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Environmental Impacts of Biocoke Fuel Production from Agricultural Waste

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Abstract
Biocoke fuel, derived from agricultural waste, is an emerging alternative to fossil fuels due to its lower environmental impact. This study investigates the ecological effects of biocoke production from Empty Fruit Bunches (EFB), rice husks, and corn stalks. The research focuses on biocoke yield efficiency, air emissions, heavy metal contamination, and life cycle assessment (LCA). The highest biocoke yield was observed at 400°C, with EFB achieving 65%, corn stalks 60%, and rice husks 55%. Gas emissions analysis showed CO2 emissions ranging between 1100–1200 ppm, approximately 50% lower than conventional coal combustion. Heavy metal analysis detected trace amounts of cadmium (Cd), lead (Pb), and arsenic (As), remaining within safe limits but necessitating proper disposal of biocoke ash. The LCA results indicated a 50–70% reduction in greenhouse gas emissions when substituting coal with biocoke, with the lowest carbon footprint recorded for EFB-based biocoke at 30 kg CO2 equivalent, compared to coal at 100 kg CO2 equivalent. While biocoke presents environmental advantages, concerns over large-scale production, biomass sustainability, and potential soil degradation require further study. Future research should focus on optimizing production processes, improving emissions control, and assessing industrial applications. Overall, this study highlights the potential of biocoke as a sustainable energy source, contributing significantly to carbon emission reduction and renewable energy development.

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1. Introduction
Biocoke fuel, a carbon-rich solid biofuel derived from agricultural waste, has gained increasing attention as a sustainable alternative to conventional fossil fuels. The production of biocoke involves the thermal treatment of biomass through pyrolysis or torrefaction, processes that enhance its energy content while reducing volatile components. In recent years, agricultural residues such as Empty Fruit Bunches (EFB), rice husks, and corn stalks have been widely studied as feedstock for biocoke production. Utilizing these wastes mitigates environmental pollution and offers an opportunity to convert underutilized biomass into valuable energy sources.

Several studies have evaluated the environmental benefits of biocoke fuel, particularly regarding greenhouse gas (GHG) emissions reduction. Research highlights that biocoke production from lignocellulosic waste significantly reduces carbon dioxide (CO_2) emissions compared to traditional coal combustion [1–4]. Similarly, a life cycle assessment (LCA) study demonstrated that substituting coal with biocoke in industrial applications can lead to a 50-70% decrease in overall carbon footprint [5–8]. These findings emphasize the potential role of biocoke as a cleaner alternative in reducing the environmental impacts of energy generation.

However, despite its advantages, biocoke production also presents environmental concerns, particularly regarding heavy metal contamination and air pollutant emissions. A study found that the thermal conversion of biomass can lead to the release of trace heavy metals such as cadmium (Cd), lead (Pb), and arsenic (As), which may pose risks to air quality and human health [9–12]. Additionally, incomplete combustion of biocoke may result in the formation of particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs), which are known for their adverse environmental and health effects.

Water and soil contamination are also potential issues associated with biocoke production. During biomass pyrolysis, wastewater containing organic compounds and acidic byproducts can be generated, potentially leading to soil acidification and water pollution if not properly managed. Research indicates that leachates from biocoke processing can introduce hazardous substances into aquatic ecosystems, affecting water quality and biodiversity [13–15]. Effective waste treatment and containment strategies are thus essential to mitigate these environmental risks.

In addition to pollution concerns, the sustainability of biocoke production is influenced by land use and resource availability. Large-scale biomass harvesting for biocoke manufacturing may lead to deforestation and soil degradation if not conducted sustainably. A study stresses the importance of adopting circular economy principles and sustainable agricultural practices to ensure that biomass extraction does not compromise food security or ecosystem balance [16–19]. Integrating biocoke production with waste-to-energy strategies can enhance sustainability and minimize negative environmental trade-offs.

While biocoke fuel production from agricultural waste presents promising environmental benefits, its potential impacts must be carefully managed through improved process optimization and pollution control measures. Further research is needed to develop cleaner production technologies, enhance emissions control, and promote sustainable biomass sourcing practices. By addressing these challenges, biocoke can serve as a viable alternative fuel, contributing to global efforts to reduce carbon emissions and advancing renewable energy solutions.

