



Biochar-Enriched Fertilizers for Sustainable Crop Production

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INTRODUCTION

Agriculture today faces numerous challenges, including declining soil fertility, climate change, nutrient depletion, water scarcity, and environmental pollution. The growing global population demands increased food production without further degrading natural resources. Conventional fertilizers are indispensable for achieving high crop yields, but their inefficient utilization results in nutrient losses through leaching, runoff, volatilization, and denitrification.

Biochar-enriched fertilizers represent a promising approach for improving fertilizer efficiency while restoring soil health. Biochar serves as a nutrient carrier, slow-release medium, and soil conditioner that enhance fertilizer performance. The integration of biochar with mineral fertilizers, compost, manure, or microbial inoculants provides long-term improvements in soil productivity and sustainability.

2. What is Biochar?

Biochar is a stable, carbon-rich material produced by heating organic biomass under oxygen-limited conditions in a process called pyrolysis. Common feedstocks include crop residues, rice husk, wheat straw, corn stover, sugarcane bagasse, sawdust, bamboo waste, coconut shells, animal manure, and forestry residues. Unlike ordinary charcoal, biochar is specifically designed for agricultural and environmental use, improving soil fertility, enhancing water retention, supporting beneficial microorganisms, and sequestering carbon for long-term climate change mitigation.

Characteristics of Biochar

- High carbon content (60–90%)
- Large surface area
- High porosity
- High cation exchange capacity (CEC)
- Stable carbon structure
- Excellent water-holding capacity
- Long-term persistence in soil
- Rich habitat for beneficial microorganisms



3. Biochar-Enriched Fertilizers

Biochar-enriched fertilizers are advanced fertilizer formulations in which biochar functions as a nutrient carrier, adsorbent, and slow-release matrix. Nutrients are either loaded onto the porous surface of biochar or blended with it before application to the soil. These fertilizers integrate the benefits of chemical fertilizers, organic fertilizers, biofertilizers, compost, farmyard manure, and vermicompost. The porous structure of biochar improves nutrient retention, minimizes leaching and volatilization losses, enhances nutrient use efficiency, supports beneficial microbial activity, and provides a sustained nutrient

supply, thereby improving soil fertility, crop productivity, and environmental sustainability.

4. Types of Biochar-Enriched Fertilizers

4.1 Biochar + Chemical Fertilizers Examples include:

- Biochar + Urea
- Biochar + DAP
- Biochar + NPK fertilizers
- Biochar + Potassium fertilizers

Benefits:

- Reduced nitrogen loss
- Increased nutrient use efficiency
- Improved fertilizer recovery

biochar-enriched organic fertilizers improve soil structure, enhance microbial activity, support sustainable nutrient cycling, and increase crop productivity while reducing dependence on synthetic fertilizers.

4.3 Biochar + Biofertilizers

Biochar is an excellent carrier material for beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, Phosphate Solubilizing Bacteria (PSB), Potassium Solubilizing Bacteria (KSB), and Arbuscular Mycorrhizal Fungi (AMF). Its porous structure provides a protective habitat that enhances microbial survival, colonization, and activity in

the soil. Biochar-based biofertilizers improve root colonization, increase biological nitrogen fixation and nutrient solubilization, enhance nutrient uptake, stimulate plant growth, and promote sustainable crop production while reducing reliance on chemical fertilizers.

4.4 Nano Biochar Fertilizers

Nano biochar fertilizers are an emerging innovation in sustainable agriculture, where biochar is used as a carrier for nanoparticles and nano-fertilizers to improve nutrient delivery and efficiency. Examples include nano nitrogen, nano zinc, nano iron, and nano phosphorus. The high surface area and porous structure of biochar enable the controlled and slow release of nutrients, minimizing leaching and environmental losses. These advanced formulations enhance nutrient uptake, improve crop growth and yield, increase fertilizer use efficiency, and support environmentally friendly and climate-smart agricultural practices.

5. Production of Biochar-Enriched Fertilizers

The production of biochar-enriched fertilizers involves a systematic process to maximize nutrient retention and improve fertilizer efficiency.

