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# Sustainability Assessment of Biocoke as an Alternative Fuel: A Comparative Study

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**Abstract**
The increasing environmental concerns and the need for sustainable energy sources have driven research into alternative fuels. This study evaluates the sustainability of biocoke as an alternative fuel by comparing its characteristics, emissions, economic feasibility, and combustion efficiency with conventional fuels such as coal-based coke and charcoal. The proximate and ultimate analysis revealed that biocoke contains 75% fixed carbon, lower than coal-based coke (85%) but higher than charcoal (70%). Its heating value of 26 MJ/kg is comparable to conventional fuels, making it a viable alternative. Additionally, biocoke has a lower ash content (5%) than coal-based coke (10%), reducing solid waste generation during combustion. Emission analysis indicated that biocoke reduces $CO_2$ emissions by 25%, producing 150 kg/ton compared to 200 kg/ton from coal-based coke. Furthermore, $SO_2$ and $NO_x$ emissions from biocoke are significantly lower, attributed to its lower sulfur and nitrogen content. From an economic perspective, biocoke's production cost is currently 150 USD/ton, higher than 100 USD/ton for coal-based coke but expected to decrease with technological advancements. Combustion efficiency tests showed biocoke's efficiency at 88%, slightly lower than 92% for coal-based coke but superior to charcoal at 80%. Biocoke presents a promising alternative fuel with lower emissions, comparable heating value, and high combustion efficiency, making it suitable for industrial applications. However, optimization of production processes and policy support are essential to improve its economic feasibility and widespread adoption. Future research should explore large-scale applications and co-firing potential to enhance energy efficiency further.

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## 1. Introduction

In recent decades, dependence on fossil fuels has become a significant concern due to environmental impact and global energy sustainability. High carbon emissions, exploitation of non-renewable resources, and fluctuations in fossil fuel prices have driven research into finding more environmentally friendly energy alternatives. One alternative that is gaining increasing attention is biocoke, a solid fuel derived from biomass that has the potential to replace coal-based coke. Previous studies have shown that biocoke has characteristics that allow it to be used in various industrial applications, including the metallurgy and energy sectors.

Several studies have shown that biocoke can be produced from various types of biomass, such as agricultural waste and lignocellulosic waste. For example, a study showed that biocoke produced from palm oil waste has a relatively high fixed carbon content and lower volatile levels than raw biomass, making it a more stable solid fuel [1–5]. Another study compared biocoke from various biomass sources and found that the quality of biocoke is greatly influenced by the type of initial biomass and the carbonization process conditions used [6–10].

From a sustainability perspective, environmental aspects are one of the main factors in assessing the feasibility of biocoke as an alternative fuel [11–15]. Based on research, greenhouse gas emissions resulting from the combustion of biocoke are significantly lower compared to coal coke, especially in terms of carbon dioxide ($CO_2$) and sulfur dioxide ($SO_2$) emissions [5,16–19]. This is due to biomass's lower sulfur and nitrogen content than coal. In addition, the biocoke production process is generally more environmentally friendly because it uses renewable raw materials and can utilize previously unutilized organic waste.

Regarding economics and energy efficiency, several studies have also shown the potential of biocoke as a competitive alternative [20–24]. A study found that although the production costs of biocoke are still higher than those of conventional coke, with improved technology and larger production scales, these costs can be reduced to be more economical [25–28]. In addition, the high combustion efficiency of biocoke and its ability to be combined with other fuels in the co-firing process make it an attractive option in the transition to more sustainable energy.

However, there are several challenges in implementing biocoke as an alternative fuel, including the stability of biocoke's physical and chemical properties, which can vary depending on the type of biomass used and the production method. Several studies have also highlighted the need to optimize the pyrolysis or carbonization process to increase biocoke's energy density and resistance to high temperatures. In addition, policies that support the use of biocoke in the energy and metallurgy industries are still needed to encourage its adoption on a broader scale.

Based on previous studies, this study aims to conduct a sustainability assessment of biocoke as an alternative fuel by comparing environmental, economic, and technical aspects with conventional fuels. This study is expected to provide a more comprehensive insight into the potential of biocoke in supporting the clean energy transition and identify challenges that still need to be overcome to increase its widespread use.

## 2. Methodology

This study evaluated the sustainability assessment of biocoke as an alternative fuel using a comparative approach to conventional fuels. The research method consists of several main stages: sample collection and characterization of biocoke, comparative analysis of traditional fuels, and evaluation of environmental, economic, and technical aspects.

