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Palm Kernel Shell as a Source of Functional Biochar: A Review of Recent Scientific Progress

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Abstract: This report examined the research trends in production and application of biochar derived from palm kernel shells (PKS) over the past decade. A Systematic Literature Review (SLR) was conducted on 63 articles indexed in Scopus between 2015 and 2025, with bibliometric mapping performed using VOSviewer. From 2015, the number of publications on PKS biochar grew gradually, reaching a peak in 2020 and 2023. Through the use of keyword co-occurrence mapping, four significant clusters of PKS biochar research were identified. These clusters primarily dealt with pyrolysis, activated carbon, biofuels, and biomass usage as main themes. The term "biochar" has a critical function in connecting applications pertaining to agriculture, the environment, and energy, as seen by its core positioning and strong keyword connections across clusters. Su Shiung Lam and Rock Keey Liew (Universiti Malaysia Terengganu) have the strongest collaboration link (strength 17), according to the VOSviewer study, which is supported by 6 documents and 640 citations. Based on the number of publications, Malaysia is the leader in PKS biochar research with 33, followed by Thailand with 8 and Indonesia with 6. The findings of this study can serve as a useful reference for researchers and institutions looking to understand current trends, active contributors, and major themes in PKS biochar research.

Keywords: Biochar; Palm kernel shell; Sustainable biomass

Introduction

Biomass waste, which comes from organic sources like farm leftovers, offers possibilities and threats to sustainable development. The palm oil business produces palm kernel shell waste, which is a major problem because of its large volume and low utilization rate. This waste presents opportunities through innovative management strategies. Waste-to-Value initiatives can transform palm kernel shell waste into valuable products, including biofuels (Salgado et al, 2020), adsorbent (Andrio et al., 2024; Nazarudin et al., 2018), and soil remidiation (Sulok et al., 2021). Furthermore, the use of palm kernel shells for renewable energy can decrease reliance on fossil fuels and alleviate climate change. The advancement of effective biomass waste utilization technologies is essential for optimizing these opportunities and fostering sustainable practices. Addressing the challenges associated with palm kernel shell waste can yield substantial environmental and economic advantages.

Palm kernel shells (PKS) are recognized not only as an abundant agricultural by-product but also for their broader potential beyond mere residue. Due to their carbon-rich composition, PKS can function as a sustainable feedstock for the development of high-value carbon-based materials. This carbon basis offers a scientific justification for investigating thermochemical conversion processes, including pyrolysis and hydrothermal treatment, which convert PKS into functional materials such as biochar.

This study aims to provide an overview of recent research on the utilization of PKS for sustainable biochar production. This study aims to elucidate publication

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trends, technological pathways, and significant challenges, providing insights that may inform future innovations in sustainable biomass valorization.

Significant progress has been achieved in the development of PKS-based carbon materials; however, continuous advancements necessitate regular evaluations of the research landscape. Mapping and analyzing publication trends facilitate the identification of emerging themes, research gaps, and collaborative networks. In this context, tools like VOSviewer are utilized to visualize citation patterns and thematic structures in the literature (Gan et al., 2022). This study diverges from prior reviews that primarily concentrated on the physicochemical properties of PKS-derived biochar. Instead, it adopts a holistic approach by combining bibliometric analysis with technological insights, thus providing a more thorough understanding of scientific advancements and future research strategies.

Method

Time and Place of Research

The literature data for this study were obtained from the Scopus database. An initial search was carried out on June 14, 2025 using the query TITLE-ABS-KEY (palm AND kernel AND shell AND biochar AND production).

Research Stages

An initial search yielded 68 documents. To refine the results, filters were applied to include only documents at the final publication stage ('Pub stage = Final') and written in English, resulting in 65 documents. Among these, 63 publications were released between 2015 and 2025. The article selection process for this systematic literature review followed the flow chart presented in Figure 1. The eligible records were exported in comma-separated values (*.csv) format.