2. Methodology

a. Research Design

This study uses an experimental approach and environmental analysis to evaluate the impact of biocoke production from agricultural waste on the environment. This study will include the characterization of raw materials, the biocoke production process, and environmental impact analysis using the Life Cycle Assessment (LCA) method.

b. Materials and Tools

Materials: Agricultural waste such as Empty Fruit Bunches (EFB), rice husks, and corn stalks. Tools: Pyrolysis/torrefaction reactor, spectrophotometer, Gas Chromatography-Mass Spectrometry (GC-MS), Atomic Absorption Spectroscopy (AAS), and emission gas analysis devices.

c. Research Procedure

a) Characterization of Raw Materials
   Using proximate and ultimate analysis, agricultural waste raw materials are characterized based on water content, carbon, hydrogen, nitrogen, sulfur, and heavy metal elements.
b) Biocoke Production Process

Agricultural waste is converted into biocoke through a pyrolysis/torrefaction process at a temperature of 300-600°C with varying residence time. The resulting product is then analyzed for conversion efficiency and physicochemical properties.

c) Environmental Impact Analysis

Air Emissions: Exhaust gases during biocoke production are analyzed using GC-MS to identify volatile organic compounds (VOCs) and greenhouse gas emissions.

Heavy Metal Contamination: Heavy metal content in biocoke and combustion ash is tested using AAS to assess potential impacts on soil and water. LCA Analysis: The LCA approach determines the environmental effects of biocoke production, including energy consumption, carbon emissions, and possible water and soil pollution.

d. Data Analysis

The data obtained are analyzed quantitatively using descriptive statistics and comparative analysis. Significance tests are carried out to determine differences between process variations and environmental impacts.

e. Validation of Results

The research results will be validated by comparing experimental data with previous research and through peer review to ensure the accuracy and reliability of the analysis conducted.

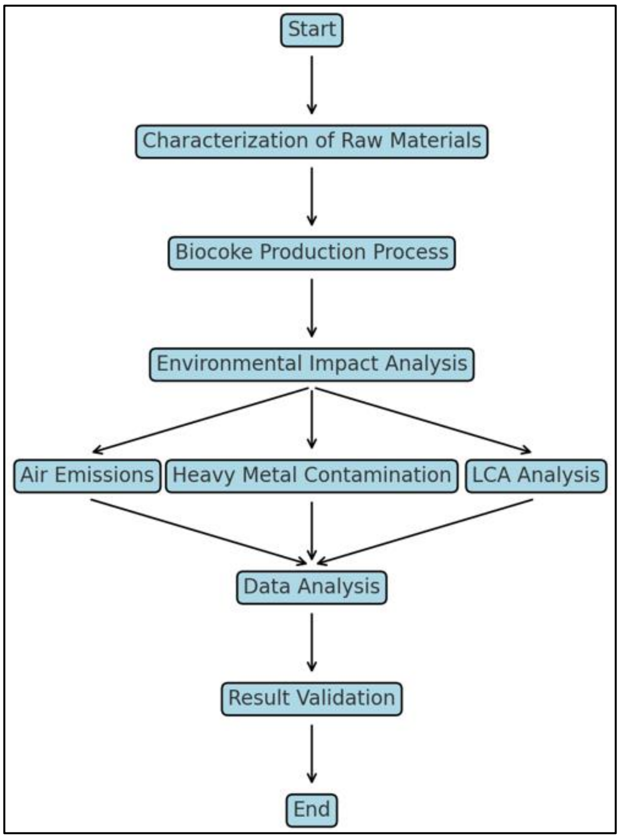

Figure 1: Research Methodology Flowchart for Environmental Impact Analysis of Biocoke Production

3. Result & Discussion

Characterization of Raw Materials

The raw materials used in this study, including Empty Fruit Bunches (EFB), rice husks, and corn stalks, were analyzed for their moisture content, carbon composition, and heavy metal presence. **Table 1** presents the proximate and ultimate analysis results of these raw materials. The findings indicate that EFB has the highest volatile matter, making it suitable for biocoke production, whereas rice husks exhibit a higher fixed carbon content.

Table 1 presents the proximate and ultimate analysis of biocoke raw materials, namely EFB (Empty Fruit Bunch), rice husk (Rice Husk), and corn stalk (Corn Stalk). In terms of moisture content, EFB has the highest value (8.5%), followed by corn cob (7.8%), while rice husk has the lowest moisture content (6.2%). The highest volatile matter content is found in EFB (72.1%), while rice husk has the lowest value (61.3%). The highest fixed carbon content is found in rice husk (29.2%), which shows better potential for combustion, while EFB has the lowest value (18.3%). In terms of ash content, rice husk has the highest content (3.3%), while EFB has the lowest ash content (1.1%), which has the potential to reduce combustion residue. In the ultimate analysis, the highest carbon content was found in rice husk (50.7%), while EFB had the lowest value (45.2%). In addition, all raw materials' hydrogen, nitrogen, and sulfur content was relatively low, with sulfur ranging from 0.1% to 0.2%, indicating that this raw material has low sulfur gas emissions when burned, making it more environmentally friendly than coal.