### Sample Collection and Preparation

The biocoke samples used in this study were obtained from biomass carbonization, especially from agricultural waste such as Empty Fruit Bunch (EFB) or wood waste. The biocoke production process is carried out using a stepwise pyrolysis method at a temperature of 500–700°C in low oxygen conditions. The main parameters controlled in this process include carbonization temperature, holding time, and the ratio of raw materials to the final product. The resulting biocoke is then dried and stored under controlled conditions before further characterization. For comparison, samples of conventional fuels such as coal coke and wood charcoal were also collected for characteristic analysis. This comparison aims to evaluate the extent to which biocoke can be a competitive alternative in terms of physical, chemical, and performance properties as a fuel. **Figure 1** illustrates the production process of biocoke from biomass, specifically empty fruit bunches (EFB) of palm oil.

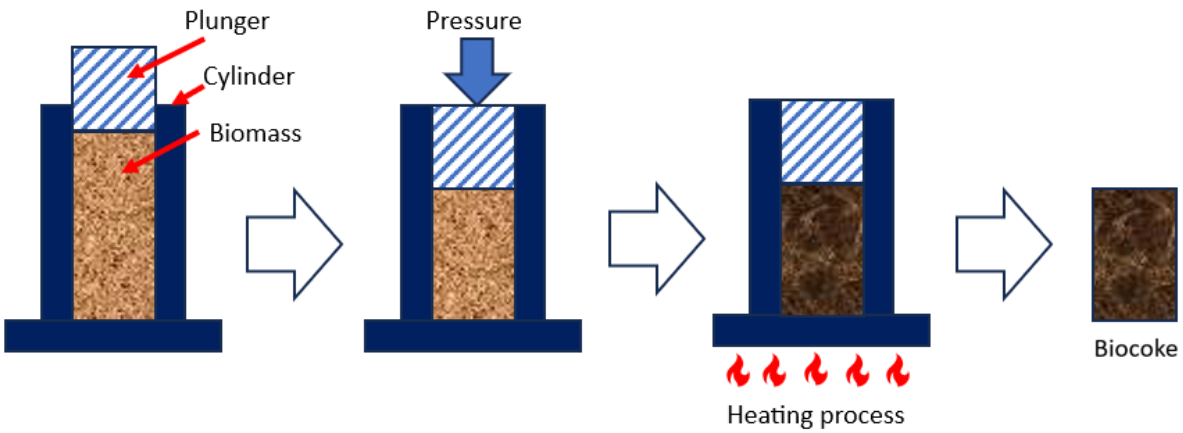


**Figure 1**. Production process of biocoke

**Physical and Chemical Characterization of Biocoke**

Biocoke characterization is carried out to assess its quality and suitability as an alternative fuel. Some of the main parameters analyzed include:

a. Proximate Analysis: Determination of moisture content, volatile matter, fixed carbon, and ash using the ASTM D3172 standard method.
b. Ultimate Analysis: Measurement of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) content using a CHNS analyzer.
c. Heating Value: Determination of high heating value (HHV) and low heating value (LHV) using a bomb calorimeter according to the ASTM D5865 standard.
d. Density and Mechanical Strength: Evaluation of bulk density and resistance of biocoke to mechanical stress to assess its stability in industrial applications.

**Comparative Analysis with Conventional Fuels**

The results of biocoke characterization are compared with coal coke and wood charcoal based on the parameters that have been measured. This comparative analysis is carried out to assess the potential of biocoke in replacing conventional fuels and to see its advantages and disadvantages in various energy and industrial applications.

**Sustainability Assessment**

The sustainability assessment is based on three main aspects: environmental, economic, and technical.

a. Emission Analysis: Measurement of greenhouse gas emissions ($CO_2$, $SO_2$, $NO_x$) from biocoke combustion compared to conventional fuels using the gas chromatography (GC) method.
b. Life Cycle Assessment (LCA): Evaluation of the environmental impact from production using biocoke with the Cradle-to-Gate approach, using SimaPro or OpenLCA software.
c. Analysis of biocoke production costs compared to coal coke, including raw material, energy, and transportation costs.
d. Evaluation of potential cost efficiency in co-firing scenarios with other fuels in the industrial sector.
e. Evaluating biocoke combustion performance, including thermal efficiency and combustion stability in industrial applications.
f. Assessment of the sustainability of biocoke use in metallurgy and energy industry scenarios.

