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Pyrolytic Conversion of Palm Kernel Shells To Biochar and Comparative Insights with Incineration and Gasification for Environmental Sustainability

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ABSTRACT

The palm oil industry produces large volumes of palm kernel shell (PKS) solid waste, most of which has been utilized as biomass, but some of which remain unused and have the potential to increase greenhouse gas emissions if not managed optimally. Pyrolysis of PKS to biochar offers a sustainable solution to reduce environmental impacts while producing value-added products. This systematic review employs the PRISMA methodology to comprehensively compare various pyrolysis methods and operational conditions used in the conversion of PKS and other palm oil wastes, and to identify the main results, applications, and environmental benefits of each approach. Through rigorous analysis of 30 peer-reviewed studies spanning 2015–2025, the findings reveal that the optimal conditions for biochar production are slow pyrolysis (400–600°C, 30–90 minutes residence time) with a yield of 33–52%. Biochar demonstrates significant multifunctional potential across diverse applications: soil improvement and agriculture (increasing soil fertility and carbon sequestration with CSP 0.63 $kgCO_2/kg$ PKS), air treatment and pollutant adsorption, energy and fuel (briquette production), health and safety (reducing environmental toxicity), and industrial and material applications (raw material for activated carbon production). Comparative environmental and economic assessment demonstrates that pyrolysis of PKS offers superior sustainability compared to incineration and gasification when biochar is sequestered or utilized in high-value applications. Its dual benefits of renewable energy recovery and carbon storage address both immediate energy needs and long-term climate change mitigation, positioning pyrolysis as an economically viable and environmentally preferable technology for palm oil industry waste valorization.

Keywords:
Palm Kernel Shell;
Biochar;
Pyrolysis;
Application

INTRODUCTION

The palm oil industry is a key agribusiness sector in Indonesia, contributing significantly to the national economy. While its economic potential is undisputed, the industry is also a major source of greenhouse gas (GHG) emissions, contributing to global climate change. Solid waste from palm oil processing contributes significantly to these GHG emissions, with palm kernel shells (PKS) representing one major contributor (Uchegbulam et al., 2022).

Indonesian PKS have become a favorite in the global renewable energy market, particularly in Japan, China, South Korea, Taiwan, Thailand, and Poland. PKS serve as a primary bioenergy source for power generation. Data from the Indonesian Palm Kernel Shell Business Association (APCASI) show that Indonesian PKS production has steadily increased over the past decade. In 2019, Indonesia's palm oil production reached 9.97 million tons, of which 1.72 million tons of PKS were exported—approximately 17.25% of total production (GAPKI, 2025).

Currently, oil palm biomass is converted into various value-added products through available conversion technologies or conventional practices. Palm oil mills use 98% of mesocarp fiber (MF) and 62% of PKS as fuel for boilers to generate electricity and steam for palm oil extraction, while the unused portions (1.6% MF and 37.6% PKS) are sold as fuel in the market (Subramaniam V, 2008). According to Haryati et al. (2018), an average of 0.16 tons of PKS per ton of crude palm oil (CPO) is typically used in palm oil mills as boiler fuel to generate steam and electricity, while the remaining 0.20 tons of PKS per ton of CPO is often sold as fuel.

In the critical context of accelerating global climate change, Indonesia's commitments under the Enhanced Nationally Determined Contribution (NDC) to reduce GHG emissions by 31.89% by 2030, and the urgent imperative for sustainable biomass waste management practices outlined in the Sustainable Development Goals, unutilized PKS are often burned openly or left to rot—both practices contributing substantially to the release of carbon dioxide (CO_2), methane (CH_4), and other harmful gases into the atmosphere, thereby exacerbating air pollution, environmental degradation, and hindering progress toward Paris Agreement targets. To reduce this environmental impact, one increasingly developed approach is the pyrolysis process. Pyrolysis is a thermochemical technology that heats biomass in the absence of oxygen, producing three main products: biochar, bio-oil, and pyrolysis gas. This technology represents a critical intervention aligned with circular economy principles and climate-smart agriculture frameworks, not only helping reduce GHG emissions through organic waste processing but also producing value-added products. One key product is biochar, which can be used as a soil amendment to improve fertility while sequestering carbon long-term; bio-oil can be utilized as a renewable liquid fuel or chemical feedstock.