Step 1: Biomass Collection involves collecting and drying suitable feedstocks such as crop residues, rice husk, sawdust, bamboo waste, or animal manure to reduce moisture content.

Step 2: Pyrolysis converts the biomass into biochar by heating it at 300–700°C under oxygen-limited conditions, producing a stable, porous, carbon-rich material.

Step 3: Biochar Preparation includes cooling, crushing, and sieving the biochar to obtain uniform particle size.

Step 4: Nutrient Loading enriches the biochar by soaking or mixing it with nutrient sources such as urea solution, phosphate solution, potassium salts, organic manure slurry, compost tea, or beneficial microbial inoculants, allowing nutrients to be absorbed into its porous structure.

Step 5: Drying removes excess moisture to improve storage stability and handling.

Step 6: Field Application involves applying the enriched biochar through basal application, band placement, seed treatment, nursery media, or potting mixtures, ensuring efficient nutrient delivery, improved soil fertility, enhanced crop growth, and reduced nutrient losses.

6. Mechanisms of Biochar-Enriched Fertilizers

6.1 Nutrient Retention

Biochar possesses a highly porous structure and large surface area that adsorb and retain essential plant nutrients such as nitrogen, phosphorus, potassium, and micronutrients. This reduces nutrient losses through leaching, runoff, and volatilization, ensuring their gradual release according to crop demand. Consequently, nutrient use efficiency improves, fertilizer requirements decrease, and soil fertility is sustainably enhanced.

6.2 Slow Nutrient Release

Biochar functions as a slow-release matrix by holding nutrients within its porous structure and releasing them gradually in response to crop demand. This controlled nutrient release minimizes losses through leaching and volatilization, ensures a continuous supply of essential nutrients throughout the growing season, enhances nutrient use efficiency, promotes healthy plant growth, and reduces the frequency and quantity of fertilizer applications.

6.3 Improved Soil Structure

Biochar improves soil structure by enhancing soil aggregation, increasing porosity, and reducing bulk density and compaction. These changes improve soil aeration, water infiltration, and root penetration, creating a favorable environment for plant growth. Improved soil structure also supports beneficial microbial activity, enhances nutrient availability, reduces erosion, and contributes to long-term soil fertility and sustainable crop production.

6.4 Enhanced Water Holding Capacity

The highly porous structure of biochar enables it to absorb and retain substantial amounts of water within its pores, increasing the soil's water-holding capacity. This stored moisture remains available to plants during dry periods, improving drought tolerance and reducing irrigation requirements. Enhanced soil moisture also promotes healthy root development, increases nutrient uptake, and supports stable crop growth under water-limited conditions.

6.5 Increased Microbial Activity

Biochar provides a favorable habitat for beneficial soil microorganisms due to its porous structure and large surface area. It protects microbes from environmental stress while supplying sites for colonization and growth. Increased microbial activity enhances nutrient cycling, organic matter decomposition, biological nitrogen fixation, and phosphorus solubilization. As a result, soil biological health, nutrient availability, and overall crop productivity are significantly improved.

6.6 Carbon Sequestration

Biochar is a highly stable form of carbon that can remain in the soil for hundreds to thousands of years without significant decomposition. By converting biomass into stable carbon and incorporating it into agricultural soils, biochar effectively sequesters atmospheric carbon dioxide, reducing greenhouse gas emissions. It also decreases methane and nitrous oxide emissions from soils, contributing to climate change mitigation while improving long-term soil fertility and supporting sustainable agricultural production.

7. Benefits of Biochar-Enriched Fertilizers

Biochar-enriched fertilizers offer numerous agronomic, environmental, and economic benefits by combining the nutrient-supplying capacity of fertilizers with the soil-improving properties of biochar. They enhance nutrient use efficiency, improve soil fertility, increase water-holding capacity, stimulate beneficial microbial activity, reduce nutrient losses through leaching and volatilization, and promote healthier crop growth. Additionally,

these fertilizers support carbon sequestration, reduce greenhouse gas emissions, improve fertilizer efficiency, lower production costs over time, and contribute to climate-smart and sustainable agricultural systems.