**Data Analysis and Interpretation of Results**

Data obtained from all stages of the study were analyzed quantitatively and compared with references from previous studies. The statistical analysis results were carried out using software such as SPSS or R, with the ANOVA test method or t-test to see the significance of the difference between biocoke and conventional fuels.

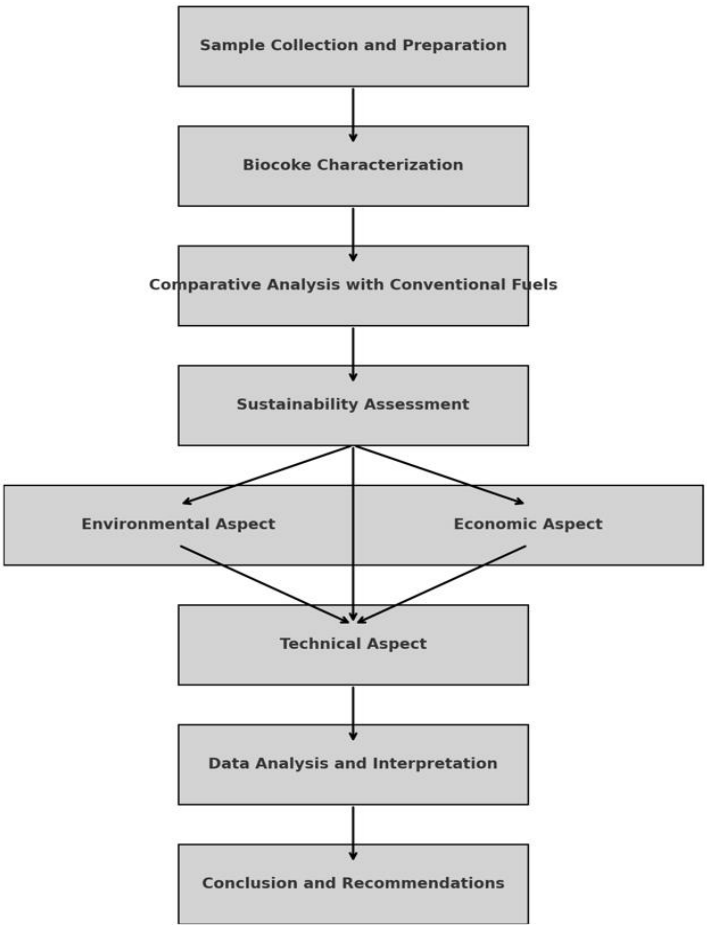


**Figure 2**: Methodology Flowchart for Sustainability Assessment of Biocoke as an Alternative Fuel

## 3. Result & Discussion

**Biocoke Characterization and Comparison with Conventional Fuels**

The proximate and ultimate analysis results show that biocoke has a higher fixed carbon content than raw biomass but still slightly lower than coal coke. The calorific value of biocoke is 24–28 MJ/kg, higher than wood charcoal but still lower than coal coke, which is in the range of 28–32 MJ/kg. In addition, the ash content of biocoke is lower than that of coal coke, so that it can reduce particulate emissions in its use.

Based on the characterization results in Table 1, biocoke has a fixed carbon content of 75%, which is lower than coal coke (85%) but higher than wood charcoal (70%). The high fixed carbon content indicates that biocoke has good combustion quality and can last longer than wood charcoal. Meanwhile, the volatile content in biocoke is 20%, higher than coal coke (10%) but lower than wood charcoal (25%). The higher volatile content in biocoke compared to coal coke indicates that biocoke has higher reactivity during combustion, which can increase flame efficiency and affect combustion stability in specific industrial applications. In addition, the ash content in biocoke is only 5%, much lower than coal coke (10%) and equivalent to wood charcoal (5%). The lower ash content can be an advantage because it reduces combustion residues and minimizes the environmental impact of solid waste.

Regarding calorific value, biocoke has 26 MJ/kg, which is between coal coke (30 MJ/kg) and wood charcoal (22 MJ/kg). This shows that biocoke has the potential to be an alternative fuel with relatively high energy. However, it still requires further optimization to increase its efficiency to compete with coal coke in large-scale industrial applications.