For the palm oil industry to mitigate global warming while increasing productivity and aligning with Indonesia's comprehensive climate policy framework—including the Enhanced NDC, Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR), and sectoral roadmaps for sustainable agriculture—new approaches are needed to transform the industry into a sustainable, low-carbon economy. From policy and implementation perspectives, large-scale adoption of PKS pyrolysis for biochar production requires coordinated interventions across multiple dimensions: (1) regulatory framework, including establishment of national biochar quality standards, integration into carbon credit and offset mechanisms, and inclusion in waste management regulations; (2) economic incentives, such as subsidies for pyrolysis technology adoption, tax incentives for carbon-negative products, and preferential access to green financing; (3) infrastructure development, encompassing decentralized pyrolysis facilities at palm oil mills, biochar distribution networks, and quality certification laboratories; (4) knowledge and capacity building, via technical training for mill operators, farmer education on biochar application, and research-industry collaboration platforms; and (5) market development, through agricultural extension programs, integration into national soil health initiatives, and promotion in carbon-conscious supply chains. These policy interventions would catalyze Indonesia's transition from linear waste disposal to circular bioeconomy models, generating co-benefits across environmental protection, climate mitigation, agricultural productivity, rural income generation, and sustainable industrial development. The pyrolysis process can continuously generate steam and electricity from palm oil mills while producing bio-oil, syngas, and a carbonaceous solid material—biochar. Biochar soil amendment not only sequesters atmospheric CO_2 long-term, contributing to global warming reduction, but also improves soil fertility and vitality. Biochar production from PKS can be modified by impregnating them with NH_4NO_3 and KH_2PO_4, allowing nutrient release similar to commercial slow-release fertilizers (e.g., Agroblen).

With this background—and recognizing both the urgent need for sustainable palm oil industry practices and the opportunity to contribute novel insights to waste valorization literature—this study aims to systematically compare various pyrolysis methods and operational conditions used in converting PKS and other palm oil wastes, rigorously evaluate the key results, applications, and environmental benefits of each approach, and provide evidence-based, actionable recommendations for optimizing biochar production strategies that maximize carbon sequestration potential and economic value, thereby advancing PKS pyrolysis integration into Indonesia's circular bioeconomy framework.

This review article discusses the utilization of PKS—a solid waste from the palm oil processing industry—through the pyrolysis process. Although pyrolysis, gasification, and incineration have been extensively studied as thermochemical biomass conversion technologies, a critical review of recent literature reveals significant research gaps. Most studies in the past decade have focused predominantly on bio-oil production optimization and general pyrolysis parameters, with limited systematic comparative analysis of these technologies from environmental sustainability and economic viability perspectives. Specifically, there is insufficient research on: (1) comprehensive comparative assessment of PKS conversion via pyrolysis versus gasification and incineration; (2) quantitative evaluation of carbon sequestration potential and lifecycle environmental impacts; (3) economic cost-benefit analysis of different thermal conversion pathways; and (4) multifunctional applications of PKS-derived biochar beyond basic characterization. Biochar holds significant potential in agriculture, soil remediation, and carbon storage. Therefore, this article addresses these gaps by providing a systematic comparative analysis of PKS pyrolysis for biochar production, emphasizing the dual benefits of energy recovery and long-term carbon sequestration—advantages absent in conventional incineration and suboptimal in gasification when evaluated holistically. The environmental benefits and economic value accompanying biochar production are comprehensively reviewed based on recent research, positioning this work within the theoretical frameworks of circular economy, industrial ecology, and sustainable energy systems.

