International Jurnal Islamic Education, Research and Multiclturalism (IJIERM)

Available online https://journal.yaspim.org/index.php/IJIERM/index

OPTIMIZATION OF HIGH-FIXED-CARBON BIOCHAR FROM PALM KERNEL SHELLS AS A SUSTAINABLE REPLACEMENT FOR METALLURGICAL COKE USING RESPONSE SURFACE METHODOLOGY

Hariyadi Asful[1], Purwanto Moch[2] Mubarok Fikan R[3], Vantoni Rama[4]

[1,2,3,4] Department of Chemical Engineering, Institut Teknologi Kalimantan

Email : aasful.hariyadi@lecturer.itk.ac.id[1], bm.purwanto@lecturer.itk.ac.id[2], cfikan.mubarok@lecturer.itk.ac.id[3], d05211068@student.itk.ac.id[4]

Abstrak

Pemanfaatan kulit inti sawit (*palm kernel shells*) sebagai bahan baku biochar berpotensi besar sebagai alternatif berkelanjutan pengganti kokas metalurgi yang selama ini bergantung pada sumber daya fosil. Namun, biochar yang dihasilkan harus memenuhi kriteria kadar karbon tetap yang tinggi agar layak digunakan dalam aplikasi metalurgi. Oleh karena itu, penelitian ini bertujuan untuk mengoptimalkan produksi biochar berkadar karbon tinggi dari palm kernel shells sebagai pengganti kokas metalurgi menggunakan metode *Response Surface Methodology* (RSM). Penelitian ini menggunakan metode pre-treatment melalui perendaman kulit inti sawit dalam air panas untuk menurunkan kadar pengotor dan abu, kemudian dilanjutkan dengan proses pirolisis dalam atmosfer inert pada suhu 400–700°C selama 1–3 jam. Biochar yang dihasilkan dianalisis secara proksimat dan dioptimasi kualitasnya menggunakan *Response Surface Methodology* (RSM) dengan desain *Central Composite Design* (CCD).

Kata Kunci: Biochar karbon tinggi, Kokas metalurgi, Kulit inti sawit (Palm Kernel Shells), Pirolisis, Response Surface Methodology (RSM)

Abstract

Palm kernel shells have significant potential as a sustainable biomass resource for producing biochar as an alternative to fossil-based metallurgical coke. However, the biochar must achieve a high fixed carbon content to meet the requirements for metallurgical applications. Therefore, this study aims to optimize the production of high-fixed-carbon biochar from palm kernel shells as a sustainable replacement for metallurgical coke using Response Surface Methodology (RSM). This study uses a pre-treatment method through hot water leaching of palm kernel shells to reduce impurities and ash content, followed by a pyrolysis process under an inert atmosphere at temperatures of 400–700°C for 1–3 hours. The produced biochar was characterized using proximate analysis and its quality was optimized using Response Surface Methodology (RSM) with a Central Composite Design (CCD).

Keywords: High-fixed-carbon biochar, Metallurgical coke, Palm kernel shells, Pyrolysis, Response Surface Methodology (RSM)

INTRODUCTION

The demand for metallurgical coke in the iron and steel industry continues to increase along with the rapid growth of global construction and manufacturing sectors (Sharma & Tiwari, 2024). However, heavy dependence on coal-based coke causes serious problems, including the depletion of fossil resources, high carbon emissions, and significant environmental impacts. These challenges have encouraged the exploration of more sustainable, environmentally friendly, and renewable alternative materials to replace conventional metallurgical coke (Wang et al., 2025). One promising biomass resource for biochar production is palm kernel shells (PKS). Palm kernel shells (PKS) are a solid waste by-product generated in large quantities by the palm oil industry, particularly during the palm oil extraction process. Indonesia, as the world's largest producer of palm oil, produces millions of tons of PKS annually (Babatunde et al., 2025).

Data from the Central Statistics Agency (BPS) compiled by PASPI (2025) indicate a significant upward trend in the total area of smallholder oil palm plantations. In 2000, the plantation area managed by smallholders was recorded at approximately 1.19 million hectares. This figure increased substantially to around 2.5 million hectares by 2010. The expansion continued steadily, exceeding 4.5 million hectares in 2015. By 2021, the total area of smallholder oil palm plantations had surpassed 6 million hectares, reflecting rapid and sustained growth over the past two decades (BPDP, 2025).

Despite this abundance, PKS is still underutilized and often treated as low-value waste, used only for limited purposes such as direct combustion for energy. This condition highlights a significant opportunity to convert PKS into higher-value products that are both economically and environmentally beneficial (Raza & Abu-Jdayil, 2023). From a material perspective, PKS possesses favorable characteristics as a feedstock for biochar production, including high inherent carbon content, low moisture, and a dense, rigid structure. These properties make PKS highly suitable for thermochemical conversion processes, particularly pyrolysis (Chee et al., 2023). Through controlled pyrolysis, PKS can be transformed into high-quality biochar with improved fixed carbon content, low volatile matter, and enhanced energy properties. As a result, PKS-based biochar has strong potential for advanced industrial applications, including as a sustainable alternative to metallurgical coke (Hassan et al., 2021).