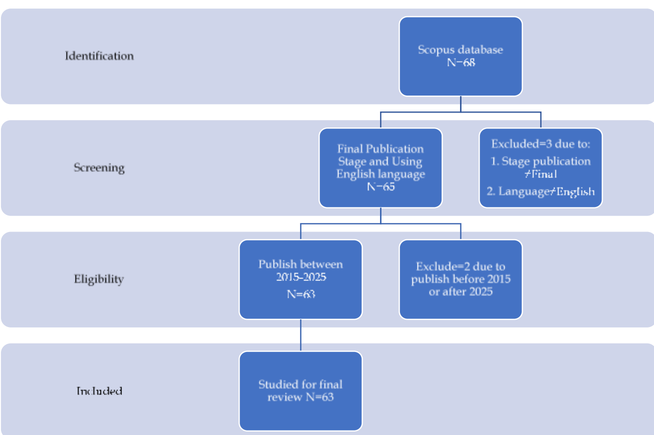

Figure 1. Flow diagram of literature screening and selection

Tools and Data Analysis

Bibliometric analysis was performed using VOSviewer software version 1.6.20 for Windows. A minimum threshold of five keyword occurrences was set to ensure a manageable and interpretable number of keywords for visualization, balancing the inclusion of commonly used terms while omitting less significant ones that may not accurately represent the thematic structure of the field. To improve accuracy and relevance, non-relevant or duplicate terms were removed, while manual refinement was also applied to eliminate overly broad or redundant terms and to merge synonyms for clarity. Although guided by the methodological principles of Hariry et al. (2025), all refinement steps were independently adapted to suit the specific context and scope of this study.

The filtered data were visualized using VOSviewer outputs network visualization. These visualizations provided insights into co-authorship networks, keyword co-occurrence patterns, and the temporal evolution of research topics within the domain of biochar production from palm kernel shells. Research design and method should be clearly defined.

Result and Discussion

Publication Trends (2015–2025)

In Figure 2, the growth of publications concerning palm kernel shells and biochar production from 2015 to 2025 is illustrated.

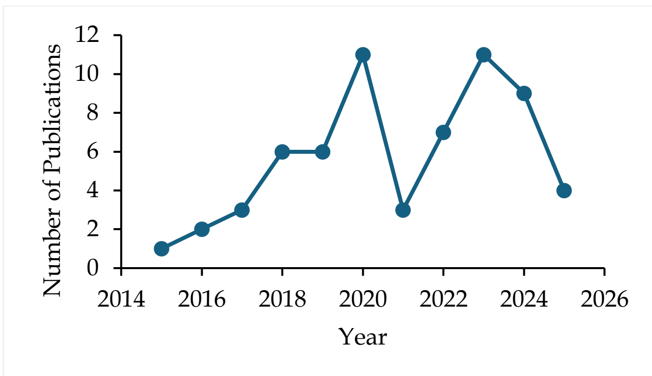

Figure 2. Total number of documents obtained related to PKS and biochar production in period 2015–2025

In 2015, the studies focused on biochar production via the fast pyrolysis method and its use as a precursor for activated carbon production. Then in 2016, studies began to explore enhanced carbonization methods to improve biochar quality (Wahi et al., 2016) and included reviews addressing biorefinery perspectives in palm oil plantation systems (Garcia-Nunez et al., 2016). Next, in 2017, attention shifted toward biochar's catalytic applications (Nuradila et al., 2017) and its potential as a substitute for fossil fuels. In 2018, studies addressed the application of carbon for enhancing soil structure (Simarani et al., 2018) and to produce solid fuels (Bazargan et al., 2014). In 2019, research on palm kernel shells expanded to include the development of PKS-derived biochar for various functional applications, including catalyst production (Rashid et al., 2019), porous carbon development, environmental remediation (Liew et al., 2019), and carbon sequestration. In the following years, research increasingly emphasized the optimization of production techniques—such as various pyrolysis methods, chemical activation, and process engineering—to yield functional biochar products like catalysts and adsorbents. Recent studies have also highlighted sustainability-oriented applications, including heavy metal adsorption, soil quality improvement, the use of biochar as filler material in rubber composites, and its incorporation into eco-friendly building materials.

Collaboration Networks and Geographic Distribution

The VOSviewer analysis indicates that Su Shiung Lam and Rock Keey Liew from Universiti Malaysia Terengganu exhibit the highest bond strength of 17, supported by 6 documents and 640 citations. Su Shiung Lam and Rock Keey Liew collaborated with multiple authors (see Fig. 3). Several countries have produced the most research on carbon emissions from palm kernel shells. Malaysia leads in publication volume with 33 documents, followed by Thailand with 8 articles and Indonesia with 6 articles.