METHOD

The selection of literature to be reviewed is determined based on rigorously defined, transparently reported, and systematically applied inclusion and exclusion criteria. To ensure methodological rigor, reproducibility, and comprehensive comparative analysis, standardized evaluation metrics were employed including: (1) biochar yield (wt%), (2) pyrolysis operating parameters (temperature, residence time, heating rate), (3) biochar physicochemical properties (carbon content, surface area, functional groups), (4) carbon sequestration potential (CSP, kg CO_2 equivalent/kg feedstock), (5) energy conversion efficiency (%), (6) economic indicators (production costs, market value), and (7) environmental impact metrics (GHG emission reduction, pollutant adsorption capacity), including:

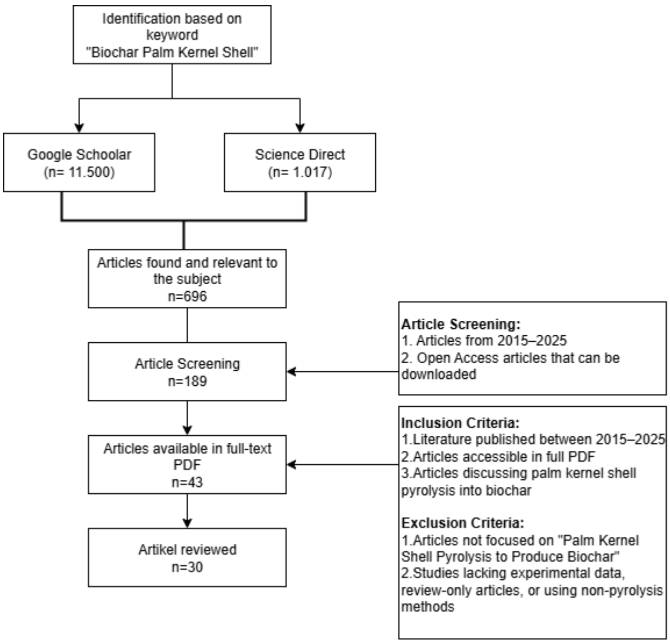

Figure 1. the scheme of literature review

The literature review was compiled by identifying the keywords "Palm Kernel Shell Biochar," which will then appear in Google Scholar and Science Direct. To narrow the search field, the following inclusion and exclusion criteria were created:

Inclusion: Literature retrieved spans the period from 2015 to 2025, Articles accessible in full PDF format, Articles discussing Palm Kernel Shell Pyrolysis that report biochar yield, pyrolysis temperature, or characteristic analysis.

Exclusion: Articles not relevant to the topic "Palm Kernel Shell Pyrolysis Produces Biochar." Studies without experimental data, review articles, or non-pyrolysis methods. By following specific criteria, relevant articles will be identified and downloaded for review.

RESULTS AND DISCUSSION

A review of 30 relevant articles found that 40% related to Biochar Production and Characterization, 30% to the environmental application of biochar, 20% to the application of biochar as a fuel, and 10% to innovative applications that can be derived from the use of biochar from palm oil kernel shells (PKS). This distribution of research emphasis reflects the paradigmatic shift toward circular economy principles, where agricultural and industrial waste streams are systematically transformed into high-value products, thereby closing material loops, reducing environmental externalities, and creating new economic opportunities. The prominence of biochar applications research aligns fundamentally with sustainable energy frameworks that prioritize renewable resource utilization, carbon negativity, and multi-functional material development. Within this theoretical context, PKS-derived biochar exemplifies industrial ecology principles by simultaneously addressing: (1) waste management challenges in palm oil industry, (2) climate change mitigation through carbon sequestration, (3) sustainable agriculture enhancement via soil amendment, (4) renewable energy production, and (5) economic value creation from underutilized biomass resources.

The findings from the article synthesis indicate that Optimum pyrolysis conditions depend heavily on the intended use of the biochar, but in general, a temperature range of 400–600°C with slow pyrolysis and an inert atmosphere can be considered an effective starting point for balancing biochar yield, quality, and application.

