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Optimized Nanobiochar Production from Oil Palm Biomass *via* High-energy Ball Milling

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Introduction

The utilization of biomass-derived carbon materials has gained significant attention due to the increasing need for sustainable and eco-friendly alternatives in various applications. Among these materials, nanobiochar has emerged as a promising candidate for environmental remediation, energy storage, and agricultural applications due to its high surface area, porosity, and functionalized surface properties. Oil palm biomass, an abundant agro-industrial waste, presents an excellent feedstock for nanobiochar production due to its rich lignocellulosic composition. High-energy ball milling has been recognized as an efficient technique to reduce biochar particle size while enhancing its physicochemical properties, thereby optimizing its performance in targeted applications. The process of nanobiochar synthesis begins with the selection of oil palm biomass as the raw material. Oil palm waste, including empty fruit bunches, palm kernel shells, and fibers, serves as a sustainable precursor for biochar production. The initial stage involves pyrolysis, a thermal decomposition process carried out under limited oxygen conditions to convert biomass into carbon-rich biochar. The operating conditions of pyrolysis, including temperature, heating rate, and residence time, significantly influence the yield and quality of the produced biochar. Typically, high-temperature pyrolysis (500–700°C) results in biochar with a higher carbon content and enhanced porosity, which is beneficial for subsequent processing.

Description

Once the biochar is obtained, it undergoes high-energy ball milling to achieve nanoscale dimensions. High-energy ball milling is a mechanical size reduction technique that utilizes the impact, shear, and attrition forces generated by rotating balls within a mill to fracture and refine the biochar particles. The milling process is conducted in a controlled environment, often under an inert gas atmosphere to prevent oxidation and preserve the structural integrity of the carbon material. The duration of milling, ball-to-biochar ratio, and rotational speed are critical parameters that dictate the final particle size and surface characteristics of the nanobiochar. Extended milling times lead to finer particles, but excessive milling may induce agglomeration and structural defects that compromise the desired properties. The structural and physicochemical modifications induced by high-energy ball milling are instrumental in enhancing the functional properties of nanobiochar. The reduction in particle size increases the specific surface area, providing more active sites for adsorption and catalytic reactions. Additionally, the milling process introduces surface defects and oxygen-containing functional groups, improving the hydrophilicity and reactivity of the nanobiochar. These characteristics are particularly advantageous in applications such as pollutant adsorption, where high surface area and functional groups enhance the biochar's affinity for contaminants [1].

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One of the most notable applications of nanobiochar is in wastewater treatment, where it serves as an effective adsorbent for heavy metals, organic pollutants, and dyes. The nanoscale dimensions and porous nature of the material facilitate rapid adsorption kinetics and high removal efficiency. Additionally, the modified surface chemistry enables enhanced interactions with contaminants, allowing for selective adsorption and improved binding mechanisms. Studies have demonstrated that nanobiochar derived from oil palm biomass via high-energy ball milling exhibits superior adsorption capacities compared to conventional biochar, making it a viable solution for addressing environmental pollution challenges. Beyond wastewater treatment, nanobiochar finds utility in soil remediation and agricultural applications. As a soil amendment, nanobiochar enhances soil fertility by improving water retention, nutrient availability, and microbial activity. Its high surface area allows for the slow release of essential nutrients, reducing the dependency on chemical fertilizers. Furthermore, the presence of functional groups contributes to the stabilization of toxic heavy metals in contaminated soils, preventing their leaching into groundwater. The incorporation of nanobiochar into agricultural practices aligns with sustainable farming initiatives, promoting soil health and crop productivity while minimizing environmental impact [2].

The role of nanobiochar in energy storage applications, particularly in supercapacitors and batteries, has also garnered attention. The unique structural properties imparted by high-energy ball milling, such as increased porosity and enhanced conductivity, make nanobiochar an attractive electrode material. In supercapacitors, the high surface area of nanobiochar facilitates efficient charge storage, leading to improved capacitance and energy density. Additionally, its lightweight nature and stability contribute to the longevity and performance of energy storage devices. Research in this domain continues to explore the integration of nanobiochar with other nanomaterials to develop hybrid electrodes with superior electrochemical properties. In catalysis, nanobiochar serves as a cost-effective and sustainable support material for metal catalysts in various chemical reactions. The functionalized surface of nanobiochar enables strong interactions with metal nanoparticles, enhancing catalytic efficiency and stability. Applications in green chemistry, such as biofuel production and environmental catalysis, benefit from the tailored properties of nanobiochar produced via high-energy ball milling. The ability to control particle size and surface chemistry through milling parameters allows for the customization of nanobiochar for specific catalytic processes [3].

The scalability and economic feasibility of nanobiochar production remain important considerations for industrial adoption. High-energy ball milling, while effective, requires optimization to balance energy consumption and production efficiency. The selection of milling equipment, operating conditions, and biochar feedstock all contribute to the overall cost-effectiveness of the process. Additionally, the environmental impact of nanobiochar production must be assessed to ensure sustainability. The integration of renewable energy sources for milling operations and the utilization of waste biomass as feedstock contribute to the overall environmental benefits of the process. Further research is needed to refine the structural and functional properties of nanobiochar for diverse applications. Advanced characterization techniques, such as electron microscopy, X-ray diffraction, and spectroscopy, provide insights into the morphological and chemical changes induced by high-energy ball milling. Understanding these modifications enables the development of tailored nanobiochar materials with enhanced performance in specific applications. Moreover, the exploration of synergistic effects between nanobiochar and other nanomaterials opens new avenues for multifunctional composite materials [4,5].

Conclusion

Collaboration between academia, industry, and government agencies is essential to drive the commercialization of nanobiochar technology. Pilot-scale studies and real-world applications will validate the effectiveness of nanobiochar in practical scenarios, paving the way for large-scale implementation. Policy support and regulatory frameworks that encourage the use of bio-based nanomaterials will further accelerate the adoption of nanobiochar in environmental and industrial sectors. In conclusion, high-energy ball milling offers a powerful and efficient approach to producing nanobiochar from oil palm biomass. The optimization of milling parameters enhances the physicochemical properties of nanobiochar, making it a versatile material for applications in environmental remediation, agriculture, energy storage, and catalysis. The continued advancement of nanobiochar technology holds great potential for sustainable solutions in multiple industries, contributing to a greener and more resource-efficient future.

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Conflict of Interest

None.

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