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REVIEW ARTICLE

Recycling Palm Shell Waste into Biochar Using Biomass-Based Pyrolysis Method for Sustainable Energy Transition: A Review

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Abstract

Palm kernel shell (PKS), a by-product of Indonesia's palm oil industry, represents both a waste management challenge and an opportunity for renewable energy transition. This review critically examines recent advancements in the conversion of PKS into biochar using biomass-based pyrolysis. By synthesizing findings across multiple studies, the review highlights how pyrolysis parameters—such as temperature (200–1200 °C), residence time (1–4 hours), and chemical activation (NaOH, H_2SO_4)—affect the physicochemical properties of biochar. Among these, the combination of 550 °C pyrolysis temperature, 2-hour residence time, and NaOH pre-treatment via microwave-assisted pyrolysis was identified as optimal for maximizing fixed carbon content, surface area, and adsorption capacity. Such biochar is suitable for a wide range of applications, including soil amendment, wastewater treatment, and long-term carbon sequestration. The review not only confirms the environmental viability of PKS biochar based on Indonesian National Standards (SNI), but also emphasizes its role in supporting sustainable agriculture and mitigating greenhouse gas emissions. Future research directions include scaling production technologies and assessing biochar performance in diverse agroecological systems.

Keywords: palm kernel shell, biochar, pyrolysis, carbon sequestration, waste valorization, renewable energy, adsorption

1. Introduction

Oil palm (*Elaeis guineensis*) plays a very important role in the Indonesian economy, particularly in the plantation and agricultural sectors, contributing to foreign exchange earnings, national income, rural development, labor absorption, and renewable energy through biofuel or biodiesel production [1-4]. With 15.08 million hectares of plantations and over 46 million tons of crude palm oil (CPO) produced annually, Indonesia leads the global palm oil market [3]. However, this vast industry also produces substantial quantities of biomass waste, both solid and liquid, including trunks from replanting, fronds, empty fruit bunches (EFB), shells, and fibers [5-8]. Palm oil mill waste, if not properly managed, contributes significantly to environmental degradation, including air pollution, water contamination, and greenhouse gas emissions[9]. Palm oil mill waste, if not properly managed, contributes significantly to environmental degradation, including air pollution, water contamination, and greenhouse gas emissions Improper handling of palm oil biomass waste, such as open burning or untreated effluents, has led to significant environmental issues including greenhouse gas emissions, water pollution, and air quality degradation [10-14].

Palm oil waste, as a by-product not involved in the main oil production process, presents storage, transportation, and processing challenges. According to Table 1, palm oil mills generate various types of waste per ton of fresh fruit bunch (FFB), with liquid waste comprising 50% and EFB being the largest contributor among solid wastes (23%), followed by fiber (13%), shell (6%), and wet decanter solids (4%) [15]. These residues have the potential for diverse utilization: as compost, animal feed, activated carbon, and energy sources. Despite their value, these wastes are often underutilized, leading to environmental issues due to improper disposal and treatment [16, 17].

Table 1. Percentage of Palm Waste Potential per Ton of Palm Fruit [15].

Waste Type	Persentage per ton (FFB) (%)	Benefit
Empty Bunches	23,0	Compost fertilizer, Paper pulp, Particle board and energy
Wet Decanter Solid	4,0	Compost fertilizer and animal feed
Shell	6	Charcoal, activated carbon and particleboard, biochar production
Fibber	13,0	Charcoal, energy, particleboard and paper pulp
Liquid waste	50,0	Fertilizer and irrigation water

The table illustrates that palm kernel shell (PKS), although a smaller fraction of the waste stream (6%), holds strategic importance due to its high carbon content, lignocellulosic composition, and abundant availability. This makes PKS highly suitable for thermochemical conversion using pyrolysis into value-added products such as biochar, activated carbon, and solid fuels[9,18]. PKS has been shown to yield a higher fixed carbon content and thermal stability compared to many other biomass types, making it ideal for pyrolysis-based biochar production [19,20]. In addition to PKS, other agricultural residues such as corn cobs, rice straw, and sugarcane bagasse have also been extensively studied for their potential as renewable bioenergy sources in Indonesia [21-25]. Biomass conversion to energy not only reduces fossil fuel dependency but also supports Indonesia's broader energy diversification goals [26-29]. PKS contains 53.85% lignin, 26.16% hemicellulose, and 6.92% cellulose, making it thermally stable and highly porous when pyrolyzed [30,31]. Moreover, PKS biochar contains essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), surpassing many other biomass types [32].