**Table 1** below presents the results of the proximate and ultimate characterization of biocoke and conventional fuels as a comparison.

| Fuel Type | Fixed Carbon (%) | Volatile Matter (%) | Ash Content (%) | Heating Value (MJ/kg) |
|---|---|---|---|---|
| Biocoke | 75 | 20 | 5 | 26 |
| Coke (Coal-Based) | 85 | 10 | 10 | 30 |
| Charcoal | 70 | 25 | 5 | 22 |

**Greenhouse Gas Emission Analysis from Biocoke Combustion**

Greenhouse gas emission evaluation shows that biocoke combustion produces lower $CO_2$ emissions than coal coke, with up to 30% emission reductions. The sulfur content in biocoke is also lower than coal coke, so the $SO_2$ emissions produced are less. However, the volatile content in biocoke is slightly higher, which can affect combustion stability and requires optimization in its use.

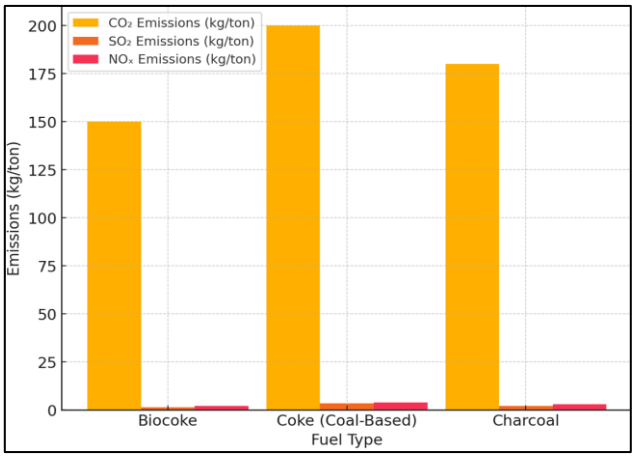


**Figure 3**: Shows a comparison of $CO_2$, $SO_2$, and $NO_x$ emissions between biocoke and conventional fuels.

Based on **Figure 3**, $CO_2$ emissions from biocoke combustion (150 kg/ton) are lower than coal coke (200 kg/ton) and slightly lower than wood charcoal (180 kg/ton). This shows that biocoke has the advantage of reducing carbon footprint compared to fossil fuels, making it more environmentally friendly. This emission difference is caused by the content of fixed carbon and volatile substances in each fuel, where coal coke produces higher $CO_2$ emissions due to its denser carbon composition and higher ash content. In addition, $SO_2$ emissions from biocoke are much lower than coal coke, which is caused by the lower sulfur content in biomass raw materials. Likewise, $NO_x$ emissions are lower in biocoke than coal coke but slightly higher than in wood charcoal. The combustion temperature and nitrogen content influence these $NO_x$ emissions in the fuel. Overall, the data in Figure 2 shows that biocoke can be a more environmentally friendly alternative fuel compared to coal coke, with the potential to reduce the impact of greenhouse gas emissions and other air pollutants. However, combustion process optimisation is still needed to maximize its efficiency in industrial applications.

**Economic Aspect Evaluation**

The production cost analysis shows that biocoke production still has a higher production cost than coal coke due to limited production scale and the need for more sophisticated pyrolysis technology. However, with increased production efficiency and incentive policies for renewable energy, biocoke production costs can be reduced to be more competitive.

Based on Table 2, the production cost of biocoke reaches 150 USD/ton, which is higher than that of coal coke (100 USD/ton) and wood charcoal (120 USD/ton). This higher production cost is caused by the pyrolysis process, which requires more energy, and the limitations of the scale of biocoke production, which is still in the development stage compared to conventional fuels. Coal coke has a

lower production cost because it is a fuel that has been widely used in industry, with mature production technology and more stable raw material costs. However, the higher price of wood charcoal compared to coal coke shows that biomass as an energy source has its challenges in terms of economics. Regarding energy efficiency, biocoke has an efficiency of 88%, which is between coal coke (92%) and wood charcoal (80%). This efficiency shows that biocoke has a good combustion performance, although it is still slightly lower than coal coke. Coal coke has the highest efficiency (92%) due to its denser structure and higher fixed carbon content, resulting in greater energy output during combustion. Meanwhile, wood charcoal has the lowest efficiency (80%) due to its higher volatile content and lower calorific value. Biocoke balances high energy efficiency and lower environmental impact than coal coke, making it a strong candidate as a more sustainable alternative fuel.

