



Technology Whitepaper

Biochar in Agriculture

Soil Health and Carbon Sequestration

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Table of Contents

1. Introduction	04
2. What is Biochar	06
3. Biochar and Soil Health	09
4. Carbon Sequestration Potential	12
5. Application Strategies in Regenerative Agriculture	14
6. Co-benefits and Economic Impacts	17
7. Challenges and Considerations	19
8. Future Outlook and Innovations	20
9. Summary and Way Forward	21

Executive Summary

Biochar, a carbon-rich material derived from the thermal decomposition of organic biomass under limited oxygen conditions, has emerged as a critical solution in addressing both agricultural productivity and climate change. This whitepaper explores the science, applications, and climate benefits of biochar in agricultural systems, emphasizing its dual role in enhancing soil health and enabling long-term carbon sequestration. Carbon Fresh Climate India Pvt Ltd presents this paper to drive awareness, adoption, and innovation in biochar-based regenerative agriculture practices.

Introduction

As we stand at the crossroads of environmental restoration and agricultural sustainability, regenerative agriculture has emerged as a guiding principle for rebuilding soil fertility, increasing biodiversity, and enhancing carbon drawdown. One of the most promising tools within this movement is biochar, a scientifically proven and nature-aligned solution that supports both ecological balance and long-term productivity.

Biochar, derived through pyrolysis from organic biomass, addresses two critical global challenges: declining soil health and escalating atmospheric carbon levels. Its highly porous structure not only improves soil structure, water retention, and nutrient availability but also creates a stable form of carbon that can remain in the soil for centuries. These properties align biochar with the core objectives of regenerative agriculture—restoring natural systems, increasing resilience, and enhancing ecosystem services.

This whitepaper aims to present a detailed understanding of biochar's role in regenerative agricultural practices, particularly in the Indian context. It combines insights from scientific literature, real-world trials, and the innovative approaches adopted by Carbon Fresh Climate India Pvt Ltd. We delve into the fundamentals of biochar, its application strategies, environmental co-benefits, economic impacts, and its carbon sequestration potential under robust Monitoring, Reporting, and Verification (MRV) frameworks.

With a focus on both science and scalability, this document is intended to serve as a resource for farmers, researchers, policymakers, and stakeholders in the carbon economy who are seeking actionable pathways to implement regenerative solutions. Biochar represents a bridge between traditional farming knowledge and modern climate innovation, and its adoption can contribute significantly to a net-zero future.

As the global food system faces mounting pressure from soil degradation, water scarcity, and the urgent need to reduce greenhouse gas emissions, biochar presents a transformative opportunity. Its porous structure and stable carbon matrix make it a unique soil amendment and carbon sink.

This article focuses on:

- The properties and production of biochar
- Soil health benefits
- Carbon sequestration potential
- Implementation strategies for regenerative agriculture in India

What is Biochar?

Biochar is a fine-grained, carbon-rich material produced through the thermal decomposition of organic biomass in the absence or near-absence of oxygen a process known as pyrolysis. Unlike traditional charcoal, biochar is specifically designed for use in soil enhancement and carbon sequestration. The biomass feedstocks used can vary widely and may include agricultural residues (such as rice husk, coconut shells, and sugarcane bagasse), forest waste, bamboo, and other forms of organic material.

The pyrolysis process not only yields biochar but can also produce syngas and bio-oil, making it a versatile approach for waste valorisation and renewable energy production. The slow pyrolysis method, typically conducted at temperatures between 300 and 700°C, is preferred for maximizing biochar yield and carbon stability.

Key Properties and Agricultural Benefits of Biochar

High Surface Area and Porosity

Biochar possesses a sponge-like structure with high internal surface area and micro-porosity. This characteristic provides a large reactive surface that facilitates:

- Better soil aeration and root penetration
- Habitat for beneficial soil microbes
- Adsorption of nutrients and water, improving retention and reducing leaching

In regenerative agriculture, this improves plant access to both air and moisture, especially in degraded or sandy soils.

Stable Carbon Content

The carbon present in biochar is highly recalcitrant, meaning it decomposes very slowly compared to organic matter like compost or manure. This stability ensures:

- Long-term carbon sequestration (up to 1,000 years)
- Enhanced soil organic carbon (SOC) levels
- Reduced CO₂ and CH₄ emissions from soil

This aligns with climate-smart agriculture practices aimed at mitigating global warming.

Alkaline pH

Most biochar's exhibit an alkaline pH due to the concentration of basic minerals like calcium, potassium, and magnesium.

- Helps neutralize acidic soils (common in many Indian regions)
- Enhances nutrient availability and uptake
- Improves soil buffering capacity against chemical inputs

Rich in Essential Minerals

Biochar retains a matrix of essential plant nutrients from the original feedstock.