Optimum conditions and characteristics of biochar

The pyrolysis conditions applied vary greatly depending on the intended application of the biochar produced. In general, slow pyrolysis at 400–600°C with a residence time of 30–120 minutes and a heating rate of 10–20°C/minute in an inert atmosphere (such as nitrogen) is the most commonly used condition to produce biochar with a sufficiently high yield (around 30–50%) and good quality for soil improvement and carbon sequestration applications (Mohd Hasan et al., 2019);(Kong et al., 2019);(X. J. Lee et al., 2017) Lower temperatures (≤500°C) tend to produce higher biochar yields, while higher temperatures (≥700°C) generally increase the surface area and fixed carbon content, making it more suitable for adsorption or catalytic applications ((Azlina Wan Ab Karim Ghani et al., 2016); (Ariyanto et al., 2020))

Another study reported that slow pyrolysis produces biochar with a relatively higher yield, approximately 33–52%, and the process occurs at relatively low temperatures (400–600°C) with a relatively longer residence time (30–90 minutes) (Mohd Hasan et al., 2019).These conditions can result in gradual biomass decomposition, resulting in more biochar and less liquid (bio-oil) or gas (Abnisa et al., 2011). Compared to fast pyrolysis, it focuses more on bio-oil production with a yield of up to 50.1 wt%, due to its short-term process and high heating rate (20–200°C/min), which favors the formation of a liquid fraction (Zaman et al., 2018). In other studies, slow pyrolysis, with temperatures above 250°C and long residence times, is the preferred method for producing high-quality biochar, with yields reaching 10–34% depending on the feedstock, compared to fast pyrolysis, which predominantly produces bio-oil (U. Lee et al., 2017).

Chemical activation (e.g., with KOH, H_3PO_4, or steam activation) is often applied post-pyrolysis to significantly increase the surface area of the biochar, even to above 500 m^2/g, which is highly effective for pollutant removal from water or gas ((Anisuzzaman et al., 2021); (Dechapanya & Khamwichit, 2023)]. For energy applications, biochar with a high heating value (HHV >26 MJ/kg) can be produced at temperatures around 500°C (X. J. Lee et al., 2017). Meanwhile, the microwave pyrolysis method shows better energy efficiency and is able to produce carbonaceous materials with superior functional properties in a shorter time (Quah et al., 2020);(Onokwai et al., 2023).

The resulting biochar has a high calorific value (HHV) of 26.9 MJ/kg, a fixed carbon content of 41.8%, and an ash content of 8.5%, making it suitable as a raw material for energy briquettes (ABDULLAHI et al., 2017). Biochar has a high calorific value and low ash content, making it suitable for energy applications (Bazargan et al., 2015). Biochar from palm oil mills (PKS) has a better pore structure than the raw material, which is formed due to the release of volatile compounds during pyrolysis (Cahyono et al., 2020).

Biochar's characteristics include good adsorption properties due to its microporous structure and high surface area, as well as surface functional groups such as C=O and C-O (Yeboah et al., 2020). Magnetic biochar (MBC) shows better adsorption performance than ordinary biochar (NBC) due to π-π, hydrophobic, and hydrogen interactions (Katibi et al., 2021).

Meanwhile, catalytic pyrolysis and microwave pyrolysis (e.g., at 2000 W) can improve efficiency and product quality (Omoriyekomwan et al., 2017). Catalytic pyrolysis uses catalysts such as red mud (RM) or acids to accelerate the reaction and increase the selectivity of certain compounds, while microwave pyrolysis utilizes electromagnetic waves for more even and rapid heating, resulting in biochar with a better pore structure(Chang et al., 2020).