High-fixed-carbon biochar can serve as a potential substitute for metallurgical coke if it meets key quality requirements, such as high fixed carbon content, low ash content, and sufficient calorific value (Wang et al., 2024). However, the quality of biochar is highly dependent on process conditions, particularly pyrolysis temperature and residence time. Without proper optimization, the resulting biochar may still contain high levels of volatile matter and ash, making it unsuitable for metallurgical applications (Chen et al., 2022). Therefore, a systematic optimization approach is required to produce biochar with characteristics comparable to metallurgical coke. Response Surface Methodology (RSM) is a powerful statistical tool for optimizing process parameters by simultaneously evaluating the interactions among variables. Through this approach, this study seeks to obtain high-fixed-carbon biochar from palm kernel shells with strong potential as a sustainable replacement for metallurgical coke.

Previous research conducted by Alonge and Obayopo (2023) demonstrated that the application of Response Surface Methodology (RSM) with a Central Composite Design (CCD) was highly effective in optimizing the carbonization process of palm kernel shells (PKS) in terms of fixed carbon content and yield. The optimum conditions were achieved at a temperature of 469.16°C, a residence time of 17.68 minutes, and a specific particle size, resulting in a fixed carbon content of 79.65% with a corresponding yield of 34.00%, with temperature identified as the most influential factor. The developed regression models showed excellent predictive accuracy with adjusted R^2 values of 0.9701 for fixed carbon and 0.9869 for yield, and the validation results confirmed close agreement between predicted and experimental values, indicating the strong potential of PKS as a solid fuel material.

Sarker, Ethen, and Nanda (2024) reviewed the potential of biochar as a sustainable substitute for coal in iron and steelmaking industries, highlighting its significant role in reducing greenhouse gas emissions. Their study reported that biochar substitution ranging from 5% to 50% is technically feasible and beneficial in various metallurgical processes, including coke making, iron sintering, blast furnaces, and electric furnaces. The findings demonstrate that biochar offers strong potential as a competitive renewable alternative to fossil fuels for supporting the decarbonization of the metallurgical industry.

Wang, Zhou, and Zhao (2025) reviewed the applications of biochar in fuel and feedstock substitution within global energy systems amid increasing carbon reduction targets. Their study emphasized that biochar, as the main solid product of biomass pyrolysis, possesses high energy density, excellent thermal stability, and a well-developed porous structure, making it a promising renewable substitute for fossil-based fuels and raw materials. Using VOSviewer analysis, the authors highlighted the significant role of biochar in fossil fuel replacement and resource utilization, providing theoretical and technical support for its large-scale and efficient application.

The novelty of this study lies in the systematic optimization of high-fixed-carbon biochar derived from palm kernel shells specifically targeted as a sustainable replacement for metallurgical coke, with an emphasis on achieving metallurgical-grade quality. Unlike previous studies that mainly focused on general biochar production, this research highlights the attainment of high fixed carbon content through controlled pre-treatment and pyrolysis conditions optimized using Response Surface Methodology (RSM). Therefore, this study aims to determine the optimum operating conditions of temperature and residence time to produce high-quality biochar from palm kernel shells with characteristics suitable for metallurgical applications.

LITERTURE REVIEW

Biochar

Biochar is a solid product obtained from the pyrolysis of biomass under limited oxygen conditions. Its main characteristics include high carbon content, good thermal stability, and a porous structure, making it effective as an adsorbent, alternative fuel, and soil amendment. Biochar has gained increasing attention due to its ability to sequester carbon, reduce greenhouse gas emissions, and support sustainable energy strategies (Bushra & Remya, 2020). In the context of the metallurgical industry, biochar has potential as a substitute for coke because it can provide the high fixed carbon content required in metal reduction processes. Previous studies by Cueva et al., (2022) indicate that biochar quality is strongly influenced by the type of biomass, pyrolysis conditions, and pre-treatment processes. Therefore, a deep understanding of biochar properties is crucial to ensure that the produced biochar meets industrial standards.

Palm Kernel Shells (PKS)

Palm Kernel Shells (PKS) are a solid by-product of the palm oil industry with limited current uses, such as direct fuel or fertilizer. PKS has relatively high carbon content and a hard structure, making it an ideal feedstock for producing high-quality biochar through pyrolysis. Utilizing

PKS for biochar production not only reduces industrial waste but also provides a more sustainable energy alternative compared to fossil-based fuels (Zulkafli et al., 2022). Usino etal., (2023) shown that the properties of biochar derived from PKS strongly depend on particle size, moisture content, and pre-treatment methods before pyrolysis. With proper treatment, PKS can produce biochar with high fixed carbon content and low ash, meeting the requirements for metallurgical applications. This highlights the potential of PKS as an environmentally friendly and high-value biochar feedstock.

Metallurgical Coke

Metallurgical coke is a solid fuel used in the iron and steel industry as a carbon source in ore reduction processes. Conventional coke is typically derived from coal, but its limited availability and high carbon emissions have raised the need for sustainable alternatives (Guo et al., 2024). Finding renewable substitutes is therefore essential to support a more environmentally friendly steel industry. High-carbon biochar, such as that produced from PKS, exhibits characteristics like metallurgical coke, including high fixed carbon content and thermal stability (Sajdak et al., 2023). Recent studies by Safarian (2023) indicate that biochar can partially or fully replace coke in various metallurgical processes, reducing reliance on fossil fuels and contributing to industrial decarbonization strategies.

