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FROM WASTE TO WEALTH: BIOCHAR AS A SUSTAINABLE SOIL CONDITIONER FOR RESILIENT AGRICULTURE IN INDIA

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ABSTRACT

Declining soil organic matter (SOM) is harming soil health quality across India, particularly in Haryana, Punjab, Uttar Pradesh, and Rajasthan, where over 90% of soils have critically low SOM levels (<2%). This depletes soil structure, reduces moisture retention, disrupts nutrient cycling, and diminishes microbial biomass, thereby increasing erosion and greenhouse gas emissions. Biochar, a stable carbon-rich material from biomass pyrolysis, enhances SOM by improving soil porosity, water retention, nutrient use, and supporting beneficial microbes. Field trials with biochar in paddy, pearl millet, and onion show improved emergence (+15%) and crop growth. Biochar combined with compost or fertilizers boosts yields, reduces chemical fertilizer use by 20–40%, and aids carbon sequestration. Large-scale conversion of crop residue to biochar in India can generate significant carbon credits and rural income. Standardized biochar quality frameworks are essential to ensure consistent benefits and environmental safety, offering a sustainable solution to restore degraded soils and support climate-resilient agriculture in India. However, India's biochar potential remains underutilised due to low stakeholder awareness, limited market incentives, and technological dependence. Absence of standardisation, inadequate infrastructure, and policy uncertainty further constrain adoption. Strengthening domestic production capacity, harmonising certification standards, and integrating biochar into agricultural policy are critical to achieving sustainable soil and carbon management.

Keywords: Biochar, Soil Organic Matter (SOM), Carbon Sequestration, Sustainable Agriculture, Crop Residue Management, Soil Health Improvement

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INTRODUCTION

Declining soil organic matter (SOM) is severely harming soil health throughout India. A nationwide survey of 50 million samples (2015–16 to 2018–19) showed that 85% of soils have organic carbon levels below the adequate range, with many showing SOM levels well under the critical ~2% in the root zone. This depletion—caused by intensive farming, limited use of organic amendments, and erosion-driven topsoil loss—is most significant in Haryana, Punjab, Uttar Pradesh, and Rajasthan, where over 90% of samples are critically low, which reduces the soil's aggregate stability, water retention, and nutrient buffering capacity, while increasing runoff, erosion, and greenhouse gas emissions. It also cuts microbial biomass by up to 30%, disrupting nutrient cycling and harming soil biodiversity.

Restoring SOM requires integrated nutrient management, organic manure, and conservation tillage, supplemented by biochar application. Biochar, a stable, carbon-rich by-product of biomass pyrolysis, resists decomposition and enhances SOM stability for decades. It improves soil structure, porosity, and moisture retention while providing habitat for beneficial microbes and increasing nutrient use efficiency. When combined with composts or farmyard manure, biochar can significantly speed up SOM recovery, sequester carbon, and boost climate resilience—making it a crucial tool for revitalizing India's degraded soils and supporting sustainable crop productivity.

Biochar is a charcoal-like material produced by the pyrolysis of biomass in an oxygen-limited environment, resulting in a stable form of carbon intended for soil amendment and long-term carbon sequestration. Defined by the International Biochar Initiative as the "solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment," biochar's properties—high porosity, large surface area, and chemical stability—make it ideally suited for enhancing soil ecosystems.

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The application of biochar to agricultural soils confers multiple benefits:

- **Improved Soil Structure and Aeration:** Biochar boosts soil aggregate stability and porosity, resulting in better drainage and root penetration.
- **Enhanced Water Retention:** Its porous matrix holds moisture, especially in coarse-textured and semi-arid soils, lowering drought stress.
- **Nutrient Retention and Cycling:** Biochar's high cation exchange capacity absorbs and slowly releases essential nutrients (NPK), reducing leaching and boosting fertilizer efficiency by up to 20%.
- **pH Buffering and Microbial Habitat**: Alkaline biochar can neutralize acidic soils, while its complex pore network provides habitat for beneficial microorganisms, boosting microbial biomass and enzyme activity.
- **Greenhouse Gas Mitigation**: Biochar reduces emissions of nitrous oxide and methane from soils by 30–50%, contributing to climate-smart agriculture.