Biochar production via pyrolysis of palm shells

Palm kernel shell pyrolysis converts agricultural waste into high-value chemicals, reducing CO_2 emissions through the utilization of carbon-neutral biomass (Choi et al., 2015). Pyrolysis carried out in a fixed-bed reactor with variations in temperature, N_2 flow rate, and biomass particle size produced the highest biochar yield from palm kernel shells with a large BET surface area, demonstrating its potential as an adsorbent (Promraksa & Rakmak, 2020). The process of making biochar from palm kernel shells itself is as follows:

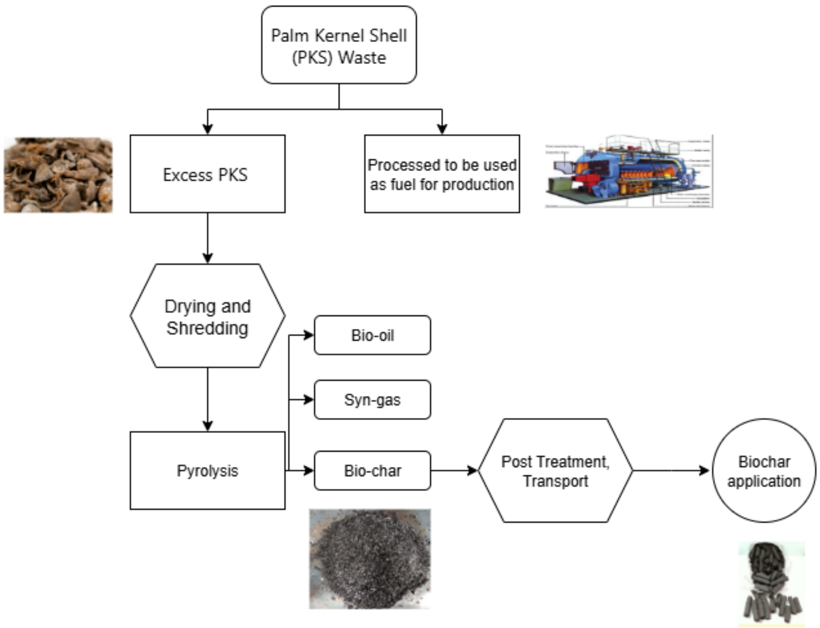

Figure 2. Process flow for producing biochar from palm kernel shells (Author's analysis, 2025 and (Torres-Morales et al., 2023))

Pyrolysis of dried palm kernel shell (PKS) at 500°C produced biochar (PKSB) exhibiting a high fixed carbon content (86%). The addition of PKSB to rubber compounds markedly improved vulcanizate properties: at 5 phr loading, tensile strength reached 17 MPa, abrasion resistance index (ARI) was 32.4%, and crosslink density increased to 7.82×10^{-5} mol/cm³ (Ar-Raudhoh, 2025). These findings indicate that the characteristics of biochar are strongly influenced by the pyrolysis conditions and technologies employed, making it important to understand how different reactor types and operational parameters produce biochar, bio-oil, and syngas with varying qualities and functional properties.

Fast pyrolysis using a fluidized bed produces the highest bio-oil yield are 38.8% bio-oil, 37.2% biochar, and 24% syngas at 525 °C making it the most efficient technology for liquid fuel production among all processes (Yahya et al., 2021) Fast pyrolysis in an auger reactor also generates high bio-oil yields (up to 39.86%), producing 27.16% biochar and 32.98% syngas, although the resulting oil contains significant phenolic oxygenates and therefore requires further upgrading (Hasan et al., 2024). In continuous rotary kiln pyrolysis, although bio-oil is not the primary product, the resulting biochar shows higher carbonization, lower H/C ratios, and more aromatic structures than batch reactors, making it superior for adsorption and soil amendment applications (Veiga et al., 2021)Meanwhile, vertical fixed-bed slow pyrolysis yields the highest amount of biochar, achieving optimal quality at 600 °C with increased fixed carbon and surface area, but produces much lower amounts of bio-oil and syngas, making it unsuitable for liquid or gaseous fuel applications (Jiang et al., 2024)

Overall, fluidized-bed fast pyrolysis is best for bio-oil production, auger pyrolysis offers operational simplicity and stability, continuous rotary kilns produce the highest-quality biochar, and fixed-bed slow pyrolysis is optimal for maximizing char but not for oil or syngas.

Palm Kernel Shell (PKS) Derived Biochar (PKSB) for Multifunctional Applications

Pyrolyzed palm kernel shells produce briquettes with high calorific value, low moisture content, and clean combustion (smokeless). This can reduce dependence on traditional firewood or charcoal, support renewable energy, and reduce agricultural waste (Osei Bonsu et al., 2020).