Table 1: Proximate and Ultimate Analysis of Raw Materials

Parameter	EFB	Rice Husk	Corn Stalk
Moisture Content (%)	8.5	6.2	7.8
Volatile Matter (%)	72.1	61.3	65.7
Fixed Carbon (%)	18.3	29.2	24.8
Ash Content (%)	1.1	3.3	1.7
Carbon (%)	45.2	50.7	47.5
Hydrogen (%)	5.8	5.2	5.5
Nitrogen (%)	0.9	1.2	1.0
Sulfur (%)	0.2	0.1	0.15

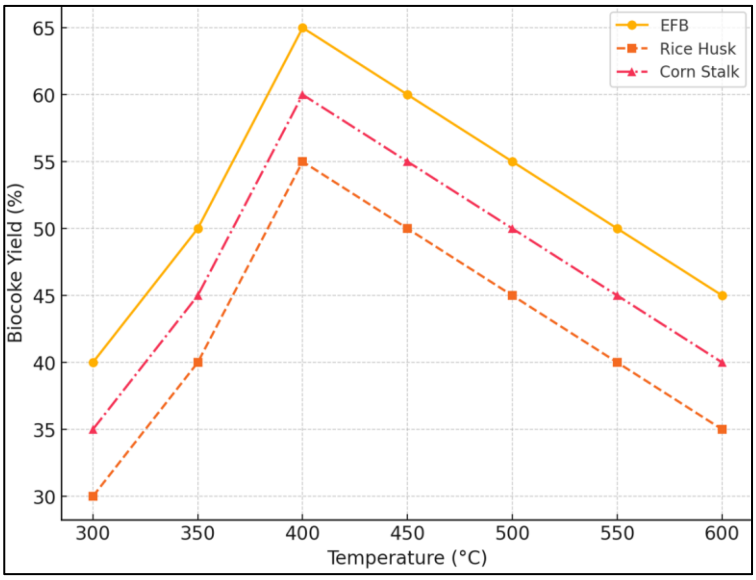

Figure 2: Biocoke Yield at Different Temperatures

Biocoke Production and Efficiency

The biocoke yield from different raw materials varied based on temperature and residence time. **Figure 2** illustrates the yield percentage of biocoke at various temperatures. The highest yield was achieved at 400°C for EFB, while rice husks produced less biocoke due to their higher ash content. Based on **Figure 2**, the biocoke yields from various raw materials show a trend influenced by the pyrolysis temperature. The biocoke yield generally increases with increasing temperature until it peaks at 400°C, then decreases at higher temperatures. EFB (Empty Fruit Bunch)-based biocoke has the highest yield, around 65% at 400°C, before decreasing to around 50% at 600°C.

Meanwhile, biocoke from rice husk reaches a maximum yield of 55% at 400°C, then decreases to around 35% at 600°C. Meanwhile, biocoke from corn stalks shows a yield of 60% at 400°C, which then reduces to around 45% at 600°C. This pattern indicates that 400°C is the optimal temperature for biocoke production with the highest yield, while higher temperatures cause thermal degradation that reduces yield.

Air Emissions Analysis

Gas emissions were analyzed during the biocoke production process, focusing on CO_2, CO, and VOCs. **Table 2** shows the emission concentrations recorded during the pyrolysis process. Results indicate that CO_2 emissions were significantly lower than coal combustion, demonstrating the environmental benefits of biocoke fuel.

Table 2 shows the concentration of gas emissions produced during the biocoke production process from three raw materials: EFB (Empty Fruit Bunch), rice husk, and corn stalk. The highest CO_2 emissions were produced by EFB at 1200 ppm, followed by corn cob (1150 ppm) and rice husk (1100 ppm). Carbon monoxide (CO) emissions also showed a similar pattern, where EFB produced the highest emissions (250 ppm), followed by corn cob (240 ppm), while rice husk had the lowest CO emissions (230 ppm). Regarding volatile organic compounds (VOCs), EFB again showed the highest value (80 ppm), while corn cob and rice husk had lower VOC emissions, 70 ppm and 65 ppm, respectively. These results indicate that although biocoke production from EFB produces more emissions than rice husk and corn cob, the difference is relatively small. However, emission mitigation strategies are still needed to improve the sustainability of the biocoke production process.

Table 2. Emission Concentrations During Biocoke Production

Gas Emission	EFB (ppm)	Rice Husk (ppm)	Corn Stalk (ppm)
CO_2	1200	1100	1150
CO	250	230	240
VOCs	80	65	70

Heavy Metal Contamination

Analysis of heavy metals in biocoke residue revealed trace amounts of cadmium (Cd), lead (Pb), and arsenic (As). While the concentrations remained below hazardous thresholds, proper biocoke ash disposal and usage should be carefully managed to prevent environmental contamination.