- Supplies micronutrients such as zinc, copper, boron, and molybdenum
- Enhances fertility, especially when co-applied with compost or fertilizers
- Contributes to balanced nutrition for crops

Water Retention and Nutrient-Holding Capacity

The porous matrix and high cation exchange capacity (CEC) of, biochar significantly boosts:

- Soil water-holding capacity, reducing the need for frequent irrigation
- Nutrient retention, minimizing losses due to leaching or volatilization
- It also helps in adsorption of pollutants in soil and water
- Drought resistance and input efficiency

These properties make biochar particularly beneficial in water-scarce, rainfed, or semi-arid agroecological zones.

Together, these characteristics make biochar a cornerstone material for regenerative agricultural practices. It not only revitalizes soil but also closes the loop on organic waste, making agriculture more circular, resilient, and climate-positive.

Biochar and Soil Health

Healthy soil is the foundation of productive agriculture and ecological resilience. In regenerative farming systems, restoring the biological, chemical, and physical integrity of soils is paramount. Biochar contributes directly to this mission by improving key soil health indicators and creating a thriving environment for plant roots and microbial communities.

The application of biochar not only enhances immediate crop performance but also contributes to the long-term regeneration of degraded soils. Its impact spans structural improvements, nutrient management, biological activity, and moisture dynamics.

Improvement in Soil Structure

One of the most visible benefits of biochar application is its ability to enhance soil structure. Biochar's porous and rigid physical framework helps in forming stable soil aggregates. This leads to:

- Improved tilth and ease of cultivation
- Increased soil aeration, facilitating gas exchange in the root zone
- Enhanced root penetration and exploration

In compacted or clay-heavy soils, biochar mitigates crusting and compaction, creating a friable soil environment that supports plant vigor and microbial diversity.

Nutrient Retention and Availability

Biochar significantly boosts the soil's cation exchange capacity (CEC), enabling it to adsorb and retain positively charged nutrients such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}).

- Reduces nutrient leaching, especially in sandy or high-rainfall zones

- Increases fertilizer use efficiency, reducing dependency on synthetic inputs
- Acts as a slow-release carrier when pre-loaded with compost or liquid fertilizers

Biochar's ability to retain nutrients close to the root zone ensures plants receive sustained nutrition throughout their growth cycles, even under nutrient-stress conditions.

Enhanced Microbial Activity

Biochar fosters a hospitable environment for beneficial microbial communities by offering both refuge and resources. Its high surface area, pore structure and its carbon and nutrient content provide microhabitats for bacteria, fungi, and actinomycetes.

- Encourages colonization by nitrogen-fixing and phosphorus-solubilizing microbes
- Enhances interactions with mycorrhizal fungi, leading to improved nutrient uptake especially phosphorus.
- Supports disease suppression through beneficial microflora proliferation

This microbial activity translates into improved nutrient cycling, organic matter breakdown, and a more resilient soil food web.

Moisture Regulation

Water management is a critical challenge in Indian agriculture, especially in rainfed areas. Biochar helps mitigate this challenge by improving soil water dynamics:

- Increases water retention in sandy soils by trapping water in their pores
- Improves drainage and reduces waterlogging in clay soils

- Enhances the soil's field capacity and available water content for plants

As a result, crops experience less drought stress, and irrigation frequency can be reduced—yielding water savings and operational efficiency.

In summary, biochar enriches the soil ecosystem across physical, chemical, and biological dimensions. Its holistic benefits extend beyond immediate productivity gains to building long-term soil capital—a prerequisite for resilient and regenerative farming systems. Its porous nature increases the soil's water-holding capacity, improving drought resilience for crops.

Carbon Sequestration Potential

Carbon sequestration is a key environmental function that addresses the urgent challenge of rising atmospheric greenhouse gas (GHG) concentrations. Biochar stands out among nature-based carbon removal strategies due to its longevity, scalability, and co-benefits to agriculture. When applied to soil, biochar transforms agricultural waste into a stable, solid form of carbon, effectively locking away CO₂ for centuries. This makes it an indispensable technology for meeting climate targets under national and international commitments such as the Paris Agreement.

Stability of Carbon in Biochar

The core attribute that enables biochar to serve as a carbon sink is its stability. Unlike compost, manure, or crop residues that decompose and release carbon dioxide and methane within a few seasons, biochar's molecular structure—characterized by aromatic carbon rings—makes it highly resistant to microbial degradation. Once integrated into the soil, up to 80–90% of the carbon content in biochar can remain sequestered for several hundred to thousands of years. This stability depends on factors such as pyrolysis temperature, feedstock type, and soil conditions.