Biochar is a carbon-rich, porous solid derived from biomass carbonization through pyrolysis—a process that decomposes organic matter at high temperatures in the absence of oxygen [33-36]. Biochar improves soil physical and chemical properties, including porosity, moisture retention, and bulk density, while also reducing dependence on chemical fertilizers and enhancing microbial activity [37-40]. Its stability allows it to remain in soil for hundreds to thousands of years, contributing to long-term carbon sequestration and improved soil fertility [41,42]. The quality of biochar is influenced by the manufacturing process and the type of raw materials used [43,44]. Due to its unique aromatic structure, biochar carbon is more resistant to decomposition compared to untreated organic matter, thus supplying carbon to the soil more efficiently [45]. However, the effects of biochar vary depending on soil conditions, plant species, and the type of biochar applied, with spatial and temporal variations in its effectiveness [46,47]. Beyond agricultural benefits, biochar contributes to climate change mitigation by reducing greenhouse gas emissions such as CO_2, CH_4, and N_2O [48-52]. Recognizing its potential, the Indonesian Ministry of Environment and Forestry launched the FOLU Net Sink 2030 program, aiming to make the forestry and land-use sector a net carbon sink by ensuring that carbon absorption exceeds emissions [53]. Greenhouse gases—including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs)—have intensified global warming due to their rising concentrations in the atmosphere [54]. In alignment with the Paris Agreement, Indonesia's Nationally Determined Contribution (NDC) pledges to reduce GHG emissions by 29% independently and up to 41% with international support by 2030 [55].

By facilitating carbon sequestration, soil remediation, and emission reduction, biochar emerges as a strategic solution to support these targets [49,50]. Converting biomass into stable carbon reduces CO_2 emissions typically released during natural decomposition, while also minimizing nitrate, nitrous oxide, and methane emissions from agricultural systems [51,52]. Thus, biochar serves as an alternative pathway in reducing pollution and achieving net-zero emissions targets [56].

2. Materials and methods

2.1 Palm Kernel Shell

Palm Kernel Shell (PKS), a solid biomass waste by-product from the extraction of tenera varieties of palm oil (*Elaeis guineensis Jacq*), has been widely reported as a potential feedstock for bioenergy development. This waste is abundant in the Southeast Asian region, particularly in Indonesia and Malaysia, the two countries with the highest palm oil production in the world [57]. According to Febriyanti [58] palm kernel shell accounts for about 60 per cent of the total solid waste generated in the palm oil processing industry, making it one of the biomass sources that has not been fully utilised optimally.

Figure 1. Palm Kernel Shell-PKS [59].

Tabel 2. Chemical Content of Palm Kernel Shell [60].

Biomass Type	Chemical content (%)		
	Lignin	**Celullose**	**Hemicelullose**
Oil Palm	53.85	6.92	26.16

The selection of PKS as a raw material through pyrolysis is strongly supported by its chemical composition which is rich in lignocellulose, especially lignin with a content of more than 45% [57]. The high lignocellulose content in palm kernel shells indicates that palm kernel shells have the potential as raw material for biochar production [61]. In addition, the local availability of large amounts of PKS in palm oil producing countries is also an important supporting factor for the development of sustainable biomass-based bioenergy.

2.2 Pyrolysis Method

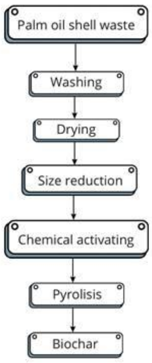

Figure 2. Biochar production process flow [62]

Table 3. Effect of residence time and chemical activation on physio chemical properties of palm kernel shell biochar

Temperature	Time (Hour)	Activation	Reference
500° - 600°	1	NaOH 1 M	[60]
500° - 600°	1	NaOH 1 M	[61]
550°	2	H_2SO_4	[63]
Up To 1202°	2	Nitrogen	[59]
200° - 300°	4	Nitrogen	[64]