Together, these improvements sustain soil fertility, increase crop yields by 10–25%, and build resilience against degradation and erosion.

Potential of Biochar Production in India

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India produces over 683 million tonnes of crop waste and an estimated 682.6 million tonnes of agricultural waste, including both edible crops and surplus materials, much of which is openly burned or landfilled. Converting just 30–50% of this biomass into biochar could generate 15–26 million tonnes annually and remove approximately 0.1 gigatonnes of CO_2-equivalent from the atmosphere. Incorporating biochar into India's upcoming carbon market, expected to launch in 2026, could create carbon credits, generate rural jobs, and improve soil health, supporting the nation's climate and agricultural objectives. This crop waste includes rice husk, wheat straw, sugarcane bagasse, and cotton stalks. Approximately 178 million tonnes of surplus residues exist, with about 92 million tonnes typically burned, resulting in severe air pollution, spikes in air quality indices, soil degradation, and water contamination. The issue is further worsened by inorganic wastes such as pesticide residues and plastics from farming practices, which persist in the environment, degrading soil and water quality and posing long-term ecological risks.

Research shows that bio-char derived from crop residues such as pigeonpea and maize stalkscan contain 40–50% total carbon, with over 90% of this being in a stable form, making it highly effective for enduring carbon storage in soils. Its production can be implemented at both decentralized farm-level using portable kilns and at community-scale facilities, ensuring practicality and accessibility for Indian farmers.

Biochar Economic and Environmental Benefits

Biochar delivers substantial economic benefits to Indian farmers, as evidenced by field studies and research. An on-farm comprehensive survey involving 962 households across Madhya Pradesh, Maharashtra, and Odisha found that biochar application led to a significant increase in net farm returns—improving profitability by 29.34%—while also raising crop yields by 4.34% and reducing overall cultivation costs by 1.52%. Specific multi-season trials in Maharashtra showed that applying 2 tons of biochar per acre increased chickpea yields by 18% and soybean yields by 40%, with even larger gains (up to 110%) observed when higher doses were used during drought-prone seasons.

Research from India indicates that incorporating biochar into inorganic fertilizers can reduce chemical fertilizer use by approximately 20% to 40% without compromising wheat yields. Biochar enhances soil nutrient retention by adsorbing nutrients such as nitrogen, phosphorus, and potassium, thereby decreasing their leaching and increasing their availability to plants. In soybean trials, combining biochar with half the typical amount of inorganic and organic fertilizers increased nitrogen, phosphorus, and potassium uptake by about 13% to 29%. Additionally, biochar enhances soil microbial activity and organic carbon content, further supporting nutrient cycling and plant growth. This improved efficiency in nutrient use reduces dependence on synthetic fertilizers, lowers input costs, and lessens environmental impacts such as greenhouse gas emissions. Overall,

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biochar serves as a cost-effective soil amendment that promotes sustainable farming among Indian farmers by reducing fertilizer reliance and enhancing soil health and crop yields.

S M Sehgal Foundation's Pilot Project on Biochar:

The S.M. Sehgal Foundation has initiated an evidence-based pilot project aimed at sustainable crop residue management and improving soil health through biochar application. This project promotes converting crop residues into biochar, using it to enhance soil fertility and structure. The pilot was Rajasthan and Maharastra during the 2024 Kharif season. The biochar was used in paddy, pearl millet, cotton and onion crops. In the first phase, a total of 30 farmers were selected for the pilot project, in which 1.2 Metric Tons (MT) of fine-grade artisan biochar are used per acre. The demo is provided for a half-acre area, serving as an experimental plot to observe the differences between conventional practices and a demonstrated plot. Before the intervention, soil samples were collected from each plot and analyzed for key parameters, including soil organic carbon (SOC) content, pH, and salinity. A total of 30 soil samples were collected across all locations for testing. The selected soil samples showed a significant deficiency in organic carbon, with 19 out of 30 samples classified as very low in SOC (<0.5%), and pH levels mostly indicated alkaline conditions (pH > 8 in 28 samples). The biochar procured for the pilot project was produced from rice straw and rice husk.