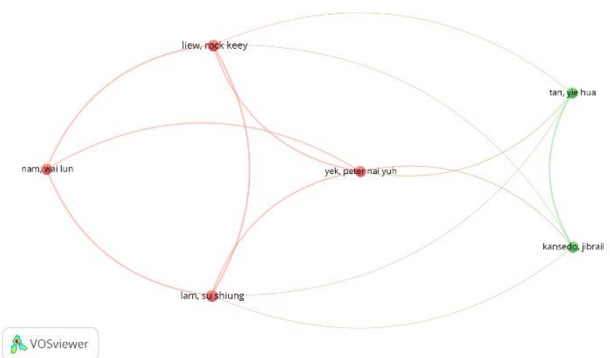

Figure 3. Author and co-author collaborative network visualization

Keyword Co-Occurrence Analysis

Figure 4 shows the keyword co-occurrence network derived from the dataset. One prominent cluster includes terms such as biochar, palm kernel shells, pyrolysis, activated carbon, charcoal, adsorption, and carbon, highlighting the central role of pyrolysis in biochar production. Another cluster includes keywords like biofuel, biodiesel, palm oil, catalyst, vegetable oil, and optimization, indicating the integration of PKS-derived biochar in biodiesel production processes, particularly as a catalyst in transesterification reactions. The lack of terms associated with life-cycle assessment, large-scale application, or economic feasibility indicates that PKS biochar research has not adequately tackled practical implementation challenges.

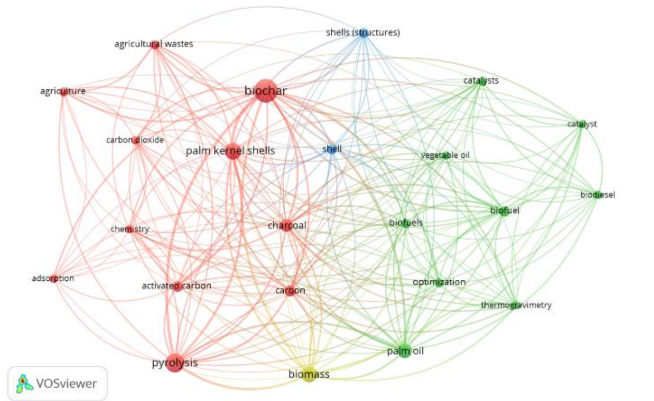

Figure 4. Keyword co-occurrence network derived from the dataset

Research Clusters in PKS Biochar Studies

The bibliometric mapping results indicate that research on biochar derived from palm kernel shell (PKS) can be classified into seven primary clusters. Each cluster signifies a distinct research focus, methodology, and developmental pathway, while also exhibiting overlaps within the context of employing PKS as a biochar feedstock.

The first cluster focuses on the methods used to create biochar, such as carbonization (Wahi et al., 2016), and pyrolysis (Keey et al., 2018; Lee et al., 2017; Sait et al., 2025). The effects of process variables including temperature, residence time, and heating rate on the physicochemical characteristics of biochar are examined in this field of study (Choi et al., 2015; Mohd Hasan et al., 2019). Considerable emphasis is also placed on the selection and diversification of biomass feedstocks, which include agricultural waste, forestry waste, and industrial byproducts. This cluster of studies aims to improve the quality of biochar materials for specific uses while also making the production process more efficient.

Building upon the understanding of its physicochemical properties, agricultural applications and soil fertility cluster highlights the role of biochar as a soil amendment to improve soil health and crop productivity (Anyaoha et al., 2018; Kosasih et al., 2022). Research has demonstrated its liming effect of acid soils, nutrient and water retention, nutrient reserves, and a suitable habitat for microbial life (Sulok et al., 2021). Despite these promising results, many studies are conducted on specific soil types, leading to inconsistent findings across soil variations, while long-term studies remain limited, leaving a significant gap in understanding the sustained benefits and potential long-term effects of biochar in agricultural systems.

