AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 02, Issue: 08 (August, 2025)
Available online at http://www.agrimagazine.in

Millet-Residue Biochar: A Climate-Smart Strategy for Sustainable Agriculture

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Millets are resilient, nutrient-rich cereals that thrive in low-input farming systems, particularly in semi-arid and marginal regions where other staple crops often underperform. Their adaptability to poor soils, drought tolerance, and high nutritional profile make them a critical component in ensuring food and nutritional security under changing climatic conditions. Biochar, a stable, carbon-rich material produced through the pyrolysis of biomass under limited oxygen supply, offers multiple agronomic and ecological benefits, including improved soil structure, enhanced water and nutrient retention, reduction in nutrient leaching, and long-term carbon sequestration.

This article explores the synergistic potential of integrating millet-based biochar into sustainable crop management systems. Particular emphasis is given to the utilization of millet residues—such as stalks, husks, and bran—as feedstock for biochar production, thereby addressing residue management challenges while adding value to farming systems. The discussion delves into biochar's role in boosting crop yield and grain quality, its physicochemical mechanisms of action in soils, and its potential to mitigate greenhouse gas emissions.

Furthermore, socio-economic aspects such as cost-effectiveness, farmer adoption behavior, and policy support mechanisms are examined alongside environmental considerations, including soil health restoration, biodiversity benefits, and contributions to climate change mitigation. By synthesizing agronomic research findings with socio-economic and environmental perspectives, the article positions millet-residue biochar as a climate-smart and resource-efficient intervention, with significant promise for scaling up in sustainable agriculture across diverse agro-ecological zones.

Introduction

Millets, often termed *"**nutri-cereals**"* represent a diverse group of small-seeded cereals such as *Pennisetum glaucum* (pearl millet), *Eleusine coracana* (finger millet), and *Panicum miliaceum* (broomcorn millet), which are highly adaptable to drought-prone, low-fertility, and marginal environments (Kumar et al., 2021). Their exceptional nutritional profile—rich in dietary fiber, essential amino acids, minerals, vitamins, and antioxidants—makes them indispensable for both food and nutritional security, particularly in regions facing climate-induced stress and resource scarcity.

Biochar, produced through biomass pyrolysis under limited oxygen supply, is a carbon-rich material characterized by high porosity, large specific surface area, alkaline pH, and remarkable stability of carbon content. As a soil amendment, it has demonstrated potential to improve key physicochemical properties, enhance soil water and nutrient retention, stimulate beneficial microbial activity, and sequester carbon for decades to centuries (Lehmann & Joseph, 2015).

Integrating biochar derived from millet residues into agricultural systems offers a sustainable pathway towards a circular agro-economy, wherein crop by-products are efficiently recycled into soil-enhancing amendments. This approach not only boosts crop productivity and soil resilience but also contributes to long-term climate change mitigation through carbon sequestration and reduced greenhouse gas emissions.

Biochar Production from Millet Residues

Pearl Millet Stover Biochar

Slow pyrolysis of pearl millet stover at approximately 400 °C yields about 40% biochar by weight (Singh *et al.*, 2024). The product typically exhibits ~65% porosity, a water-holding capacity exceeding 590%, and an alkaline pH around 10—qualities that enhance soil aeration, root development, and nutrient cycling.

Finger Millet Waste Biochar

Finger millet by-products, processed via hydrothermal liquefaction at 450 °C with a 1:10 solid–water ratio for approximately 33 minutes, yield a carbon-rich, stable biochar suitable for long-term application in nutrient-poor soils (Patel *et al.*, 2024). This process minimizes nutrient loss during conversion and produces a material with high agronomic value.

Impacts on Soil Health and Millet Productivity

Pearl Millet in Salt-Affected Soils

In saline–sodic environments, applying biochar at 5 t/ha has been shown to enhance soil organic carbon (SOC), cation exchange capacity (CEC), and aggregate stability while reducing plant sodium uptake, resulting in yield improvements of 17–58% depending on seasonal and soil conditions (Meena *et al*., 2024).

Finger Millet in Acidic Soils

For acidic soils, the combination of biochar at 125% farmyard manure (FYM) carbon equivalent with the recommended dose of fertilizers significantly increases plant height, tiller number, grain yield (~4,264 kg/ha), and nutrient uptake efficiency (Sharma *et al*., 2020).

Influence on Grain Quality

In broomcorn millet, the application of biochar combined with balanced nitrogen fertilization enhances starch granule smoothness and reduces amylose content—improving digestibility and making the grain more suitable for vulnerable groups such as children and elderly consumers (Zhao *et al*., 2023).

Mechanisms of Biochar Action in Millet Systems

Biochar’s influence on millet cultivation can be attributed to multiple mechanisms (Lehmann & Joseph, 2015):

1. **Physical:** Increased porosity and surface area improve water retention, aeration, and root penetration.
2. **Chemical:** Elevated CEC enhances nutrient retention while reducing leaching losses.
3. **Biological:** Biochar’s porous structure fosters microbial colonization and activity.
4. **Climatic:** Stable carbon sequestration mitigates greenhouse gas emissions.

The magnitude of these effects varies according to feedstock characteristics, pyrolysis temperature, application rates, and site-specific agro-climatic conditions.

Practical Considerations for Adoption

Successful incorporation of millet-residue biochar requires:

- **Feedstock quality control** to ensure uniform composition and absence of contaminants.
- **Appropriate production techniques** such as slow pyrolysis for high stability.
- **Optimized application rates** to prevent over-alkalization or salinity buildup.
- **Economic evaluations** including residue availability, processing costs, and potential yield benefits.

- **Farmer training** for effective handling and application

Future Research and Policy Directions

Future frameworks should prioritize:

- Multi-site field trials across varying millet species and ecologies.
- Integration of biochar use with other climate-smart practices such as conservation agriculture and precision nutrient management.
- Life cycle assessments quantifying biochar's carbon footprint reduction potential (Woolf *et al*., 2010).
- Development of socio-economic adoption models tailored to smallholder conditions.

Conclusion

Biochar derived from millet residues holds significant potential to drive soil restoration, boost crop productivity, and strengthen climate resilience in semi-arid regions. When strategically integrated into millet-based production systems, it offers a triple win—improving food security, advancing environmental sustainability, and enhancing rural livelihoods. By enriching soils with stable organic carbon, improving water and nutrient retention, and mitigating greenhouse gas emissions, millet-residue biochar can become a cornerstone of climate-smart agriculture. With robust scientific research, enabling policy frameworks, accessible financing, and farmer-centered capacity building, this innovation can move beyond experimental trials to become a mainstream, scalable practice with transformative impacts.

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