8. Application of Biochar in Different Crops

Biochar is widely used in cereals, pulses, oilseeds, vegetables, and fruit crops to improve soil health and crop productivity. In cereals such as rice, wheat, and maize, it enhances grain yield, nitrogen uptake, and root development. In pulses including chickpea, lentil, and pigeon pea, biochar promotes nodulation, biological nitrogen fixation, and protein content. Oilseed crops like mustard, soybean, and groundnut benefit from improved nutrient availability and higher oil yield. In vegetables such as tomato, potato, onion, and cabbage, biochar enhances fruit quality and marketable yield. Fruit crops including mango, citrus, banana, and guava show improved soil fertility, better water retention, enhanced nutrient-use efficiency, and superior fruit quality, leading to sustainable and profitable production.

9. Environmental Benefits

Biochar-enriched fertilizers provide numerous environmental benefits and play an important role in sustainable agriculture. They recycle agricultural and organic waste into valuable soil amendments, reducing waste disposal problems while promoting a circular bioeconomy. Biochar improves long-term soil carbon storage, helping mitigate climate change through carbon sequestration. It enhances nutrient-use efficiency, reducing the need for chemical fertilizers and minimizing nutrient losses to the environment. These fertilizers also lower greenhouse gas emissions, improve soil water retention, conserve water resources, and support beneficial soil microorganisms, thereby enhancing biodiversity. Overall, biochar-enriched fertilizers promote regenerative agriculture by restoring soil health, improving ecosystem resilience, and supporting environmentally friendly, climate-smart crop production systems.

10. Challenges and Limitations

Despite their significant benefits, the adoption of biochar-enriched fertilizers faces several challenges. High production and transportation costs can limit their affordability for smallholder farmers. Biochar quality varies depending on the feedstock and pyrolysis conditions, making standardization difficult. Limited awareness, technical knowledge, and inadequate large-scale manufacturing facilities further restrict widespread adoption. In addition, crop- and soil-specific application guidelines are still lacking, and long-term field studies across diverse agro-climatic regions remain limited. Addressing these challenges through research, policy support, quality standards, and farmer training is essential for the sustainable and large-scale use of biochar-enriched fertilizers.

11. Future Prospects

Biochar-enriched fertilizers hold immense promise for advancing climate-smart and sustainable agriculture. Future developments include nano-biochar-based fertilizers for enhanced nutrient delivery, AI-assisted nutrient management, and integration with precision agriculture technologies. Sensor-based fertilizer recommendations and customized biochar formulations tailored to specific crops and soil types will improve nutrient-use efficiency. Biochar-supported microbial inoculants are expected to strengthen soil biological activity and plant health. Additionally, carbon credit programs can encourage biochar adoption by rewarding carbon sequestration, while circular bioeconomy approaches will convert agricultural residues into valuable soil amendments. Integration with digital soil health monitoring and decision-support systems will further optimize fertilizer management, increase crop productivity, reduce environmental impacts, and enhance long-term agricultural sustainability.

CONCLUSION

Biochar-enriched fertilizers represent a transformative innovation for sustainable crop production by integrating nutrient supply with

long-term soil improvement. Their unique ability to enhance nutrient use efficiency, improve soil physical, chemical, and biological properties, increase water retention, and sequester carbon makes them a valuable tool for climate-resilient agriculture. By reducing nutrient losses, minimizing environmental pollution, and improving crop productivity, these fertilizers support the transition toward resource-efficient and environmentally sustainable farming systems. Although challenges such as production costs, quality standardization, and limited farmer awareness remain, continued research, technological advancements, supportive policies, and effective extension services are expected to accelerate their adoption. The integration of biochar-enriched fertilizers with precision agriculture, microbial technologies, and digital farming platforms offers promising opportunities to achieve higher productivity while preserving soil health and mitigating climate change, thereby contributing significantly to global food security and sustainable agricultural development.

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