Pyrolysis temperature is one of the most crucial parameters in biochar synthesis because it directly affects yield, carbon stability, surface area, and final porosity. Increasing the pyrolysis temperature generally enhances pore development in the biochar structure; however, it simultaneously reduces the overall yield due to greater mass loss during the thermal decomposition process[65]. The function of temperature in the pyrolysis process is to provide the heat needed to break down the chemical bonds of the biomass[66]. Biochar obtained from different variations, showed very different physical and chemical properties. Where the higher the temperature the higher the yield of the organic phase, water phase, and gas, while the char decreases[67]. The properties also depend on other factors such as pyrolysis mode, pyrolysis temperature and pyrolysis duration[68]. pyrolysis temperature affects the quality of activated carbon where there is an increase in fixed carbon content[69]. From the reviewed studies, temperatures were classified in three main categories: low (200-300 °C), medium (500-600 °C), and high (≥1000 ◦C).

2.2.1 Temperature Variation

In the low-temperature pyrolysis process used in the 200-300 °C range, pyrolysis is carried out using simple gas stove-based technology. Although it does not produce a very stable carbon structure, this temperature is sufficient to form a basic biochar that can be used as a raw material for briquettes. The resulting biochar at this temperature generally still has a fairly high level of fly matter (40-43%), but with a good calorific value (around 6000 cal/g), showing potential as a solid fuel[64]. The intermediate temperature (500-600 °C) used in pyrolysis is done to produce biochar with better adsorption properties. This temperature is high enough to remove most of the volatiles, but has not yet reached the full degree of aromatization. Biochar at this temperature range is characterized by a more structured morphology and a more reactive surface [60],[61]. Meanwhile, using a temperature of 550 °C is controlled through a microwave-assisted pyrolysis system. This technology allows for rapid temperature increase and higher energy efficiency than conventional methods. A temperature of 550 °C was chosen as the optimal temperature based on considerations between porosity, carbon content, and energy efficiency of the process[63]. The use of high temperatures up to 1202 °C was associated with thermogravimetric analysis (TGA) and changes in biochar composition[59]. These extreme temperatures produce biochar with a more thermally stable structure and high fixed carbon content, although the biochar yield tends to be lower due to more complete decomposition of volatiles. However, large amounts of nutrients such as N, K and S are lost through evaporation at higher temperatures during pyrolysis[56].

Overall, various studies show that pyrolysis temperature has a significant effect on the biomass decomposition process, especially on lignocellulose content such as hemicellulose, cellulose, and lignin. As the applied temperature increases, the decomposition of volatile compounds also increases, and the carbon structure formed in biochar becomes more stable, resulting in biochar with high porosity, larger surface area, and better carbon content retention. However, if the temperature is too high, there will be a decrease in biochar yield due to significant mass loss during the process. Based on the study results, a temperature of 550 °C is considered the most ideal as it balances carbon stability, adsorption capacity, and energy efficiency during the pyrolysis process. Generally, temperatures in the range of 500–600 °C are effective for producing biochar with good adsorption quality, while lower temperatures are more suitable for producing biochar as fuel, and temperatures above 1000 °C are more suitable for highly stable biochar but with low nutrient content.

2.2.2 Time Comparison

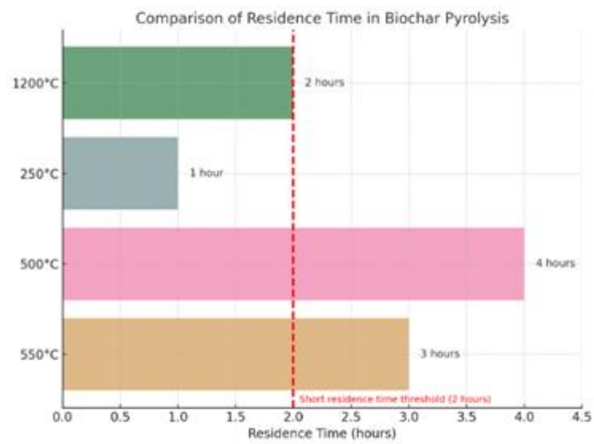

Figure 3. Comparison of residence time in biochar pyrolysis process at various pyrolysis temperatures (250°C-1200°C)