Response Surface Methodology (RSM)

Response Surface Methodology is a statistical and mathematical technique widely used for process optimization by examining the relationships and interactions among multiple variables (Chelladurai et al., 2021). This method allows researchers to model and analyze complex processes, providing a systematic approach to understand how input variables affect the desired responses. By using RSM, it is possible to reduce the number of experimental runs while still obtaining reliable information on the influence of each factor. RSM is particularly useful for determining the optimal conditions such as pyrolysis temperature, residence time, and particle size. Proper optimization through RSM can enhance biochar quality by increasing fixed carbon content and reducing ash and volatile matter. Viegas et al., (2024) studies have demonstrated that RSM improves the efficiency of biomass carbonization processes and ensures reproducibility in biochar production.

Moreover, RSM is often applied with experimental designs like Central Composite Design (CCD), which allows precise modeling of the response surface and prediction of optimal conditions. Using these approaches, researchers can accurately forecast the outcome of biochar characteristics and validate them experimentally (Mariyam et al., 2023).

This makes RSM a powerful tool not only for optimization but also for ensuring consistent biochar quality that meets industrial standards and application requirements.

RESEARCH METHODS

Palm kernel shells (PKS) were sourced from PT. Waru Kaltim Plantation. Water leaching was applied to reduce ash content before pyrolysis.

Figure 1	Description
	**Figure 1.** ***Biochar*** **Experimental Setup;** Pyrolysis was performed in a retort furnace at varying temperatures (400–700°C) and residence times (1–3 hours). The process aimed to maximize fixed carbon content while minimizing ash and volatile matter (15).

Methods

(1) **Pre – treatment**
The pre-treatment stage involved water leaching to remove impurities, particularly minerals contributing to ash content. PKS was submerged in hot water at 60°C with continuous stirring for 2 hours. Afterward, the shells were dried in an oven at 105°C until a constant weight was achieved (Anika et al., 2022; Liu et al., 2018).

(2) **Pyrolisis Process**
The dried PKS was subjected to pyrolysis in a retort furnace under an inert atmosphere. Temperature variations of 400–700°C and residence times of 1–3 hours were applied. The biochar yield, bio-oil, and syngas composition were recorded at each temperature level.

(3) **Biochar Characterization and Testing**
To evaluate the quality of biochar, proximate analysis was performed to determine moisture content, ash content, volatile matter, and fixed carbon. The following tests were conducted:

a. Moisture Content Analysis**:** Biochar samples were heated at 105°C for 1 hour, and weight loss was measured.
b. Ash Content Determination: Samples were combusted at 750°C for 3 hours in a muffle furnace to determine residual ash.
c. Volatile Matter Analysis**:** Samples were heated at 950°C for 7 minutes in a sealed crucible.

d. Fixed Carbon Calculation**:** The percentage of fixed carbon was derived from subtracting moisture, ash, and volatile matter from the total composition (Raza et al., 2021).

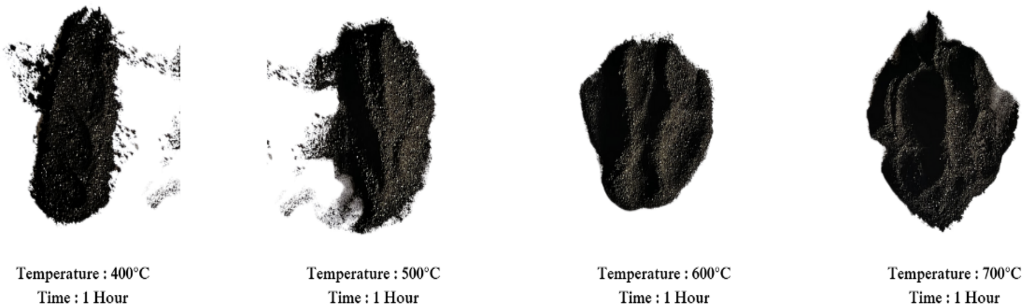


Figure 2. Biochar Temp 400^{o}C, 500 ^{o}C,600^{o}C and 700 ^{o}C at 1 Hour

(4) **Optimization Using RSM**

Response Surface Methodology (RSM) is a statistical and mathematical technique widely used to optimize processes by analyzing the interactions among multiple variables (Chelladurai et al., 2021). In this study, Central Composite Design (CCD) was employed to investigate the effects of pyrolysis temperature and residence time on biochar quality. The response variables included moisture content, ash content, volatile matter, fixed carbon, and calorific value, which are critical parameters for assessing metallurgical-grade biochar.

While RSM allows prediction of optimal conditions and evaluation of factor interactions, the statistical analysis should be completed with ANOVA tables to determine the significance of each factor and interaction. Key statistical metrics such as R^2, adjusted R^2, and predicted R^2 are essential to assess model fit and predictive accuracy. In addition, 3D response surface and contour plots visually demonstrate the interaction between factors and their influence on biochar quality, providing a more intuitive understanding of the optimization process.

For full validation, the model must also be assessed through lack-of-fit tests and residual diagnostics to ensure its reliability and applicability in industrial conditions. Including these analyses ensures that the RSM results meet the rigorous statistical standards required by Scopus-indexed journals, while providing a robust basis for determining the optimum pyrolysis conditions for high-fixed-carbon biochar production.

