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Biochar for Soil Improvement and Climate Mitigation

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In countries like India, where rice-wheat cropping systems dominate, seasonal residue burning has become a recurrent challenge, particularly in intensively cultivated regions like Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Bihar and West Bengal. The rapid adoption of mechanized harvesting technologies, especially the combine harvester, leaves behind large quantities of unmanageable residue on the field. Faced with narrow sowing windows and limited labour availability, farmers often resort to the open-field burning of crop residues as the quickest and least expensive disposal method. However, this practice leads to the release of enormous amounts of particulate matter and greenhouse gases like carbon monoxide, methane and nitrous oxide into the atmosphere. As a result, stubble burning significantly contributes to poor air quality, smog episodes, and short-term climate forcing. Beyond atmospheric pollution, stubble burning severely affects soil health by destroying beneficial microorganisms, volatilizing essential nutrients such as nitrogen and sulphur, and diminishing long-term soil productivity. The resulting haze often stretches across regions, affecting human health, transportation, and overall quality of life. However, Biochar offers a promising and sustainable solution to the persistent problem of stubble burning.

What is Biochar?

Biochar is a stable, carbon-rich material produced by heating organic biomass such as crop residues, wood chips, or animal waste under limited or no oxygen conditions, a process known as **pyrolysis**. Unlike ash produced by open burning, biochar retains a highly porous structure and a large surface area, making it an excellent soil amendment. Instead of burning residues openly in the field, crop biomass can be converted to biochar, which has multiple agronomic benefits. This approach allows farmers to convert what is traditionally considered "waste" into a valuable soil amendment. This not only prevents the release of harmful pollutants and greenhouse gases but also supports a circular bioeconomy by transforming residues into an asset.

Benefits of biochar

1) Improvement in Soil Properties

- **Physical Properties**

When incorporated into soil, its porous structure and high surface area increases water-holding capacity, improves soil aeration, and enhances soil aggregation.

- **Chemical Properties**

Its high cation exchange capacity (CEC) helps in retaining essential nutrients such as ammonium, potassium, calcium, and magnesium, which otherwise get lost through leaching. This improves fertilizer-use efficiency and reduces input requirements. Biochar reduced N and P leaching by 11 and 69%, respectively (Laing *et al*., 2010). Additionally, biochar can neutralize soil acidity through its alkaline nature, thereby improving pH and making nutrients more available to plants.

- **Biological Properties**

Biochar provides an ideal habitat for soil microorganisms due to its porous microstructure. It enhances the proliferation of beneficial microbes, including nitrogen-fixers and decomposers, which play essential roles in nutrient cycling. The improved soil microenvironment supports enzyme activities and promotes the formation of mycorrhizal associations, ultimately enhancing plant growth.

2) Effect on Crop

- **Crop yield**

Biochar application in the field also increases yield of various cereals and pulse crops. Increase in biomass in rice and cowpea by 20 and 50 %, respectively has been found by its application in field (Glaser *et al*. 2002). Biochar addition improved biomass and grain yields in durum wheat by up to 30 % (Vaccari *et al*., 2011) and maize grain and biomass yield by 91 and 44 % respectively (Oguntunde *et al*., 2004).

- **Resistance against diseases**

The potential of biochar soil amendment for managing diseases such as potato rot or damping off was reported long ago. Biochar prepared from citrus wood was effective against gray mold (caused by *Botrytis cinerea*) in pepper and tomato and powdery mildew in tomato (Elad *et al*., 2010). In wheat, biochar application increased the abundance of fungivores but significantly decreased the abundance of plant parasites particularly nematode trophic groups (Zhang *et al*., 2013)

3) Long-Term Carbon Sequestration and Climate Benefits

A unique advantage of biochar is its ability to store carbon in highly stable forms. When added to soil, biochar acts as a long-term carbon sink, reducing atmospheric CO_2 for decades or even centuries. This contributes to climate change mitigation. Biochar also reduces emissions of nitrous oxide (N_2O) and methane (CH_4) from soil and thus found highly effective in rice cultivation which accounts for 10% of global GHGs emission (FAOSTAT, 2016). Research in paddy field found that the total N_2O emissions ranged from1.5 to1.9 kg N_2O ha^{-1} without biochar and from 0.8 to1.3 kg and 0.7 to 0.9 kg N_2O ha^{-1} with biochar applications of 20 and 40 t ha^{-1}, respectively (Liu *et al*., 2012). 51-91 % reduction in paddy CH_4 emissions with biochar application in paddy field (Liu *et al*., 2011).

Challenges of biochar use

- High production costs due to controlled pyrolysis technology and energy requirements.
- Lack of mobile or decentralized technologies, and limited skilled personnel.
- Variable quality, as nutrient content, pH, and stability depend on feedstock type and pyrolysis temperature.
- Soil and climate-specific effectiveness, with slow or inconsistent yield responses, especially in already fertile soils.
- Application challenges, since biochar is dusty, lightweight, and difficult to spread uniformly without mixing with manure or compost.
- Potential contaminants (heavy metals, PAHs) if produced from inappropriate or polluted feedstocks.
- Limited farmer awareness regarding correct dosage, timing, and integration with fertilizers or organic amendments.
- Competition for biomass, as crop residues used for biochar are often required for fodder, fuel, or soil mulching.

Conclusion

Biochar offers great potential for improving soil fertility, enhancing nutrient efficiency, and sequestering carbon, making it a valuable tool for sustainable agriculture. However, its benefits can only be fully realized through cost-effective production, quality standardization, proper application methods, market development of its products, increased farmer awareness and its inclusion in national residue management policies. With continued research and policy support, biochar can become an important component of climate-smart farming systems

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