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Nano-Biochar as a Soil Amendment for Sustainable Soil Fertility Management

*Dr. Shruthi, G. S.[1] and Dr. Chandrakant[2]
[1]Senior Research Fellow, AICRP on MSPE, Dept. of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, GKVK, Bengaluru-560065, India
[2]Scientist (Soil Science), ICAR-Krishi Vigyana Kendra, Janwada Road, Bidar, University of Agricultural Sciences, Raichur-585401, Karnataka, India
*Corresponding Author's email: shruthigsgowda1997@gmail.com

Nano-biochar is an emerging nanotechnology-based soil amendment with potential applications in sustainable agriculture. Its high surface area, porosity and reactivity improve nutrient retention, soil structure, microbial activity and crop productivity. It enhances fertilizer efficiency, supports soil carbon sequestration and helps immobilize contaminants. However, challenges related to production cost, environmental safety and long-term impacts require further research. This review summarizes the production, properties, applications, benefits and future prospects of nano-biochar for improving soil fertility.

Keywords: Nano-biochar, Soil amendment, Soil fertility, Nanotechnology, Sustainable agriculture.

Introduction

Soil fertility is fundamental to sustainable agriculture and global food security, yet it is increasingly threatened by intensive cultivation, erosion, nutrient depletion and climate change. These factors reduce soil productivity and highlight the need for sustainable soil management practices (FAO, 2022). Biochar, a carbon-rich material produced by the pyrolysis of biomass under limited oxygen conditions, has gained considerable attention as a soil amendment due to its ability to improve soil physical, chemical and biological properties. It enhances soil organic carbon, nutrient retention, water-holding capacity and microbial activity, thereby contributing to improved crop productivity and environmental sustainability.

Recent advances in nanotechnology have led to the development of **nano-biochar**, which possesses a higher surface area, greater adsorption capacity and enhanced surface reactivity than conventional biochar. These unique properties improve nutrient use efficiency, facilitate contaminant immobilization, enhance soil microbial activity and support sustainable soil fertility management (Wang *et al*., 2023). Despite its promising applications, concerns regarding the environmental fate, long-term effects and safe use of nano-biochar remain. Further field-based research is needed to optimize its application and assess its ecological impacts. This article summarizes recent advances in nano-biochar, focusing on its mechanisms, applications, challenges and future prospects for improving soil fertility.

Production Techniques of Nano-Biochar

Nano-biochar is produced from biomass feedstocks such as agricultural residues, wood waste and manure through a combination of pyrolysis and nano-engineering processes. Initially, biomass is dried, ground and thermally decomposed under oxygen-limited conditions (300–700°C) to produce conventional biochar. This biochar is further converted into nano-biochar using techniques such as ball milling, ultrasonication and chemical activation, which reduce particle size, increase surface area and enhance surface functional groups. Surface modification with activating agents or metal-based nanoparticles can further improve nutrient adsorption, contaminant removal and soil amendment properties. These advanced production approaches enhance the effectiveness of nano-biochar for sustainable soil fertility management (Zhang *et al*., 2019).

Biomass Feedstock

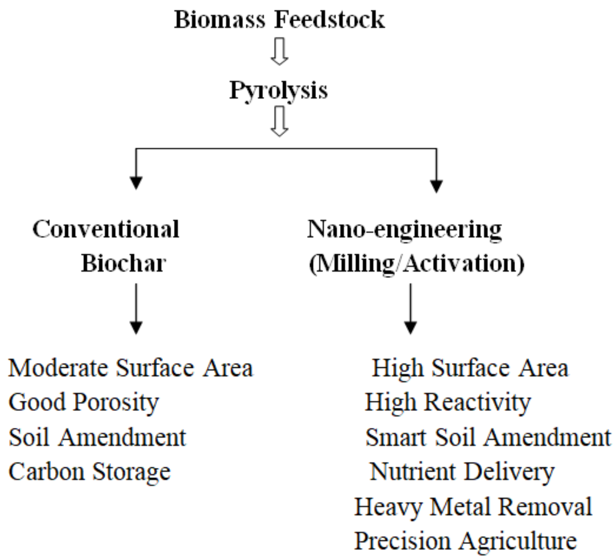

Fig.1: Comparison between biochar and nano-biochar showing their size, properties and major applications in soil fertility management.