RESULTS AND DISCUSSION

Characteristics of Palm Kernel Shell

Table 1. Specifications Raw PKS

Parameter	Satuan	Nilai
Proximate		
Moisture	%adb	9.37
Fixed Carbon	%adb	21.19
Volatile Matter	%adb	63.76
Ash	%adb	5.68
Ultimate		
Carbon (C)	%adb	48.49
Hidrogen (H)	%adb	6.51
Nitrogen (N)	%adb	0.54
Sulfur (S)	%adb	0.007
Oksigen (O)	%adb	42.31
Gross Calorific Value	kcal/g	4698

Evaluation of the Effect of Temperature and Time on Pyrolysis Products

1. **Effect of Temperature on Pyrolysis Yield**
   Biochar Yield : As temperature increased from 400°C to 700°C, biochar yield decreased from 41.07% to 32.12% within 1-hour residence time. This decline is due to thermal decomposition of the main biomass components, such as cellulose, hemicellulose, and lignin (Khitab et al., 2021). Bio-Oil Yield : Increased with higher temperatures, peaking at 27.67% at 700°C. This increase results from greater volatilization of organic compounds at higher temperatures. Gas Yield : Remained relatively stable but peaked at 46.37%, indicating enhanced gasification at higher temperatures.
2. **Effect of Residence Time on Pyrolysis Yield**
   2 Hours Residence Time: (1) Biochar yield decreased from 38.69% (400°C) to 31.11% (700°C); (2) More complete lignin decomposition led to higher bio-oil production.
3. **Hours Residence Time:** (1) Biochar yield declined further, from 37.83% (400°C) to 24.85% (700°C); (2) Longer residence time caused secondary reactions, converting biochar to lighter gases like CO_2 and CH_4; (3) Bio-oil yield peaked at 30.12% at 600°C, but decreased slightly at 700°C due to thermal cracking into gases (Vasudev et al., 2021).

4. Effect of Temperature and Time on Biochar Chemical Composition

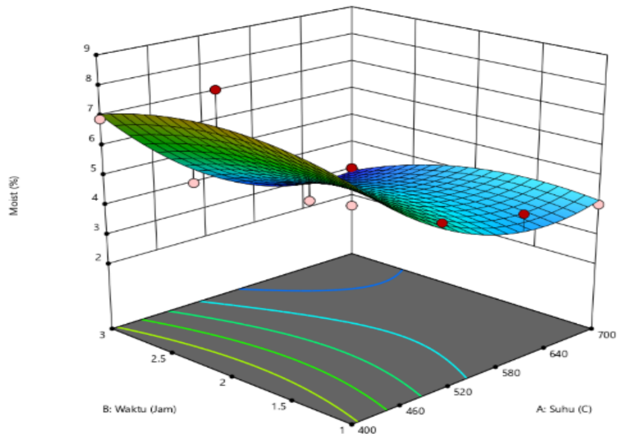
Table 2. Proximate Analysis

No.	Suhu (°C)	Waktu (Jam)	%Moisture	%Ash Content	%Volatile Matter	%Fixed Carbon	*Gross Calorific Value* (kcal/kg)	AISI Standard
1.	400°C	1	6.46	3.65	27.45	62.44	5631.27	□
		2	8.83	3.88	22.97	64.32	5790.14	□
		3	6.91	3.97	21.22	67.90	5940.67	□
2.	500°C	1	5.1	4.40	12.70	77.80	5832.45	□
		2	4.58	4.44	11.78	79.20	6015.32	□
		3	4	4.67	7.23	84.10	6248.67	□
3.	600°C	1	4.55	4.46	11.49	79.50	6542.19	□
		2	4.12	4.66	7.50	83.72	6890.45	□
		3	3.65	4.77	5.38	86.20	7025.34	√
4.	700°C	1	4.05	4.67	7.23	84.05	6895.42	□
		2	3.85	4.82	5.02	86.31	7058.91	√
		3	3.02	6.04	5.05	85.89	7237.68	√

The study examined the impact of pyrolysis temperature and residence time on the chemical composition of biochar from palm kernel shells (PKS). Higher temperatures and longer residence times led to an increase in fixed carbon content while reducing volatile matter and moisture. At 400°C, fixed carbon was 53.12%, rising to 78.43% at 700°C, with an optimal value achieved at 600°C for 3 hours, meeting metallurgical coke standards (Jamilatun et al., 2020). Ash content increased with temperature due to the accumulation of inorganic minerals, from 3.65% at 400°C to 6.04% at 700°C. Volatile matter showed a significant decline, dropping from 38.56% at 400°C to 18.32% at 700°C, indicating enhanced carbon stability. Additionally, moisture content decreased as temperature increased, making the biochar drier and more stable, with values declining from 5.23% at 400°C to 3.02% at 700°C. Overall, the optimal pyrolysis condition of 600°C for 3 hours produced biochar with high fixed carbon (>85%), low ash content, and properties that meet metallurgical coke specifications, positioning it as a sustainable alternative for the steel industry (Jamilatun et al., 2020).