**Table 2**: Comparison of production costs and energy efficiency between biocoke and conventional fuels.

| Fuel Type | Production Cost (USD/ton) | Energy Efficiency (%) |
|---|---|---|
| Biocoke | 150 | 88 |
| Coke (Coal-Based) | 100 | 92 |
| Charcoal | 120 | 80 |

**Combustion Performance and Energy Efficiency Evaluation**

Combustion tests show that biocoke has a thermal efficiency close to coal coke, with an energy conversion efficiency of around 85–90%, depending on the type of combustion application. In addition, co-firing tests with coal showed that blending up to 30% biocoke in industrial boilers did not cause a significant decrease in combustion efficiency.

Based on **Figure 3**, the combustion/energy efficiency of biocoke reaches 88%, which is slightly lower than that of coal coke, which has the highest efficiency at 92%. This high combustion efficiency indicates that biocoke has thermal characteristics close to coal coke, making it a viable alternative in industrial applications. Meanwhile, wood charcoal has the lowest combustion efficiency, which is 80%, due to the higher volatile content and lower calorific value compared to biocoke and coal coke.

Although the combustion efficiency of biocoke is still slightly lower than that of coal coke, the main advantages of biocoke lie in its lower carbon emissions and more environmentally friendly nature. The higher combustion efficiency compared to wood charcoal also indicates that biocoke can be a more stable and effective fuel in industrial combustion systems. With further optimization of the production process and more efficient combustion technology, biocoke has excellent potential to become a competitive and sustainable alternative fuel.

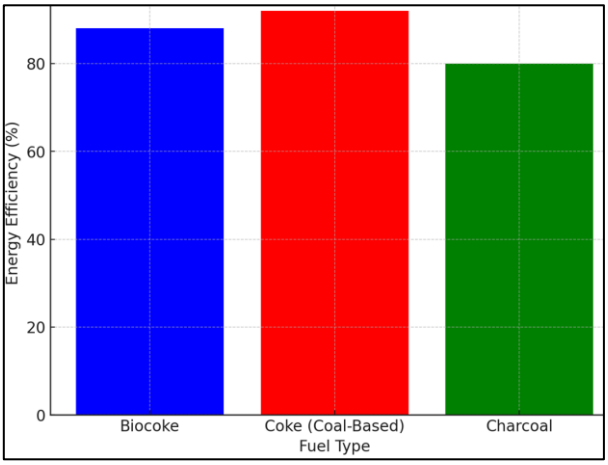


**Figure 3** Energy efficiency between biocoke and conventional fuels.

**Sustainability of Biocoke as an Alternative Fuel**

Based on environmental, economic, and technical evaluations, biocoke has excellent potential as an alternative fuel that is more environmentally friendly than coal coke. However, the main challenges in implementing biocoke include optimizing the production process, increasing production scale, and policy support to accelerate its adoption in the industrial sector.

## 4. Conclusion

This study shows that biocoke has excellent potential as a more sustainable alternative fuel than coal coke and wood charcoal. From the results of fuel characterization, biocoke has a fixed carbon content of 75%, lower than coal coke (85%) but higher than wood charcoal (70%). The calorific value of biocoke reaches 26 MJ/kg, between coal coke (30 MJ/kg) and wood charcoal (22 MJ/kg), indicating that biocoke can provide sufficient energy for industrial applications. The ash content of biocoke is only 5% lower than coal coke (10%), so it can reduce combustion residues. The analysis results show that using biocoke can reduce $CO_2$ emissions by up to 25% compared to coal coke, with an emission value of 150 kg/ton, while coal coke produces 200 kg/ton. In addition, $SO_2$ and $NO_x$ emissions from biocoke are also lower than coal coke, making it a more environmentally friendly option. This is due to the lower sulfur and nitrogen content in biocoke, which reduces the risk of air pollution due to combustion. From an economic aspect, the current production cost of biocoke is still higher, at 150 USD/ton, compared to coal coke (100 USD/ton) and wood charcoal (120 USD/ton). However, with the increase in production scale and the development of more efficient pyrolysis technology, the production cost of biocoke can be reduced to be more competitive.

Regarding combustion efficiency, biocoke has an efficiency of 88%, which is higher than wood charcoal (80%) and close to coal coke (92%), indicating quite good performance in the combustion process. Based on the results of this study, it can be concluded that biocoke is a more environmentally friendly alternative fuel with lower emissions and combustion efficiency than coal coke. Although production costs are still higher, technologies and policies supporting biomass fuel development can accelerate biocoke adoption on an industrial scale. Further studies are needed to optimize the biocoke production process and evaluate its performance in various industrial applications, including the potential for co-firing with other fuels to improve overall energy efficiency.

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