Biochar Activation and Application:

Biochar was activated by mixing it with compost at a 1:1 ratio and using a 3 kg inoculum of Vesicular-Arbuscular Mycorrhizae (VAM) fungi for 7 days. This bio-activation aimed to enrich the biochar surface with microbial communities and nutrients, optimizing its effect on soil biogeochemical processes. The activated biochar was broadcast and incorporated into the soil using a rotavator to achieve homogenous distribution and maximize contact with the sub-surface.

Preliminary Observations and Data Collection:

Initial observations revealed that the emergence rate was 15% higher than that of the control plot for all crops. Other visible traits, such as seedling growth and leaf color, were also recorded and observed to be more positive compared with the control plot. Biochar had a more substantial positive effect on pearl millet than on onion and paddy because pearl millet is grown in sandy soil, where biochar helps retain soil moisture, which benefits this crop more.

In the second phase, similar farmers provided an additional 1.2 MT of activated biochar to use in the same field. To assess the impact of biochar application on soil organic carbon, the soil samples were retested for second year. The following table presents the net change observed for two parameters: SOC and soil pH.

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Location	Location		Soil Type	Sample Count	pH (Baseline)	pH First Year	pH Second Year
	State	District					
1	Haryana	Kaithal	Sandy loam	4	7.5-8.5	7.2-8.2	7.0-7.9
2			Sandy Loam	3	8.5-8.8	8.2-8.4	8.0-8.3
3			Sandy Loam	3	6.5-7.5	6.4-7.2	6.4-7.5
1	Rajasthan	Alwar	Alluvial	4	7.2-7.8	7.2-7.8	7.1-7.8
2			Alluvial	3	7.8-8.0	7.7-7.9	7.6-7.9
3			Alluvial	3	7.2-7.8	7.2-7.8	7.1-7.8
1	Maharastra	Aurangabad	Black	4	8.1-8.4	8.0-8.2	8.0-8.1
2			Black	3	7.9-8.2	7.9-8.2	7.5-8.0
3			Black	3	7.8-8.1	7.6-7.8	7.6-7.8

The data in the table show distinct pH variations among three soil types observed over two years. Sandy loam soils in Haryana recorded the largest decline, with average pH dropping by 0.33 units from the baseline value of 7.88 to 7.55 in the second year, indicating a progressive acidification trend. Black soils in Maharashtra showed a moderate decrease of 0.23 units, from 8.08 to 7.85, reflecting gradual stabilization. In contrast, alluvial soils in Rajasthan remained stable, with no measurable change in pH (7.63 to 7.63), maintaining a neutral condition throughout the period.

Although biochar is naturally alkaline and its influence on soil pH is generally limited, a slight decrease in pH was observed across different sampling locations. This reduction is primarily attributed to the addition of equal quantities of farmyard manure (FYM) and the small amount of biochar applied—approximately 2.4 metric tons per acre over two years. The observed pH decline is likely due to the continuous incorporation of compost into each field for two consecutive years.

Organic carbon (OC) content range	# Samples (Before Biochar Application)	# Samples (After one year Biochar Application)	# Samples (Second year Biochar Application)
OC less than 0.5%	19	12	10
OC in between 0.5%-0.7%	5	12	14
OC in between 0.7%-1.5 %	6	6	6
OC higher than 1.5 %	0	0	0

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Organic Carbon (OC) content shows a distinct improvement in soil organic carbon over two years of observation. 47% of the samples with less than 0.5% OC at baseline reported an increase in OC after the application of 1.2 MT biochar consecutively for two years. Conversely, samples in the 0.5-0.7% OC range increased from 5 (baseline) to 14 (second year), indicating an improvement in OC levels following biochar application. Samples with OC 0.7-1.5% remained stable across all years. None of the soil samples reported with OC range >1.5% after biochar application. Building on these efforts, the project expanded further during Kharif 2025, incorporating 300 farmers, including those from the previous year. The 20 initial farmers continued applying 1.5 MT/acre for the third year in a row, allowing for long-term impact assessment.