Evaluation of the Effect of Time and Temperature on Biochar quality

1. **Effect of Temperature and Time on Moisture Content**

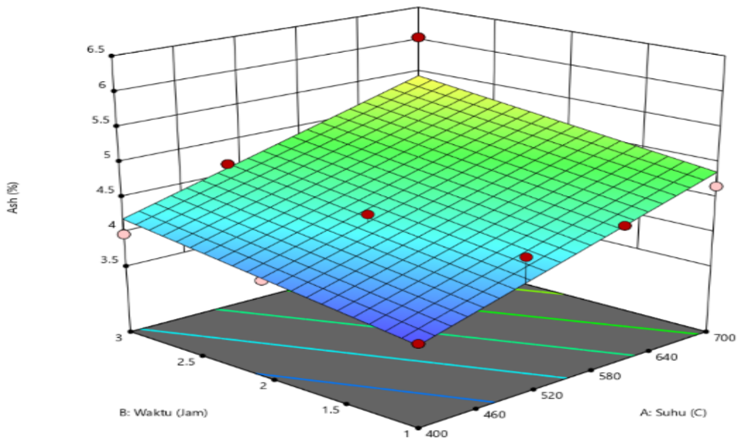


Moisture content is an important factor in determining the quality of biochar. Based on the ANOVA test, temperature has a significant effect on moisture content with a p-value of 0.0009, while residence time is not very significant. The model used is Quadratic and Linear with the equation:

$$Y = 4.60 - 1.76A - 0.3225B - 0.3180AB + 1.34A^2 - 0.6275B^2. \quad (1)$$

The results showed that the higher the temperature and residence time, the more the moisture content decreased. For example, at 500°C for 1 hour, the moisture content was 5.1%, while at 600°C for 2 hours it dropped to 4.12%. In accordance with previous research, increasing the temperature decreases the moisture content and increases the fixed carbon (Rahman et al., 2020).

2. **Evaluation of the Effect of Time and Temperature on %Ash**

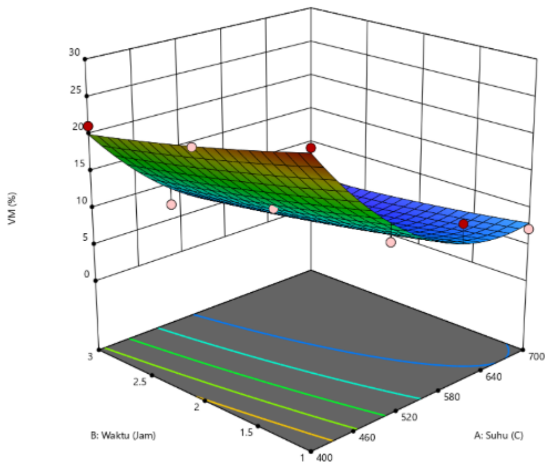


Ash content increases as the temperature and residence time increase, as the inorganic minerals in the biomass are not decomposed during pyrolysis. Based on the ANOVA test, temperature and residence time have a significant effect on ash content with p-values of 0.0004 and 0.0235, respectively. The model used is Linear with the equation:

$$Y = 4.54 + 0.6235A + 0.2837B$$

The results showed that temperature was more influential than residence time on ash content. At 400°C for 1 hour, the ash content was 3.65%, while at 700°C for 3 hours, the ash content increased to 6.04%. This result is in accordance with previous research which states that the higher the temperature, the higher the ash content due to an increase in mineral residues (Rahman et al., 2020).

3. Evaluation of the Effect of Time and Temperature on %Volatile Matter

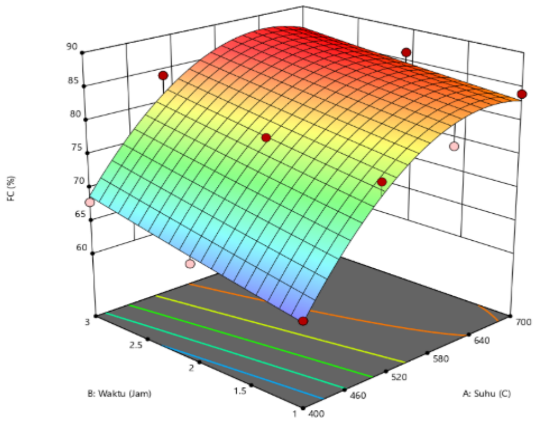


Volatile matter content is affected by temperature and residence time during the pyrolysis process. Based on ANOVA test, temperature has the most significant effect on volatile matter with p-value <0.0001, while residence time also has an effect with p-value 0.0123. The model used is Quadratic with the equation:

$$Y = 8.39 - 8.52A - 2.50B + 0.8633AB + 6.16A^2 + 0.4013B^2. (3)$$

The results showed that the higher the temperature and residence time, the lower the fly content. At 400°C for 1 hour, the fly content was 27.45%, while at 600°C for 3 hours, the fly content dropped to 5.38%. This indicates that higher temperatures vaporize more volatile substances, resulting in a more stable biochar suitable for metallurgical applications (Wang et al., 2021).

4. **Evaluation of the Effect of Time and Temperature on %Fixed Carbon**

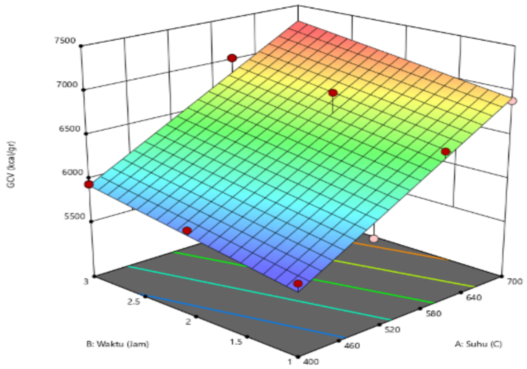


The fixed carbon content is directly proportional to the heating value of biochar. The higher the fixed carbon, the higher the heating value produced. Based on ANOVA test, temperature has the most significant effect on fixed carbon with p-value <0.0001, while residence time also has an effect with p-value 0.0199. The model used is Quadratic with the equation:

$$Y = 82.51 + 9.65A + 2.54B - 0.7845AB - 7.43A^2 + 0.0975B^2.(4)$$

The results showed that as the temperature and residence time increased, the carbon content continued to increase. At 500°C for 1 hour, the fixed carbon content was 77.8%, while at 600°C for 2 hours, the fixed carbon content reached 83.72%. This increase occurs because the water content and volatile substances are reduced, resulting in biochar with a more stable carbon structure (Wang et al., 2021).

