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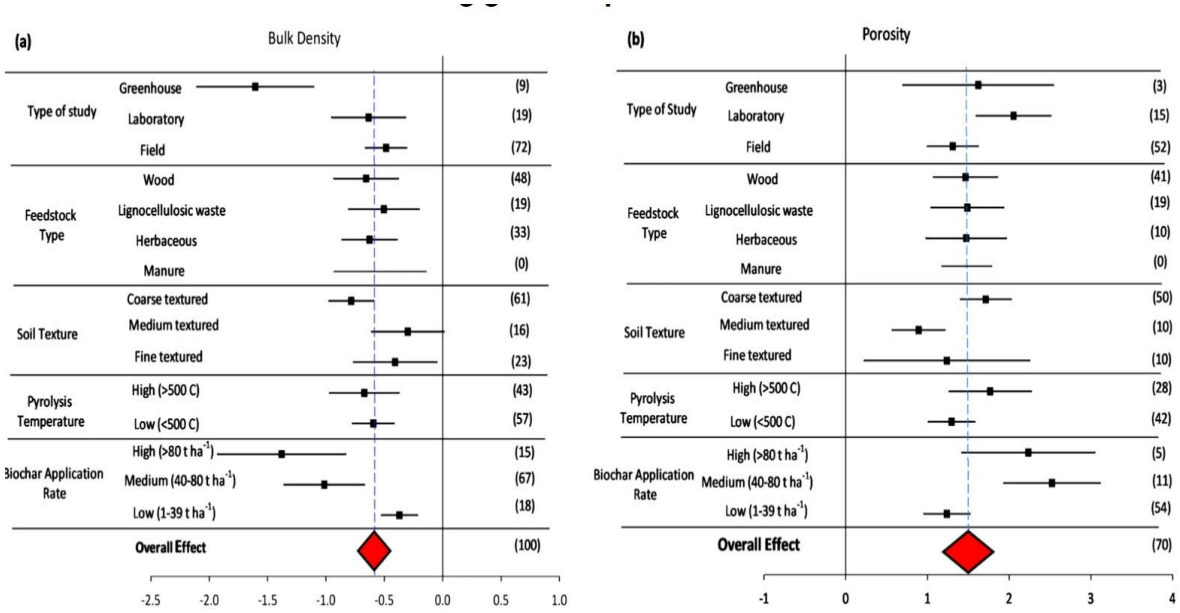
BIOTECHNOLOGICAL SIGNIFICANCE OF BIOCHAR AND BENEFICIAL MICROORGANISMS IN IMPROVING SOIL FERTILITY

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Soil fertility decline is one of the major challenges affecting sustainable agricultural production. The combined application of biochar and beneficial microorganisms represents a promising biotechnological approach for improving soil quality and crop productivity. Biochar plays an important role in modifying soil physical and chemical properties, enhancing microbial diversity, and regulating nutrient cycling processes. It provides a favorable habitat for beneficial microorganisms, increasing their activity and improving nutrient availability, water retention, and soil structure. The interaction between biochar and microbial communities contributes to carbon sequestration, soil health improvement, and sustainable agricultural development. Biochar–microbe synergy has significant potential as an environmentally friendly strategy for increasing soil fertility and supporting sustainable farming systems.

Biochar can be generated from a range of different feedstocks, including organic and industrial wastes, plant-based materials (e.g., leaves, husks, seeds, cobs), and wood-based products (e.g., woodchips, wood pellets, tree bark). Biochar can also be produced at different pyrolytic temperatures and durations of pyrolysis. The combination of feedstock type and pyrolysis conditions allows the production of biochars with a range of physical and chemical properties. Variations in physical properties of soil (bulk density and porosity) in response to biochar additions grouped by different categories (type of study, feedstock type, soil texture, pyrolysis temperature, and biochar application) are presented in Fig. 1 [1].