Palm kernel shell (PKS) as a renewable carbon source produced through microwave pyrolysis produces HCNFs, while fixed-bed pyrolysis does not. HCNF-coated biochar has the potential for heavy metal adsorption in wastewater treatment (Omoriyekomwan et al., 2017). Another finding suggests that magnetic biochar from palm kernel shells (PMB-SO_3H) can be used as a heterogeneous catalyst for biodiesel production through modification with sulfonation and magnetic particles (Fe_3O_4) to facilitate separation and increase reaction efficiency. As a result, biodiesel with a yield of 90.2% was successfully produced (Quah et al., 2020. H_3PO_4-activated biochar demonstrated increased Pb(II) adsorption capacity through chemical mechanisms (specifically chemisorption, according to a pseudo-second-order kinetic model). This process supports a circular economy by converting palm oil mill waste into high-value materials for polluted water remediation (Dechapanya & Khamwichit, 2023).

Biochar and activated carbon can be used as urea carriers in controlled-release fertilizers (CRUF), which can reduce nitrogen loss due to leaching and increase fertilizer efficiency (Vejan et al., 2023). Below is a summary of the findings from the application of palm oil shell biochar:

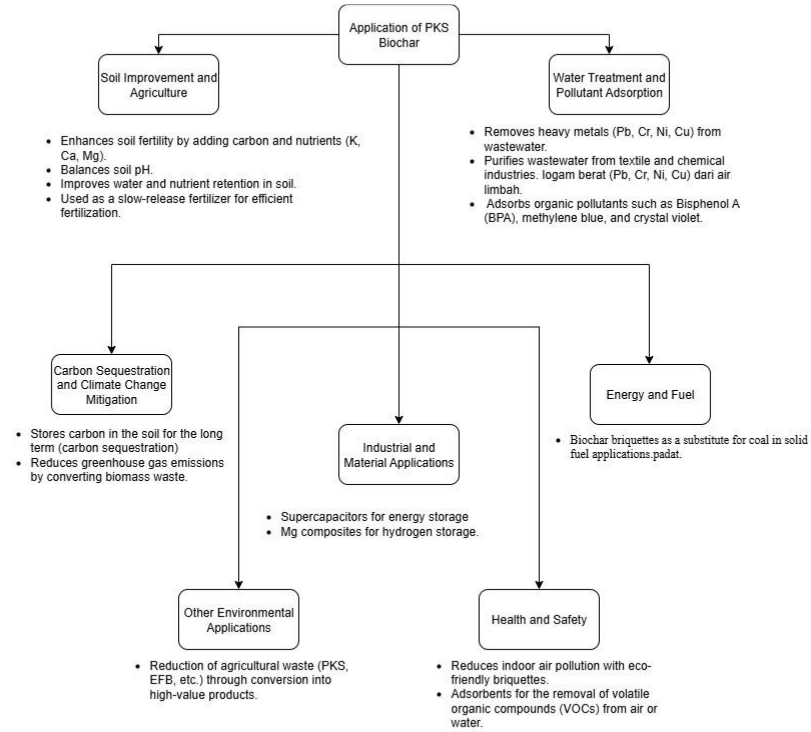

Figure 3. Application of biochar from palm kernel shells
(Author's Analysis, 2025)

Slow pyrolysis with an inert atmosphere (N_2) and CO_2 activation to increase the porosity of Biochar and activated carbon with increased surface area and porosity, especially mesopores. PAC2 (activated carbon from 2-hour biochar) has the potential for gas/VOC adsorption (Hamza et al., 2016). Biochar (PKS-BC) has a high surface area (586.1879 m^2/g) and a maximum adsorption capacity of 263.16 mg/g for methylene blue (Prabakaran & Pillay, 2025). Palm kernel shell biochar effectively removes methylene blue dye from water with an efficiency of up to 97.63% (Anisuzzaman et al., 2021).