Table 1. Research Clusters in PKS Biochar Studies

Cluster	Main Focus	Dominant Methods
Production Methods & Characterization	Pyrolysis, hydrothermal carbonization, gasification	Optimization of temperature, residence time, feedstock ratio
Agricultural Applications & Soil Fertility	Soil amendment, nutrient retention, microbial enhancement	Pot trials, field experiments
Adsorbents for Environmental Remediation	Adsorption of heavy metals, dyes, organic pollutants	Batch adsorption, isotherm & kinetic models
Energy & Fuel Applications	Cofiring, upgrading biochar to activated carbon, bio-oil	Proximate/ultimate analysis, calorific value tests
Biochar as Functional Materials	Supercapacitor electrodes, batteries, catalysts	Chemical/physical activation, metal doping
Biochar & Environmental Sustainability	CO_2 sequestration, GHG mitigation, waste management	Life Cycle Assessment (LCA), carbon footprint analysis
Biochar & Food Applications	Additives, preservation, drinking water filtration	Safety assessment, toxicity tests

Environmental remediation and adsorption cluster encompasses research on the application of biochar as an adsorbent for environmental remediation (Liew et al., 2019; Promraksa & Rakmak, 2020) and particularly in addressing heavy metals (Dechapanya & Khamwichit, 2023). Studies in this area often rely on batch adsorption experiments combined with isotherm and kinetic modeling to elucidate predominant adsorption mechanisms (e.g., physical adsorption, complexation, precipitation) and evaluate efficiency. Biochar has shown strong potential for wastewater treatment and contaminated soil remediation, highlighting its role as a low-cost and sustainable solution. Despite these promising findings, challenges remain regarding large-scale implementation and adsorbent regeneration, which currently limit its practical deployment in real-world remediation systems.

Research within energy and fuel applications cluster explores the utilization of biochar as a renewable energy carrier and alternative fuel source (Heredia et al., 2020; Salgado et al., 2020; Sunnu et al., 2023). Common analytical approaches involve proximate and ultimate analyses, calorific value measurements, and combustion performance testing to assess fuel quality and energy efficiency. Although biochar shows promise in diversifying renewable energy pathways, significant challenges persist in improving conversion efficiency and addressing the economic feasibility of large-scale deployment.

Biochar as advanced functional materials cluster explores the engineering of biochar into advanced functional materials designed for specialized applications, particularly in energy storage and catalysis (Abbas et al., 2019; Abidinet al, 2023; Karunanayake et al., 2025). Despite this advanced potential, significant challenges remain in ensuring long-term performance stability and reducing high production costs, which currently hinder large-scale commercial adoption.

Climate change mitigation & circular economy cluster examines the capacity of biochar to address pressing global environmental challenges, particularly through long-term carbon sequestration, greenhouse gas (GHG) mitigation, and sustainable waste management (Anak Erison et al., 2022; Hosseinzadeh-Bandbafha et al., 2023; Karunanayake et al., 2025). Research in this area frequently employs Life Cycle Assessment (LCA) and carbon footprint analysis to quantify the net environmental impact and potential contributions of biochar systems to achieving carbon neutrality and a circular economy. The applications position biochar as a versatile, nature-based solution for climate change mitigation, resource recovery, and sustainable development. Despite this significant potential, critical barriers to widespread adoption remain, primarily the scarcity of long-term field validation data and the lack of integration into national and international policy frameworks.

Biochar shows promising applications in the food sector, particularly as a bio-fertilizer in mushroom cultivation (Nam et al., 2018; Wan Mahari et al., 2020). Its porous structure enhances nutrient availability and microbial growth, leading to improved yields, while its catalytic properties support greener energy pathways. However, limitations include inconsistent performance due to feedstock and pyrolysis conditions, high production costs, and potential environmental burdens from chemical use. Moreover, the lack of clear regulations and food safety standards remains a critical barrier to its broader adoption.

Conclusion

The bibliometric analysis indicates substantial growth in PKS biochar research over the past decade, highlighting a heightened focus on sustainable biomass utilization. The visualization of keyword clusters identifies three primary research streams: methods of biochar production, characterization of materials, and applications in energy and environmental systems. Nonetheless, significant gaps persist in domains including life-cycle assessment, techno-economic feasibility, and scaling strategies for industrial applications. Collaboration patterns indicate that Malaysia, Indonesia, and Thailand are the primary contributors; however, international cooperation is still constrained. Enhancing cross-country research networks may facilitate knowledge exchange and expand application pathways. In conclusion, although research on PKS biochar has progressed significantly, the bibliometric analysis indicates a necessity to transition from laboratory-scale investigations to more extensive evaluations that encompass sustainability, economic factors, and practical implementation.

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Author Contributions
Conceptualization, MNC, DKAK, SH; methodology, DKAK; software, DKAK; validation, MNC and DKAK; formal analysis MNC; data curation, MNC; writing—original draft preparation, MNC, DKAK; writing—review and editing, MNC, DKAK, SH; visualization, MNC; funding acquisition, MNC. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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