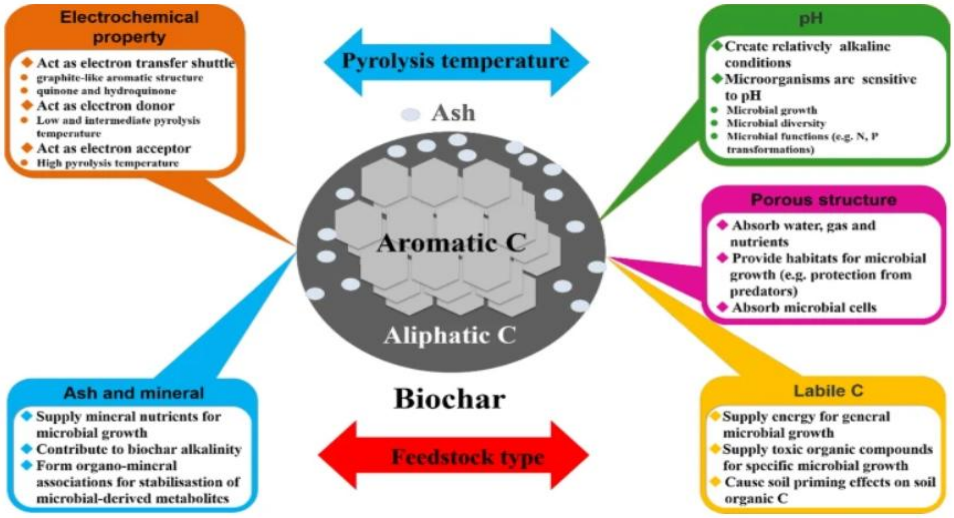
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Forest plots showing mean changes in physical properties due to biochar addition to soil for different categories grouped by type of biochar, feedstock type, soil texture, pyrolysis temperature, and application rate; **a** bulk density; and **b** porosity. Points show treatment effects for a given group and bars represent 95% confidence interval for specific categories; blue tick lines show overall effects (grand mean) and numbers at right represent total numbers of replicates (n) from the combined [1].

Biochar can change soil physicochemical properties, which in turn alters soil microbial communities and related functions via following ways (Fig. 2). First, biochar can serve as a potential porous habitat for microbial growth and protection from predators. Second, it provides carbon source (in particular labile C) and mineral nutrients for microorganisms. Third, biochar changes soil basic properties such as increase in soil pH. Furthermore, it acts as an electron shuttle for microbial metabolisms[2].

The special physicochemical properties (i.e., pH, labile C, porous structure, electron shuttle and ash) of biochars that play important roles in altering the activity, diversity and community structure of bacteria, fungi and fauna



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Effectiveness of biochar-inoculum relies on the choice of microbes. These include Plant Growth Promoting Rhizobacteria (PGPR), Nitrogen Fixers, Phosphorus Mobilizers, Mycorrhizal Fungi, and Stress-Resistant Endophytes. Mixing them with charcoal improves the formation of Hormones, Nitrogen Cycling, and the suppression of Soil Pathogens. Biochar containing Bacillus subtilis and Azospirillum brasilense increases root surface area and Nitrogen (N) absorption by wheat and rice crops [3].

In addition to acting as a means of providing nutrients to plants, biochar inoculants using microorganisms play an important role in dealing with both abiotic and biotic stress. Salinity, dehydration, toxic substances, and pathogens contribute to reduced performance and productivity of soils. Microbial species like Pseudomonas fluorescens and Trichoderma harzianum, when immobilized within charcoal, increase the activity of antioxidant enzymes and the resistance of plants against pathogens and oxidative stress [4]. Biochar can make microorganisms more efficient through its ability to absorb excessive amounts of salts and heavy metals; therefore, increasing their efficiency. The relationship between biochar and microbes is controlled by biochars physicochemical properties that help retain soil structure and moisture, creating a strong system of microbes, plants, and soils, which can withstand climate change [5].

Overall, biochar application helps boost microbial activities, change their community composition, thereby contributing to soil nutrients cycling, carbon fixation, and increased yield

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