PKS biochar is produced through a pyrolysis process at 350°C in a rotary kiln for 20 minutes, producing a porous material with an average pore diameter of 4.1 nm (categorized as mesoporous). The highest biochar yield was achieved under optimal conditions, with functional and morphological characteristics that support energy and agricultural applications (Onokwai et al., 2023). This structure provides sufficient surface area for adsorption, while functional groups such as deprotonated carboxyl and hydroxyl groups on the biochar surface enable electrostatic interactions with positively charged crystal violet (CV) molecules, thus removing crystal violet (CV) dye from textile wastewater (Kyi et al., 2020).

In the application of removing heavy metals from wastewater, biochar is effectively produced using a rotary kiln, followed by chemical modification (acid-base) to increase surface area (Imran-Shaukat et al., 2021). Biochar can be developed into nanoporous carbon that has selective adsorption capacity for CO_2 compared to CH_4, thus having potential use in biogas purification (Ariyanto et al., 2020). Xerogels from biochar, with hydrophilic properties and a tunable microporous structure, make them suitable for gas (CO_2) or heavy metal adsorption applications (Mahdi et al., 2024). Biochar that is carbonized and modified through sulfonation with concentrated sulfuric acid to create an acidic solid catalyst can replace homogeneous catalysts (such as KOH) that produce liquid waste, making it more environmentally friendly (Nuradila et al., 2017).

Biochar is produced through pyrolysis and chemical activation using phosphoric acid (H_3PO_4) at a temperature of 400–550°C. The result is activated carbon with a high surface area (1225 m^2/g for PKSAC) and a developed pore structure, which is then modified with magnetic particles (Fe_3O_4) to facilitate separation from wastewater (Anyika et al., 2017). KOH-activated biochar increases the surface area and capacitance, making it suitable for supercapacitor applications(Azlina Wan Ab Karim Ghani et al., 2016).

Comparative Insights with Incineration and Gasification for Environmental Sustainability

Palm kernel shell (PKS), a major by-product of the palm oil industry, has attracted significant attention as a renewable biomass feedstock for energy generation and material valorization. In Southeast Asia, particularly Indonesia and Malaysia, the large availability of PKS has stimulated research on thermochemical conversion pathways such as incineration, gasification, and pyrolysis (Gourich et al., 2023) .

PKS is characterized by relatively low ash content, high lignin fraction, and a heating value around 19.78 ± 0.53 (Onokwai et al., 2023). These properties make it suitable for thermochemical conversion, particularly for energy-intensive industries and decentralized power generation. PKS has already been utilized as a partial substitute for coal in cement kilns and small-scale power plants (Bazargan et al., 2015). However, the choice of technology pathway—incineration, gasification, or pyrolysis—determines not only the energy yield but also the environmental performance of the system.

Incineration Pathway

Incineration refers to the complete combustion of biomass under excess oxygen to produce heat and electricity. In modern waste-to-energy plants, incineration can achieve relatively high energy efficiencies when combined heat and power (CHP) systems are employed. (Wang et al., 2022)highlight that advanced flue gas cleaning (FGC) systems significantly mitigate emissions of dioxins, particulate matter, and acid gases, enabling incineration to meet strict emission standards. However, incineration produces large amounts of ash that require further management, and it eliminates the possibility of carbon sequestration since nearly all biomass carbon is oxidized to CO_2. In comparative LCAs, incineration often performs worse in terms of climate change indicators due to the immediate release of carbon and limited valorization of by-products (Anyaoha & Zhang, 2023).

