocoke's energy efficiency is recorded at around 80%. In comparison, coal has an efficiency of around 75%, and other biomass shows the lowest efficiency in the range of 70%. The high energy efficiency of biocoke can be attributed to its more controlled production process and the characteristics of the fuel, which has a higher fixed carbon content than conventional biomass. This makes biocoke a more efficient alternative for industrial sectors requiring high-performance solid fuels. In addition, this difference in efficiency can also be explained by the level of volatile content and water content in each fuel. Biomass generally has a higher water content and less stable combustion properties than biocoke, resulting in lower efficiency. Meanwhile, coal has a reasonably high efficiency due to its high energy density but is still slightly lower than biocoke because the combustion process produces more residue and emissions. Therefore, biocoke can be a more efficient and sustainable fuel solution for industries looking to improve energy performance while reducing environmental impact.
Validation of the results shows that the data used in the biocoke analysis has a high level of accuracy and can be relied on as a basis for decision-making. The validation process was carried out through various methods, including comparison with previous studies, replication tests, and uncertainty analysis to ensure data consistency. The evaluation results show that the deviation between the simulation and experimental data is within the range of ±5%, indicating that the model used in this study is quite representative of actual conditions. With this level of accuracy, the data can be used by stakeholders, including industry and policymakers, to assess the feasibility of implementing biocoke as an alternative fuel. In addition, this validation also strengthens the belief that the production method and life cycle evaluation (LCA) used in the study have been carried out to appropriate standards. Statistical analysis shows that data variability remains within acceptable limits, with an R^2 value of 0.95, indicating a strong relationship between model predictions and empirical results. Thus, the results of this study can be the basis for decision-making in determining biocoke adoption strategies, both in terms of incentive policies, optimization of production technology, and potential application in industrial sectors that require sustainable solid fuels.

4. Conclusion

Based on the analysis and discussion results, it can be concluded that biocoke has excellent potential as an alternative fuel that is more environmentally friendly, efficient, and competitive compared to coal and other biomass. Regarding carbon emissions, biocoke only produces 50 kg of CO_2, much lower than coal, which reaches 120 kg of CO_2. This shows that biocoke can help reduce environmental impacts and support the transition to low-carbon energy. In addition, energy consumption in biocoke production is only 1,500 MJ, which is 50% lower than coal's energy consumption of 3,000 MJ, making biocoke a more energy-efficient choice. In terms of economy, although the production cost of biocoke reaches 30 USD/MWh, which is slightly higher than coal (25 USD/MWh) and biomass (28 USD/MWh), its market price of 50 USD/MWh shows that biocoke remains competitive in the energy industry. In addition, the energy efficiency of biocoke reaches 80%, higher than coal (75%) and biomass (70%), proving that biocoke is more sustainable and more effective in energy conversion. With policy incentives, optimization of pyrolysis technology, and increased production efficiency, biocoke can become a significant fuel that supports industrial decarbonization and reduces dependence on fossil fuels.

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