Pyrolysis time is the length of the pyrolysis process that takes place to process oil palm shells into biochar[70]. Charcoal yield decreases as pyrolysis time increases[71]. In the literature, residence time is divided into short (≤2 hours) and long (>2 hours). Using a residence time of 2 h in a microwave reactor, after reaching a temperature of 550 °C [63]. This time is considered sufficient to form a stable carbon structure without wasting energy, as well as preventing over-decomposition that could reduce the adsorptive properties of biochar. Meanwhile, only uses 1 h residence time in conventional pyrolysis, which is commonly used in small-scale laboratories to produce activated biochar. Different from the above two approaches, which used a residence time of 4 hours, reflecting the simple furnace-based slow pyrolysis process of[64]. Time refers to the length of time the raw material is in the pyrolysis reactor at the target temperature. The longer the pyrolysis time, the higher the ash content and flying substance content, and the lower the moisture content, bound carbon content, and heating value [72]. The long residence time allows the complete release of water and volatiles, but also indicates the low energy efficiency of the small-scale technology. The duration of pyrolysis is not explicitly mentioned, but the discussion of TGA shows that the weight change continues until temperatures above 1000 °C, indicating a long enough residence time for thermal and chemical characterization studies[59].

Based on the analyzed research results, the duration of pyrolysis is also an important factor influencing the carbonization level of biochar and the energy efficiency of the process. A pyrolysis time of 2 hours is considered the most balanced duration, especially in microwave-based pyrolysis processes, as it produces biochar with a stable carbon structure and high adsorption capacity without causing excessive energy consumption. Meanwhile, longer pyrolysis times, such as 4 hours, can indeed optimize the complete removal of volatile compounds, but they are less energy-efficient and do not always result in a significant improvement in biochar quality. Therefore, when determining the pyrolysis duration, it is essential to balance energy efficiency with the intended use of the biochar, where a duration of 1 to 2 hours is generally sufficient to produce high-quality biochar, particularly in terms of structural stability and adsorption capacity.

2.2.3 Chemical Activation

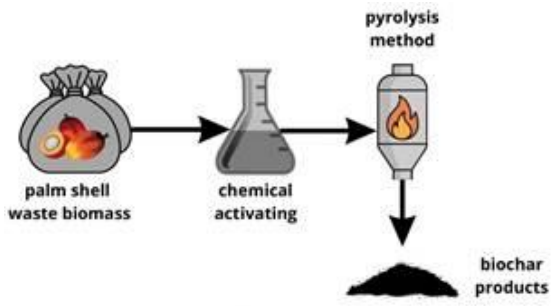

Figure 4. Addition of chemical activation to the pyrolysis process[73]

Chemical activation is often preferred because it allows the production of activated carbon with higher carbon content using lower heating temperatures and faster reaction times [74].Chemical activation is the process of breaking the carbon chain of organic compounds with the use of chemicals[75]. Based on Arrhenius' theory, which states that catalysts can accelerate the reaction rate. A catalyst is a substance that can accelerate the reaction rate because the catalyst has the ability to interact with at least one reactant molecule to produce a more reactive intermediate compound[76]. This is because activation energy is inversely proportional to the speed of a reaction. The greater the speed of the reaction, the more the product will be produced [77]. In the pyrolysis process, the presence of a catalyst is a positive thing because it can reduce energy requirements compared to the thermal pyrolysis process and also serves to reduce reaction time and catalysts can improve the quality and quantity of output results[78]. This activation is generally done before or during pyrolysis, and can use basic agents such as NaOH or acids such as H_3PO_4. However, it is important to distinguish between pyrolytic activation and post-pyrolysis modification. Using basic chemical activation (1 M NaOH) before pyrolysis, which aims to enlarge the pore and increase the adsorption capacity of biochar to heavy metal contaminants[60][61].This process is categorized as pyrolytic activation, as chemical reagents are added before the pyrolysis process takes place, and the end result is activated biochar. Meanwhile, there are those who do not perform activation in the context of pyrolysis[63]. After the pyrolysis process is complete, the resulting biochar is then modified through sulfonation using sulfuric acid (H_2SO_4). Sulfuric acid has properties that are easily soluble in water, a dhydrating agent, and can oxidize and have extensive active sites [79]. The purpose of this process is to introduce $-SO_3H$ groups to the surface of the biochar, thereby improving the catalytic and magnetic properties of the material. Since it is performed after pyrolysis, this process is more appropriately referred to as post-pyrolysis modification, rather than conventional chemical activation as in biochar adsorption. not classified as studies with "chemical activation" in the general context of adsorption, but as studies applying chemical post-treatment for specific applications[63]. While there are those that do not use chemical activation at all, producing biochar through direct pyrolysis without additional chemical treatment. The resulting biochar better reflects the natural properties of palm kernel shells and is suitable for applications such as energy (briquettes) or soil amendment [59][64].