5. **Evaluation of Time and Temperature Effect on %Gross Calorific Value**



Calorific value indicates the amount of heat energy that can be produced by biochar and is influenced by fixed carbon content, ash, volatile substances, and moisture content. Based on ANOVA test, temperature has the most significant influence on heating value with p-value <0.0001, while residence time also has an effect with p-value 0.0046. The model used is Linear with the equation:

$$Y = 6425.71 + 692.57A + 193.88B \quad (5)$$

The results showed that the higher the temperature and residence time, the higher the heating value of biochar. At 400°C for 1 hour, the heating value was 5631.27 kcal/kg, while at 700°C for 3 hours, the heating value increased to 7237.68 kcal/kg. This increase is due to the increase in fixed carbon and the decrease in water content and volatile substances, which increases the combustion efficiency of biochar.

Thus, increasing the pyrolysis temperature (from 400°C to 700°C) and extending the residence time consistently led to a decrease in biochar yield, while simultaneously producing biochar with significantly higher fixed carbon content, reduced volatile matter and moisture, and increased calorific value indicating enhanced carbonization and devolatilization. The main mechanism is that at higher temperatures, volatile components in the biomass (cellulose, hemicellulose, and lignin) are devolatilized, releasing gases and bio-oil, which reduces the overall mass but enriches the solid residue in carbon and enhances its structural stability. The remaining inorganic minerals in the PKS largely remain as ash, slightly increasing the ash content, but the proportion of fixed carbon and its thermal quality improve, resulting in biochar that more closely resembles the characteristics of metallurgical coke.

These findings are consistent with previous studies on PKS and other lignocellulosic biomass. For instance, Onokwai et al., (2023) reported that optimizing carbonization conditions using Response Surface Methodology (RSM) increased fixed carbon content to nearly 80% while reducing biochar yield, confirming that temperature is the most significant factor affecting carbon content and ash formation. Similarly, Lu & Gu (2022) found that longer residence times enhanced lignin decomposition, increasing fixed carbon and calorific value while decreasing volatile matter, highlighting the critical role of thermal treatment in stabilizing the carbon structure.

Zhang et al. (2021) observed that pyrolysis temperature plays a critical role in determining the composition and properties of biochar, bio-oil, and gaseous products. At lower temperatures (around 200 °C), cellulose begins to decompose, producing organic compounds with conjugated π-bond structures, while extensive degradation to bio-oil occurs around 300 °C, peaking at 450 °C with heavier bio-oil fractions. Structural analyses revealed that at approximately 430–440 °C, cellulose undergoes significant structural reconstruction, forming abundant C=O functionalities in biochar.

Liao et al. (2022) emphasized that the preparation of biochar from three common agricultural wastes bamboo, rice husks, and corn cobs at pyrolysis temperatures ranging from 300 °C to 600 °C, focusing on the effects of biomass type and temperature on physicochemical properties, adsorption performance, stability, and economic feasibility. The results showed that increasing pyrolysis temperature decreased biochar yield, oxygen-containing functional groups, and polarity, while enhancing ash content, alkalinity, stability, and adsorption capacity. Economic analysis indicated that rice husk biochar produced at 500 °C had the highest cost-effectiveness for heavy metal adsorption, with 292.73 mg/$ for Pb^{2+} and 84.29 mg/$ for Cu^{2+}. Additionally, rice husk biochar exhibited superior adsorption stability due to the dominance of complexation and ion exchange mechanisms. Qing et al. (2025) additionally demonstrated that prolonged heating promotes secondary reactions that convert remaining volatile matter into permanent gases, further increasing carbon purity and calorific value.

Collectively, these studies corroborate that controlled pyrolysis of PKS under optimized temperature and residence time can produce biochar with high fixed carbon content, low ash and volatile matter, and superior thermal properties. Such characteristics align with metallurgical coke standards, confirming the feasibility of using PKS-derived biochar as a sustainable alternative in steelmaking processes.

CONCLUSION

The study demonstrated that both pyrolysis temperature and residence time significantly affect biochar yield, chemical composition, and calorific value. As temperature increased from 400°C to 700°C and residence time was extended from 1 to 3 hours, biochar yield decreased due to thermal decomposition, while fixed carbon content, calorific value, and carbon stability increased, with the optimal condition achieved at 600°C for 3 hours producing biochar with over 85% fixed carbon, low ash content, and properties meeting metallurgical coke standards. ANOVA analysis confirmed that temperature is the most influential factor on moisture, ash, volatile matter, fixed carbon, and calorific value, while residence time also contributes significantly. Overall, these results indicate that PKS-derived biochar can serve as a sustainable alternative to metallurgical coke, and future work should focus on scaling up production, assessing economic feasibility, evaluating carbon footprint, and testing integration into EAF/BOF steelmaking systems.

