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Biochar for Sustainable Cereal Production: Transforming Agricultural Residues into a Climate-Smart Soil Amendment

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Wheat, maize, rice, and barley are major cereal crops that play a vital role in global food security. However, increasing food demand, resource limitations, climate change, and declining soil quality create challenges for sustainable cereal production. At the same time, large quantities of crop residues such as straw, husks, and stalks are generated, which are often burned, causing environmental concerns. Converting these residues into biochar offers an alternative approach for residue management while improving soil quality and retaining carbon. Biochar is a carbon-rich, stable material produced by heating biomass under oxygen-limited conditions through pyrolysis. Its porous structure can enhance soil water and nutrient retention and provide suitable habitats for soil microorganisms. However, its effectiveness varies according to the feedstock, production conditions, and soil properties.

Biochar Production from Agricultural Residues

Biochar production converts agricultural residues into a stable, carbon-rich soil amendment through pyrolysis, a thermochemical process carried out under limited oxygen. It produces three main products—biochar, bio-oil, and combustible gases—whose yield and properties depend mainly on feedstock characteristics, moisture content, heating rate, and pyrolysis temperature (Li et al., 2023). Crop residues such as rice husk, rice straw, wheat straw, maize stalks, and maize cobs are suitable feedstocks for biochar production due to their availability. The properties and yield of the resulting biochar depend mainly on the feedstock type and pyrolysis temperature, which influence its physical and chemical characteristics (Li et al., 2023). Production temperatures significantly influence biochar's porosity, nutrient content, and carbon stability. Consequently, biochar is best viewed as a diverse family of materials rather than a uniform product, with its final properties dictated by the feedstock source and processing conditions. Tailoring both the choice of raw materials and the production process is essential for achieving optimal agricultural outcomes (Jindo et al., 2020; Li et al., 2023).

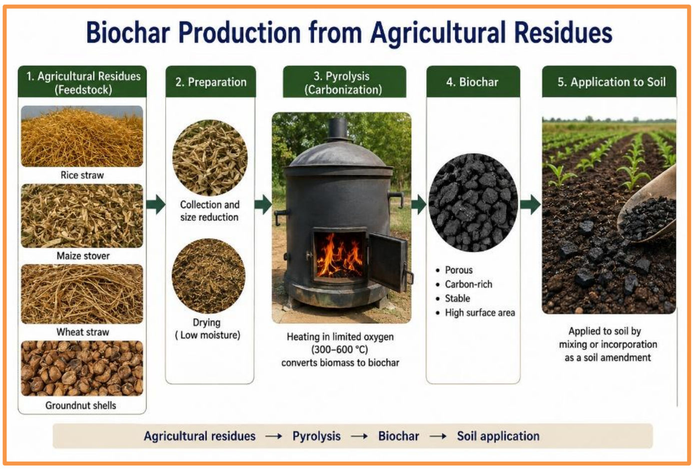

Fig. 1. Biochar production from agricultural residues

Effects on Soil Properties

1. Water and Nutrient Retention: Improves soil water-holding capacity and nutrient retention, particularly in sandy soils (Singh et al., 2022).
2. Soil pH and Fertility: Raises soil pH, increases soil organic carbon and cation exchange capacity, and influences phosphorus availability (Singh et al., 2022; Zhang et al., 2025).
3. Nutrient Cycling and Microbial Activity: Enhances microbial activity and nutrient cycling by modifying soil moisture, pH, and nutrient availability (Singh et al., 2022).
4. Soil Physical Condition: Reduces soil bulk density and increases porosity, improving soil structure and physical condition.

Effects on Growth and Yield of Cereals

1. Grain Yield: Increases grain yield of wheat and maize, while responses in rice are comparatively variable (Farhangi-Abriz et al., 2021; Singh et al., 2022).
2. Biomass, Grain Weight and Plant Growth: Enhances plant biomass, grain weight, leaf growth, chlorophyll content, and plant water status (Ababsa et al., 2023).
3. Performance under Stress Conditions: Improves cereal crop resilience to drought and salinity through better water, nutrient, and soil biological management (Ababsa et al., 2023; Singh et al., 2022).
4. Variations Across Crop Species: Biochar responses vary among crops, with generally positive effects in maize and wheat but more variable effects in rice.

Putting Biochar to Work in the Field

1. **Application Methods:** Biochar can be incorporated into soil before planting, placed near the root zone, or applied to the surface followed by tillage; uniform soil incorporation is commonly used (Osman et al., 2022).
2. **Combination with Other Inputs:** Combining biochar with compost, manure, or fertilizers can improve nutrient retention and complement nutrient supply (Osman et al., 2022).
3. **Application Rate:** The appropriate biochar rate depends on soil properties, crop requirements, and management conditions, with moderate rates often providing better responses than excessive application (Farhangi-Abriz et al., 2021).

Agronomic Importance

1. Circular-Economy Input: Converts cereal residues into valuable soil amendments, promoting residue recycling, reducing waste, and enhancing carbon retention (Jindo et al., 2020; Osman et al., 2022).
2. Long-Term Soil Improvement: Provides stable carbon that decomposes slowly and can maintain beneficial effects on soil properties over extended periods (Singh et al., 2022).
3. Climate and Environmental Benefits: Stabilizes biomass carbon, reduces the need for open residue burning, and may influence greenhouse-gas emissions and nutrient losses (Osman et al., 2022).
4. Improved Nutrient-Use Efficiency: Enhances the retention and availability of nutrients such as N, P, and K and can complement fertilizers in integrated nutrient management (Zhang et al., 2025).

Challenges

1. Cost and Scale: High production, transportation, and application costs can limit large-scale adoption, highlighting the need for economical local production systems (Li et al., 2023).
2. Inconsistent Effects: Biochar performance varies with feedstock, production conditions, and soil characteristics, resulting in different responses across fields (Singh et al., 2022).
3. Crop and Condition Specificity: Effectiveness depends on crop species, environmental conditions, soil properties, application rate, and management practices.
4. Limited Long-Term Research: More long-term studies are needed to understand biochar stability, ageing, and interactions with different cropping systems (Singh et al., 2022).

5. Quality and Safety: Proper quality control is necessary to prevent contamination by undesirable substances such as heavy metals and plastics and to ensure safe agricultural use.

Conclusion

Biochar offers a sustainable approach to converting agricultural residues into a stable carbon-rich soil amendment, while improving soil water and nutrient retention and supporting climate-smart agriculture. Its effectiveness, however, depends on soil properties, crop type, biochar characteristics, application rate, and management practices; therefore, it should be considered a complementary input rather than a complete substitute for conventional fertilizers. Further research on production technologies, long-term soil effects, application strategies, and economic feasibility is needed to promote its reliable and wider adoption in sustainable agriculture.

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