Patterns observed from various studies indicate that the process plays a crucial role in enhancing biochar quality, particularly in increasing specific surface area and adding active functional groups to biochar. Activation with NaOH prior to pyrolysis has proven effective in opening micro- and mesopores, as well as enhancing biochar adsorption capacity, especially for pollutants such as heavy metals. On the other hand, activation using H_2SO_4 after pyrolysis is more effective in improving the catalytic properties of biochar, making it more suitable for use as a catalyst. Therefore, the choice of activation method should be tailored to the intended application of biochar; NaOH activation is ideal for adsorption applications, while H_2SO_4 activation is more suitable for catalytic needs. Meanwhile, biochar without chemical activation tends to retain the natural characteristics of the raw material, making it more suitable for applications as fuel or soil conditioner.

3. Results and discussion

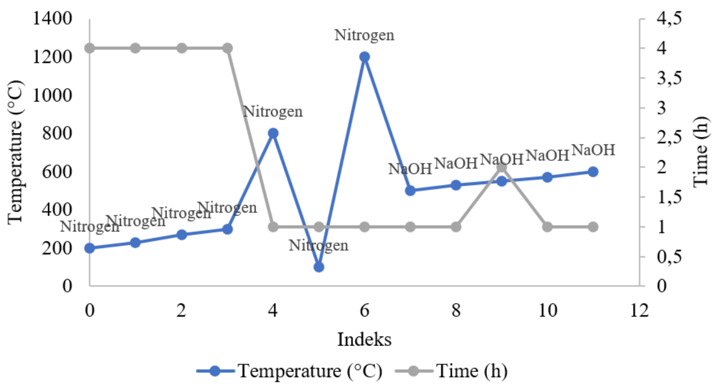

Figure 4. Graph of Effect of Residence Time and Chemical Activation on Physicochemical Properties of Palm Kernel Shell Biochar[59][60][63][64]

The results of biochar produced at low temperatures (200 °C - 300 °C) have high levels of fly substances around 40-43% and a heating value of around 6000 cal/g. Pyrolysis with relatively low heating temperatures can produce relatively high charcoal products[80]. Medium temperatures with a range of 500 °C - 600 °C produce most of the volatile substances can be removed, so that the biochar has a more structured morphology and a more reactive surface [60][61][63]. The use of microwave-assisted pyrolysis method with optimal temperature control (550 °C) that enables high energy efficiency makes it an excellent choice from a technical perspective[63]. On the other hand, biochar production with high temperatures of up to 1202 °C produces biochar with a very stable carbon structure and high carbon content[59]. It is assumed that elevated temperatures result in significant yeast cell death, which leads to a slower rate of glucose being converted into ethanol[81]. However, the high pyrolysis temperature can cause the volatile content to decrease[80]. During the pyrolysis process, short residence times during the process (≤2 hours) produce biochar with a fairly stable carbon structure without sacrificing energy efficiency [60][61][63]. While a longer residence time of 4 hours (Yanti) can help the complete release of volatile substances, it is less energy efficient.

Based on the activation approach given, the use of chemical activation with 1 M NaOH before pyrolysis [60][61] which is categorized as pyrolytic activation because of its use before the pyrolysis process is carried out, aims to increase the surface area and adsorption capacity of biochar, especially against heavy metals. In another study, post-pyrolysis modification was also carried out through sulfonation with sulfuric acid (H_2SO_4)[63] which aims to improve the catalytic properties of biochar. Meanwhile, the use of Nitrogen[59][64] without any other chemical activation, produced biochar that reflected the natural properties of the raw materials. Based on the overall study, the most optimal pyrolysis method was carried out at a combination of 550 °C temperature with 2 h residence time, and the use of microwave-assisted pyrolysis method because it provides high energy efficiency and produces biochar with structures with good surface properties, especially for catalytic and adsorption applications. However, the incorporation of medium temperature and NaOH chemical activation can be the best choice in adsorption capacity to pollutants such as heavy metals. As for the production of biochar as solid fuel such as briquettes, a method using low temperature to produce biochar with high heating value is more suitable.