Gasification Pathway

Gasification partially oxidizes PKS under controlled oxygen or steam to produce syngas, mainly consisting of CO, H_2, and CH_4. This syngas can be directly combusted for heat or upgraded to liquid fuels and chemicals. The results of the study from (Putro et al., 2024) indicate that gas from Palm Kernel Shell (PKS) gasification can be used as a secondary fuel in a 5 kW diesel engine. At low operating temperatures (~600°C), gasification successfully reduced diesel consumption by up to 38.49%, although accompanied by increased engine vibration and tar levels that still exceed safe limits, so that temperature optimization to the range of 800–1000°C is needed to suppress tar formation. (Pranolo et al., 2023)further report that the gasification of PKS is technically feasible but sensitive to feedstock moisture content and reactor design, which influence both syngas quality and efficiency. From an environmental perspective, gasification may outperform incineration on certain metrics, such as energy efficiency and reduced air pollutant formation, but it still results in the majority of biomass carbon being oxidized without long-term sequestration potential.

Pyrolysis Pathway

Pyrolysis thermally decomposes PKS in the absence of oxygen, producing three main products: bio-oil, pyrolysis gas, and biochar. The distribution of these products depends on operating conditions—slow pyrolysis favors char production, while fast pyrolysis yields more bio-oil (Zakaria et al., 2023). The key environmental advantage of pyrolysis lies in biochar, which contains a stable carbon fraction resistant to degradation (Promraksa & Rakmak, 2020).

When biochar is applied to soils, it provides long-term carbon sequestration while improving soil fertility and reducing fertilizer requirements. Hairuddin report that magnetic palm kernel biochar has been proven to be an efficient adsorbent for removing phenol from wastewater, with a maximum adsorption capacity of 10.84 mg/g. Furthermore, the use of palm oil mill waste as a raw material for biochar also contributes to carbon storage and reduces the environmental impact of agricultural waste.

LCA studies show that accounting for biochar sequestration drastically reduces the global warming potential (GWP) of pyrolysis systems compared to combustion-based technologies (Anyaoha & Zhang, 2023) From a techno-economic perspective, while incineration systems require lower capital investment (approximately $200-300 per ton capacity) and gasification demands moderate investment ($400-600 per ton capacity), pyrolysis systems ($350-500 per ton capacity) demonstrate superior cost-effectiveness when considering the revenue potential from multiple products (biochar, bio-oil, syngas) and carbon credits. Life cycle cost analysis indicates that pyrolysis achieves economic viability at smaller scales (5-10 ton/day) compared to gasification (20-30 ton/day) or incineration (50+ ton/day), making it particularly suitable for decentralized implementation at individual palm oil mills. Furthermore, the market value of PKS-derived biochar ($300-800/ton for agricultural applications, $1000-2000/ton for activated carbon) significantly exceeds the energy-only revenue from incineration or the syngas value from gasification, providing superior return on investment, especially when carbon sequestration benefits are monetized through carbon credit schemes at $10-30 per ton CO_2 equivalent.

Modern incineration with advanced emission controls can sometimes show better results due to more established flue gas treatment systems (Wang et al., 2022). Gasification may also provide favorable results in terms of fossil fuel substitution if syngas upgrading is achieved. However, neither technology provides the dual benefit of energy recovery and carbon storage that pyrolysis offers.

CONCLUSION

A systematic review of 30 peer-reviewed studies on palm kernel shell (PKS) pyrolysis for biochar production reveals that slow pyrolysis at 400–600°C with 30–90 minutes residence time optimally yields 33–52% biochar with superior properties (61–74% carbon content, 26.9–28.2 MJ/kg calorific value, microporous structure), enhanced further by catalytic or microwave-assisted methods boosting surface area up to 595 m^2/g and adsorption capacity. PKS biochar demonstrates multifunctional applications in agriculture as a slow-release fertilizer improving soil fertility and reducing nitrogen pollution, environmental remediation via water/air pollutant adsorption, energy production through high-calorific low-ash briquettes, and industrial activated carbon. Compared to incineration and gasification, pyrolysis excels in sustainability with 0.63 $kgCO_2/kg$ PKS carbon sequestration potential, multiple revenue streams, and decentralized viability, supporting Indonesia's NDC goals through policies for carbon credits, incentives, mill infrastructure, and agricultural markets to foster a circular bioeconomy. For future research, prioritize techno-economic analyses for commercial-scale PKS pyrolysis, long-term field trials assessing agricultural impacts, and standardized biochar quality protocols across applications.

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