The form and genesis of biochar play a significant role in holding the soil's moisture. A lab test was done to measure the amount of water absorbed by two different forms of biochar. The biochar produced from Woodstock is taken into two forms: granular (a particle size between 3-5 mm) and cubical (a particle size between 15-20 mm). The sample was pulverized from cubical to granular form.

Both samples were immersed in distilled water for 24 hours and then oven-dried for 2 hours at 100 °C. The weight was taken before and after the oven dried. The result is given below;

	Sample 1	**Sample 2**
	Granular Charcoal, Particle size 3-5mm	Cube charcoal, particle size 15-20 mm
Dry weight (gm)	17.01	48
Wet weight (gm)	119.01	82.54
Moisture content (%)	85.7	41.8

The test shows that the granular form has more capacity to hold water than the cubical form. This also anticipates the benefits of using small particle sizes for even mixing into the soil.

Synergistic Effects of Biochar with Biologicals for Enhanced Soil Health

Bioaugmentation of biochar through microbial inoculation with specific bio-agents, including phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), Trichoderma spp., and Azotobacter spp., as well as Mycorrhizae, enhances the biofunctional properties of biochar by creating optimal micro-environmental conditions within the soil. This biochar inoculated with microbe helps establish and grow beneficial microbial populations, which then improve nutrient availability through various biochemical processes such as organic acid production, enzymatic activities, and mineralization.

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Studies show that PSB-enriched biochar increases phosphorus uptake by up to 72.5% in crops while enhancing nitrogen uptake by 23.1% compared to controls. When combined with KSB, biochar treatment increases the available potassium content by 52.1% and enhances plant biomass by 46%. The integration of Azotobacter with biochar supplies approximately 20 kg N/ha/year through biological nitrogen fixation while producing growth-promoting hormones and improving soil nitrogenase activity. Trichoderma-inoculated biochar demonstrates dual benefits of disease suppression—reducing fusarium wilt by 27% and collar rot by 33%—while also promoting root development and increasing plant height. Multi-species formulations containing these microbes, mixed with biochar, perform even better. One study reported a 26.3% increase in fresh weight and a 110% improvement in photosynthetic efficiency. The porous structure of biochar creates an ideal habitat for microbial colonization, protecting beneficial organisms from harsh soil conditions and enabling sustained nutrient release. This integrated approach presents a promising sustainable agriculture strategy that reduces reliance on chemical fertilizers while enhancing soil health, crop yield, and disease resistance through increased microbial diversity and activity.

Needs for a Standard Framework for Biochar Application.

A standard framework for biochar application is crucial to ensure product quality, environmental safety, and reliable performance across various applications. Biochar, a carbon-rich material made through biomass pyrolysis, varies significantly depending on feedstock and production methods. Without uniform standards, there is a risk of inconsistent product quality, potential soil contamination, and diminished trust among consumers and regulators.

Several agencies, such as the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC), have set IBI Biochar Standards, which define biochar quality, testing methods, and criteria mainly for soil use. In India, there is a need for a tailored standard framework for small and marginal farmers. These standards ensure consistent biochar quality, including carbon content and safety, promoting soil health and carbon capture. They also provide guidelines on environmental impact, sustainable sourcing, safe use, and certification for various applications, including feed, agriculture, organic farming, and industry.

In conclusion, establishing standardized frameworks for biochar application is crucial for mitigating risks, ensuring environmental benefits, and supporting the growing biochar industry with reliable, trustworthy, and safe products.