BIBLIOGRAPHY

1) Alonge, O. I., & Obayopo, S. O. (2023). Optimization study on carbonization of palm kernel shell using response surface method. *International Journal of Integrated Engineering,* 15(7), 135–144. https://doi.org/10.30880/ijie.2023.15.07.013
2) Anika, N., Mahardika, M., Panjaitan, J. R. H., Achmad, F., Bindar, Y., Azizah, I. N., Anggraini, R., & Ramadhani, D. A. (2022). Effect of Production Technique on Corncob Biochar Quality. *IOP Conference Series: Earth and Environmental Science*, *1038*(1), 012007.
3) Babatunde, E. O., Enomah, S., Akwenuke, O. M., Ibeh, M. A., Okwelum, C. O., Mundu, M. M., Adepoju, P. O., Aki, A. O., Oghenejabor, O. D., Adepojua, T. F., Ifedora, C. O., & Majanja, M. K. (2025). Preparation and characterization of Palm Kernel Shell (PKS) based biocatalyst for the transformation of kernel oil to biodiesel. *South African Journal of Chemical Engineering,* 52(1). https://hdl.handle.net/10520/ejc-chemeng-v52-n1-a19
4) Badan Pengelola Dana Perkebunan (BPDP). (2025). *Peran strategis perkebunan sawit rakyat di Indonesia.* https://www.bpdp.or.id/peran-strategis-perkebunan-sawit-rakyat-di-indonesia
5) Bushra, B., & Remya, N. (2024). Biochar from pyrolysis of rice husk biomass—characteristics, modification and environmental application. *Biomass Conversion and Biorefinery,* 14, 5759–5770. https://doi.org/10.1007/s13399-020-01092-3
6) Chee, A. L. K., Chin, B. L. F., Goh, S. M. X., Chai, Y. H., Loy, A. C. M., Cheah, K. W., Yiin, C. L., & Lock, S. S. M. (2023). Thermo-catalytic co-pyrolysis of palm kernel shell and plastic waste mixtures using bifunctional HZSM-5/limestone catalyst: Kinetic and thermodynamic insights. *Journal of the Energy Institute,* 107, 101194. https://doi.org/10.1016/j.joei.2023.101194
7) Chelladurai, S. J. S., Murugan, K., Ray, A. P., Upadhyaya, M., Narasimharaj, V., & Gnanasekaran, S. (2021). Optimization of process parameters using response surface methodology: A review. *Materials Today: Proceedings,* 37(2), 1301–1304. https://doi.org/10.1016/j.matpr.2020.06.466
8) Chen, D., Zhuang, X., Gan, Z., Cen, K., Ba, Y., & Jia, D. (2022). Co-pyrolysis of light bio-oil leached bamboo and heavy bio-oil: Effects of mass ratio, pyrolysis temperature, and residence time on the biochar. *Chemical Engineering Journal,* 437 (Part 1), 135253. https://doi.org/10.1016/j.cej.2022.135253
9) Cueva, L. L. Z., Griffin, G. J., Ward, L. P., Madapusi, S., Shah, K. V., & Parthasarathy, R. (2022). A study of chemical pre-treatment and

pyrolysis operating conditions to enhance biochar production from rice straw. *Journal of Analytical and Applied Pyrolysis,* 163, 105455. https://doi.org/10.1016/j.jaap.2022.105455

10) Guo, Y., Wang, X., & Deng, K. (2024). The road to carbon neutrality in the metallurgical industry: Hydrogen metallurgy processes represented by hydrogen-rich coke oven gas, short-process metallurgy of scrap and low-carbon policy. *In Journal of Physics: Conference Series (Vol. 2798, 012053).* IOP Publishing. https://doi.org/10.1088/1742-6596/2798/1/012053
11) Hassan, N., Abdullah, R., Khadiran, T., et al. (2023). Biochar derived from oil palm trunk as a potential precursor in the production of high-performance activated carbon. *Biomass Conversion and Biorefinery,* 13, 15687–15703. https://doi.org/10.1007/s13399-021-01797-z
12) Jamilatun, S., Mufandi, I., Budiman, A., & Suhendra, S. (2020). Biochar from slow catalytic pyrolysis of spirulina platensis residue: Effects of temperature and silica-alumina catalyst on yield and characteristics. *Jurnal Rekayasa Proses*, *14*(2), 137–147.
13) Khitab, A., Ahmad, S., Khan, R. A., Arshad, M. T., Anwar, W., Tariq, J., Khan, A. S. R., Khan, R. B. N., Jalil, A., & Tariq, Z. (2021). Production of biochar and its potential application in cementitious composites. *Crystals*, *11*(5), 527.
14) Liao, W., Zhang, X., Ke, S., Shao, J., Yang, H., Zhang, S., & Chen, H. (2022). Effect of different biomass species and pyrolysis temperatures on heavy metal adsorption, stability and economy of biochar. *Industrial Crops and Products*, 186, 115238. https://doi.org/10.1016/j.indcrop.2022.115238
15) Liu, M., Shen, Z., Liang, Q., Xu, J., & Liu, H. (2018). New slag–char interaction mode in the later stage of high ash content coal char gasification. *Energy & Fuels*, *32*(11), 11335–11343.
16) Lu, X., & Gu, X. (2022). A review on lignin pyrolysis: Pyrolytic behavior, mechanism, and relevant upgrading for improving process efficiency. *Biotechnology for Biofuels,* 15, 106. https://doi.org/10.1186/s13068-022-02203-0
17) Onokwai, A. O., Okokpujie, I. P., Ajisegiri, E. S. A., Oki, M., Onokpite, E., Babaremu, K., & Jen, T.-C. (2023). Optimization of pyrolysis operating parameters for biochar production from palm kernel shell using response surface methodology. *Mathematical Modelling of Engineering Problems,* 10(3), 757. https://doi.org/10.18280/mmep.100304
18) Mariyam, S., Alherbawi, M., Pradhan, S., et al. (2024). Biochar yield prediction using response surface methodology: Effect of fixed carbon