Physicochemical Properties of Nano-Biochar

Nano-biochar exhibits unique physicochemical properties compared with conventional biochar due to its nanoscale particle size and enhanced surface characteristics. It possesses a high specific surface area, increased porosity, abundant functional groups and greater surface charge, which improve nutrient adsorption and retention in soils. The presence of oxygen-containing groups (–OH, –COOH and C=O) enhances cation exchange capacity and interactions with soil nutrients and contaminants. Nano-biochar also shows improved electrical conductivity, higher reactivity and strong adsorption capacity for heavy metals and organic pollutants. These properties make nano-biochar an effective soil amendment for improving nutrient availability, water retention, microbial activity and overall soil fertility (Wang *et al.*, 2023).

Mechanisms of Soil Fertility Improvement by Nano-Biochar

Nano-biochar enhances soil fertility by increasing nutrient retention, water-holding capacity and microbial activity**.** Its high surface area and functional groups improve the adsorption and slow release of essential nutrients (N, P and K), reduce nutrient losses and promote soil aggregation. It also supports beneficial microorganisms and immobilizes toxic metals, thereby improving soil quality and crop productivity.

Effects of Nano-Biochar on Soil Properties

- **Soil Physical Properties:** Nano-biochar improves soil aggregation, porosity, aeration and water-holding capacity**,** creating better conditions for root growth and moisture retention.
- **Soil Chemical Properties:** It enhances cation exchange capacity, nutrient retention and nutrient availability (N, P and K) while reducing nutrient leaching and immobilizing soil contaminants.
- **Soil Biological Properties:** Nano-biochar promotes microbial activity, enzyme functions and nutrient cycling **by** providing suitable habitats and carbon sources for beneficial microorganisms.

Applications of Nano-Biochar in Sustainable Agriculture

- **Nano-fertilizer carrier:** Enables controlled and slow release of nutrients, improving fertilizer use efficiency and reducing nutrient losses.
- **Soil fertility improvement:** Enhances soil structure, nutrient availability, water retention and microbial activity.
- **Heavy metal remediation:** Adsorbs and immobilizes toxic metals such as Pb, Cd and Cr, reducing their availability to plants.
- **Carbon sequestration:** Promotes long-term carbon storage and contributes to climate-smart agriculture.
- **Crop productivity enhancement:** Improves seed germination, plant growth and nutrient uptake under different soil conditions.
- **Precision agriculture:** Supports targeted nutrient delivery and efficient soil management through nano-enabled technologies.

Environmental Benefits of Nano-Biochar

- Enhances soil carbon sequestration and reduces greenhouse gas emissions.
- Improves nutrient use efficiency, reducing fertilizer losses and environmental pollution.
- Removes or immobilizes heavy metals and organic pollutants in contaminated soils.
- Promotes sustainable soil management and improves ecosystem resilience.

Limitations and Risks

- Limited information is available on the long-term fate and behavior of nanoparticles in soil systems.
- Potential toxicity to soil microorganisms, plants and soil fauna requires further evaluation.
- High production costs and complex processing techniques may limit large-scale application.
- Lack of standardized production methods and regulatory guidelines remains a challenge.

Future Research Directions

- Conduct long-term field studies to evaluate nano-biochar stability and environmental impacts.
- Develop low-cost and eco-friendly production methods**.**
- Investigate interactions between nano-biochar, soil microbes and plants.
- Develop smart nano-biochar systems for controlled nutrient delivery and precision agriculture.
- Establish safety guidelines for sustainable agricultural applications.

Conclusion

Nano-biochar is an emerging soil amendment with significant potential to improve soil fertility, nutrient management and environmental sustainability**.** Its unique physicochemical properties enhance soil quality, crop productivity and contaminant removal. However, further research is needed to understand long-term ecological impacts, optimize production methods and ensure safe application in agricultural system.

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