Challenges in the production and adoption of biochar

India possesses significant potential for biochar production and application, particularly in agriculture, due to its vast biomass resources. However, despite its promise in enhancing soil

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health, carbon sequestration, and sustainable waste management, the adoption of biochar in India faces multiple structural, economic, and policy barriers that hinder its widespread implementation.

Limited Awareness and Stakeholder Engagement: A major barrier lies in the lack of awareness across stakeholders—farmers, policymakers, and investors. Most farmers remain unaware of biochar's benefits for soil fertility and carbon sequestration, which restricts its agricultural adoption. At the policymaking level, existing biochar initiatives primarily emphasise carbon offsetting rather than agricultural applications that could directly support farmers. This gap in focus delays the integration of biochar into mainstream sustainable farming policies. Similarly, investors often view biochar projects primarily through the lens of carbon credits, rather than considering the long-term benefits to agriculture and the environment. Consequently, financial engagement remains shallow and fragmented.

Absence of Market Catalysts and Large-Scale Infrastructure: India's biochar sector lacks strong market incentives such as subsidies, carbon pricing mechanisms, or targeted support programmes that would make biochar commercially attractive. Establishing large-scale biochar production facilities requires heavy capital investment and access to stable feedstock supplies. As a result, the market is dominated by low-tech, small-scale producers, while industrial-scale projects remain rare and underfunded.

Standardisation and Certification Challenges: The lack of harmonised certification standards for carbon removal projects complicate the evaluation and comparison of biochar projects. India's diverse feedstocks further complicate standardisation since biochar properties vary by source material. While the Ministry of Agriculture has initiated efforts to develop national guidelines, consistent enforcement and alignment with international norms remain incomplete.

Technological Dependence and Infrastructure Gaps: India's reliance on imported biochar technologies restricts scalability and increases costs. Domestic technology providers are emerging but remain insufficient to meet surging demand. Infrastructural deficiencies—particularly in feedstock aggregation, transport, and processing—create additional bottlenecks. Strengthening local supply chains and developing indigenous pyrolysis technologies are key for improving efficiency and resilience.

Competition and Market Fragmentation: Competition from other biomass-based solutions, such as biogas or composting, diverts attention and investment away from biochar. While such alternatives also promote sustainable waste management, they often crowd out funding and policy focus. With minimal local demand, Indian producers rely heavily on exporting biochar and carbon credits to international markets. However, this dependence limits internal growth and keeps domestic utilisation low.

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Policy and Carbon Market Uncertainty: India's evolving carbon market presents both opportunities and risks. Integration into global carbon trading systems could unlock large-scale investment, but unclear regulations, fragmented certification schemes, and lack of alignment with international carbon credit standards generate uncertainty. Stable policy frameworks, market incentives, and harmonised certification standards will be crucial to attract investment and make biochar a central tool in India's pathway toward sustainable agriculture and carbon neutrality.

CONCLUSION

Restoring India's depleted soils demands urgent action to rebuild soil organic matter. Biochar—produced from abundant crop residues—offers a durable, carbon-sequestering soil amendment that enhances structure, moisture retention, nutrient efficiency, and microbial health. Field trials demonstrate biochar's capacity to boost emergence, reduce fertilizer use, and increase yields, while converting biomass into biochar supports carbon markets and rural livelihoods. However, achieving wide scale impact hinges on standardized production and quality guidelines tailored to Indian contexts. Integrating biochar with organic and conservation practices can revitalize soil fertility, mitigate greenhouse gas emissions, and underpin resilient, sustainable agriculture across India. Despite India's strong potential for biochar production, its widespread adoption is hindered by limited awareness, lack of market incentives, and weak policy support. Farmers, investors, and policymakers remain disconnected, inconsistent certification standards, dependence on imported technologies, inadequate infrastructure. Strengthening domestic technology, ensuring standardisation, and introducing supportive incentives and awareness programs are vital to position biochar as a key solution for sustainable agriculture and carbon reduction in India.

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