and pyrolysis operating conditions. *Biomass Conversion and Biorefinery*, 14, 28879–28892. https://doi.org/10.1007/s13399-023-03825-6
19) Rahman, M. S., Haque, M. E., & Noman, M. R. A. F. (2020). An overview of biochar production and biochar producing stoves in Bangladesh. *International Journal of Science and Management Studies (IJSMS)*, 14–31.
20) Raza, M., & Abu-Jdayil, B. (2023). Synergic interactions, kinetic and thermodynamic analyses of date palm seeds and cashew shell waste co-pyrolysis using Coats–Redfern method. *Case Studies in Thermal Engineering*, 47, 103118. https://doi.org/10.1016/j.csite.2023.103118
21) Raza, M., Inayat, A., Ahmed, A., Jamil, F., Ghenai, C., Naqvi, S. R., Shanableh, A., Ayoub, M., Waris, A., & Park, Y.-K. (2021). Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing. *Sustainability*, *13*(19), 11061.
22) Safarian, S. (2023). To what extent could biochar replace coal and coke in steel industries? *Fuel,* 339, 127401. https://doi.org/10.1016/j.fuel.2023.127401
23) Sajdak, M., Muzyka, R., Gałko, G., Ksepko, E., Zajemska, M., Sobek, S., & Tercki, D. (2023). Actual trends in the usability of biochar as a high-value product of biomass obtained through pyrolysis. *Energies,* 16(1), 355. https://doi.org/10.3390/en16010355
24) Sarker, T. R., Ethen, D. Z., & Nanda, S. (2024). Decarbonization of metallurgy and steelmaking industries using biochar: A review. *Chemical Engineering & Technology*. https://doi.org/10.1002/ceat.202400217
25) Sharma, N., & Tiwari, H. P. (2024). Sustainable cokemaking technology: Future needs for ironmaking. *Coke and Chemistry,* 67, 210–223. https://doi.org/10.3103/S1068364X24701321
26) Usino, D. O., Sar, T., Ylitervo, P., & Richards, T. (2023). Effect of acid pretreatment on the primary products of biomass fast pyrolysis. *Energies,* 16(5), 2377. https://doi.org/10.3390/en16052377
27) Vasudev, V., Ku, X., & Lin, J. (2021). Combustion behavior of algal biochars obtained at different pyrolysis heating rates. *ACS Omega*, *6*(29), 19144–19152.
28) Viegas, C., Nobre, C., Correia, R., Gouveia, L., & Gonçalves, M. (2021). Optimization of biochar production by co-torrefaction of microalgae and lignocellulosic biomass using response surface methodology. *Energies,* 14(21), 7330. https://doi.org/10.3390/en14217330
29) Qing, H., Shagali, A. A., Mostafa, M. E., Hu, S., Xu, K., Xu, J., Jiang, L., Wang, Y., Su, S., & Xiang, J. (2025). Nonlinear mechanism of carbon dioxide on the release of volatile matter from bituminous coal

combustion at high heating rate. *Fuel,* 398, 135531. https://doi.org/10.1016/j.fuel.2025.135531

30) Wang, B., Li, C., & Cao, W. (2021). Effect of polyacrylonitrile precursor orientation on the structures and properties of thermally stabilized carbon fiber. *Materials*, *14*(12), 3237.
31) Wang, H., Zhou, P., & Zhao, X. (2025). Applications of biochar in fuel and feedstock substitution: A review. *Energies,* 18(17), 4511. https://doi.org/10.3390/en18174511
32) Wang, L., Yang, Y., Ou, Y., Dong, Y., Zhong, Q., Zhang, Y., Li, Q., Huang, Z., & Jiang, T. (2024). Enhancement of coal tar pitch carbonization with biochar: A metallurgical formed biocoke product produced by waste coke breeze and bamboo powder. *Fuel,* 358(Part B), 130238. https://doi.org/10.1016/j.fuel.2023.130238
33) Wang, S., Yu, S., Feng, T., Li, W., & Zhang, R. (2025). Life cycle environmental impacts based on detailed stages and synergistic environmental benefits of coke production in China. Journal of Environmental Chemical Engineering, 13(5), 117527. https://doi.org/10.1016/j.jece.2025.117527
34) Zhang, C., Chao, L., Zhang, Z., Zhang, L., Li, Q., Fan, H., Zhang, S., Liu, Q., Qiao, Y., Tian, Y., Wang, Y., & Hu, X. (2021). Pyrolysis of cellulose: Evolution of functionalities and structure of bio-char versus temperature. *Renewable and Sustainable Energy Reviews,* 135, 110416. https://doi.org/10.1016/j.rser.2020.110416
35) Zulkafli, A. H., Hassan, H., Ahmad, M. A., et al. (2024). Co-pyrolysis of palm kernel shell and polypropylene for the production of high-quality bio-oil: Product distribution and synergistic effect. *Biomass Conversion and Biorefinery,* 14, 13391–13406. https://doi.org/10.1007/s13399-022-03476-z