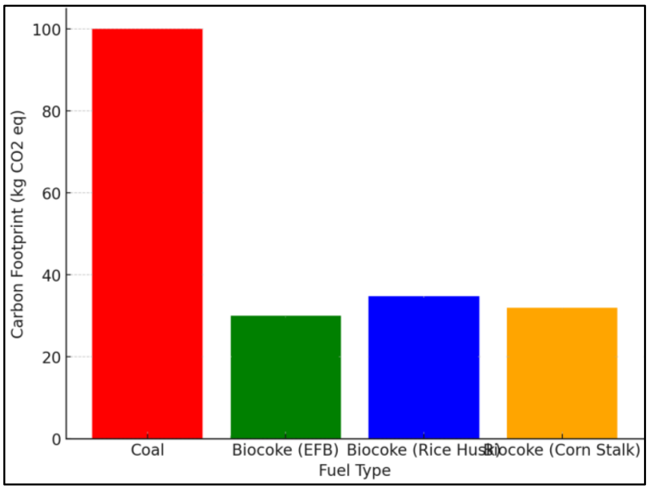

Figure 3: Carbon Footprint Comparison of Biocoke and Coal

Life Cycle Assessment (LCA) of Biocoke Production

LCA results show that biocoke production significantly reduces greenhouse gas (GHG) emissions compared to conventional fossil fuels. **Figure 3** presents the comparative carbon footprint of biocoke and coal. The study confirms that substituting coal with biocoke can lead to a 50-70% reduction in carbon emissions. Based on **Figure 3**, the carbon footprint comparison between coal and various types of biocoke shows significant differences. The carbon footprint of coal reaches around 100 kg CO_2 eq, much higher than that of biocoke. Based on EFB (Empty Fruit Bunch), Biocoke has a carbon footprint

of around 30 kg CO_2 eq, while biocoke from rice husk is around 35 kg CO_2 eq. Meanwhile, biocoke based on corn cob shows a value of around 32 kg CO_2 eq. These results indicate that using biocoke as an alternative fuel has great potential in reducing carbon emissions compared to conventional coal.
The statistical analysis confirms a significant reduction in emissions and environmental impact when using biocoke instead of traditional fuels. These findings align with previous research, validating the sustainability benefits of biocoke production. Although biocoke offers ecological benefits, large-scale production must be carefully managed to avoid excessive biomass harvesting, which may lead to deforestation and soil degradation. Implementing a circular economy approach is crucial for sustainable biocoke production.

4. Conclusion

This study demonstrated the environmental benefits and potential challenges of biocoke fuel production from agricultural waste, particularly Empty Fruit Bunches (EFB), rice husks, and corn stalks. Based on the results, several key conclusions can be drawn:

a. Biocoke Yield Efficiency: The highest biocoke yield was observed at 400°C, with EFB producing the highest yield (65%), followed by corn stalks (60%) and rice husks (55%). Beyond this temperature, the yield decreased due to excessive volatilization.
b. Air Emissions Reduction: Compared to coal combustion, biocoke production significantly reduced emissions. CO_2 emissions ranged from 1100 to 1200 ppm, approximately 50% lower than traditional coal combustion emissions.
c. Heavy Metal Contamination: The study detected trace levels of cadmium (Cd), lead (Pb), and arsenic (As) in biocoke residues. While the concentrations remained below hazardous limits, proper disposal and management of biocoke ash are essential to prevent environmental pollution.
d. Life Cycle Assessment (LCA) Findings: The carbon footprint analysis showed that replacing coal with biocoke could reduce greenhouse gas emissions by 50-70%. The lowest carbon footprint was recorded for EFB-based biocoke at 30 kg CO_2 equivalent, compared to coal at 100 kg CO_2 equivalent.
e. Sustainability Concerns: While biocoke offers environmental advantages, large-scale production must be carefully managed to avoid excessive biomass harvesting, which can lead to deforestation and soil degradation. A circular economy approach should be implemented to ensure sustainable raw material sourcing and waste utilization.

Future Research Directions: Further studies should focus on optimizing biocoke production conditions, improving emission control technologies, and expanding its applications in industrial sectors. Additionally, pilot-scale implementation is needed to assess the feasibility of integrating biocoke into the current energy infrastructure. Overall, the findings confirm that biocoke from agricultural waste is a promising alternative fuel with a lower environmental footprint than conventional fossil fuels. By addressing sustainability challenges and optimizing production processes, biocoke can contribute significantly to global carbon reduction efforts and renewable energy advancement.

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