Figure 5. Palm Kernel Shell Biochar-PKSBC[59]

Biochar produced from oil palm shells shows physical and chemical qualities suitable for various environmental and energy applications[82]. The results showed that pyrolysis at 600°C for 1 hour and activation using NaOH produced biochar with 1% moisture, 8% ash, 20% volatile, and 71% fixed carbon[60]. This value meets the SNI 06-3730-1995 standard[83], so that the biochar can be utilized as a carbon storage medium, soil improver, and adsorbent in environmental remediation[84]. These characteristic values are similar to other studies, although the moisture content is slightly higher (2%) due to the hygroscopic nature of biochar[61]. The high fixed carbon content and low ash strengthen the potential of this biochar as an alternative fuel and purifying agent in wastewater treatment[85]. SEM analysis shows the porous and rough surface of biochar, which supports its ability to absorb pollutants[86]. Supported by BET analysis, the specific surface area was recorded at 299.76 m^2/g, with a pore size of 2.18 nm and a pore volume of 0.1632 cm^3/g. These characters make biochar ideal for use in water filtration systems, heavy metal sorption such as Pb and Cd, and as a catalyst support medium[87]. Characterization of functional groups through FTIR reveals the presence of -OH, C=O, and C-O which play an important role in chemical bonding with contaminants[88]. The semi-crystalline pattern in the XRD results shows the stability of the biochar structure, which is beneficial for long-term applications in improving soil fertility and nutrient binding[89].

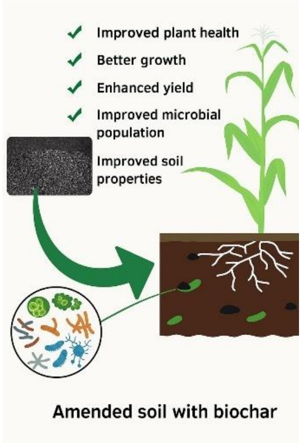

Figure 6. Potential Biochar in enviromental field[90]

Based on these properties, biochar from oil palm shells has wide application potential. In the environmental field, biochar can be used as an adsorbent for heavy metals, dyes, and harmful organic compounds in wastewater[91]. Its high adsorption capacity makes biochar an economical and environmentally friendly alternative to commercial activated carbon[92]. In addition, biochar also acts as a soil amendment, increasing water retention, nutrient availability, and soil microbial activity[93]. The high carbon content allows biochar to be used as a medium for long-term carbon sequestration, which is relevant for climate change mitigation[94]. In the energy sector, biochar is combustible and can be used as a solid fuel or briquette mixture, especially if produced at low to medium pyrolysis temperatures[95]. Furthermore, surface modification of biochar (e.g. sulfonation) can produce heterogeneous catalyst materials useful in biodiesel production or other biomass conversion reactions. Thus, it can be concluded that pyrolysis temperature, activation technique, as well as feedstock composition greatly influence the character of the biochar produced. Biochar from appropriately processed oil palm shells shows high potential as a versatile material in renewable energy and environmental mitigation approaches[62].

Conclusions

The transformation of palm kernel shell (PKS), a significant agro-industrial waste in Indonesia, into biochar via pyrolysis represents not only a waste valorization approach but also a meaningful contribution to the national transition toward sustainable and circular bioeconomy. The review of recent studies highlights that optimized pyrolysis conditions—particularly at 550 °C for 2 hours with NaOH activation—consistently yield biochar with desirable properties for environmental remediation, including high fixed carbon, porosity, and functional surface chemistry. More broadly, the findings underscore that biochar from PKS is not merely an end product but a multifunctional material with cross-sectoral applications: from enhancing soil fertility and nutrient retention in agriculture, to acting as a sorbent for pollutants in water treatment, and even as a pathway for long-term carbon sequestration. This implies that, with appropriate standardization and policy support, PKS biochar could be scaled for regional and international applications—especially in other palm-oil-producing nations facing similar waste management and climate challenges. While the lab-scale studies reviewed provide compelling evidence for the material’s utility, broader field-based validations, techno-economic assessments, and life cycle analyses are necessary to fully unlock its potential. Future integration of PKS biochar into climate-smart agriculture and green infrastructure could position it as a strategic material in global decarbonization efforts and sustainable land-use management.

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