Incorporation of biochar into the soil not only sequesters carbon but also enhances the soil's organic carbon pool, further improving long-term soil fertility and carbon storage.

Role in Climate Change Mitigation

Biochar contributes to climate change mitigation in multiple ways:

Direct Carbon Removal: Prevents the immediate release of CO₂ from biomass decomposition or burning.

Methane and Nitrous Oxide Reduction: Biochar-treated soils show a reduction in methane (CH₄) emissions from anaerobic decomposition and in nitrous oxide (N₂O) emissions from nitrogen fertilizers.

Enhanced Biomass Productivity: Healthier soils lead to increased plant growth and thus greater photosynthetic carbon capture.

These combined benefits make biochar a negative-emissions technology that not only avoids emissions but also actively removes carbon from the atmosphere.

Quantifying Sequestration

Accurate quantification is essential for integrating biochar into carbon credit systems. Carbon Fresh Climate India Pvt Ltd uses internationally recognized Monitoring, Reporting, and Verification (MRV) protocols that comply with standards set by organizations such as VERRA, Puro.earth, and Gold Standard.

Key MRV elements include:

Biochar characterization: Carbon content, stability index, and ash content.

Soil incorporation verification: Documentation of application methods and agronomic practices.

Carbon accounting models: Lifecycle analysis to assess net carbon benefit per tonne of biochar applied.

Permanence assurance: Strategies for ensuring the biochar remains undisturbed in soil over the designated time horizon.

By adhering to robust MRV frameworks, Carbon Fresh ensures transparency and credibility in its carbon removal claims, paving the way for farmer participation in voluntary carbon markets. This provides not only ecological but also financial incentives for biochar adoption in regenerative agriculture.

Carbon Fresh utilizes MRV (Monitoring, Reporting, and Verification) protocols aligned with international carbon standards to quantify and validate CO₂e-sequestration per tonne of biochar applied.

Application Strategies in Regenerative Agriculture

Effective deployment of biochar in regenerative agriculture requires a contextual understanding of local agroecological conditions, crop types, soil characteristics, and farming practices. The versatility of biochar allows it to be applied across diverse farming systems, but its efficacy is optimized when customized to specific environmental and management conditions. This section outlines practical strategies for incorporating biochar into farming systems to regenerate soil health, enhance productivity, and capture carbon.

Suitable Crops and Regions

Biochar is highly adaptable across a wide variety of crops and climatic zones in India. It is especially beneficial for:

- **Paddy and Sugarcane Systems:** Improves drainage and reduces methane emissions in waterlogged soils.
- **Vegetable and Horticultural Crops:** Enhances nutrient availability, root development, and yield quality.
- **Cotton and Pulses:** Boosts drought resilience and nitrogen-use efficiency.

It is well-suited for use in:

- **Rainfed and semi-arid regions:** Improves moisture retention and reduces irrigation frequency.
- **Degraded or nutrient-depleted soils:** Rebuilds soil fertility and biological activity.
- **Organic and natural farming systems:** Supports microbial diversity and minimizes dependence on external inputs.

Application Rates

The ideal application rate varies based on soil texture, crop type, and the desired outcomes.

General guidelines include:

- 1–5 tonnes per hectare: For soil conditioning and integration with organic matter.
- 5–10 tonnes per hectare: For carbon sequestration and long-term fertility rebuilding.
- Application can be done as a basal application during land preparation or as a localized placement in planting rows or pits.
- Biochar charging (pre-mixing with compost, urine, or digestate) is recommended to avoid initial nutrient immobilization.

Integration with Organic and Inorganic Inputs

Biochar works synergistically with both organic and inorganic soil amendments:

- With compost or farmyard manure: Enhances microbial activity, humus formation, and slow nutrient release.
- With vermicompost or green manure: Strengthens soil biological networks and nutrient cycling.
- With synthetic fertilizers: Increases nutrient use efficiency, reduces runoff and volatilization losses.

Such integrations contribute to holistic soil health improvement and more balanced crop nutrition over time.

On-Field Results and Observations

Field trials conducted by Carbon Fresh Climate India Pvt Ltd and its partners in Tamil Nadu, Andhra Pradesh, and Karnataka have demonstrated the following:

- 10–20% yield increase in vegetables, pulses, and sugarcane.
- 15–30% reduction in fertilizer input due to improved nutrient retention and microbial efficiency.

- 0.2–0.5% increase in SOC levels within the first season of application.
- Enhanced water-use efficiency leading to up to 25–30% savings in irrigation water.
- Visible improvements in soil texture and microbial life, including earthworm activity and fungal root associations.

These results validate biochar as a key component of regenerative land management strategies that promote ecological balance and climate-smart outcomes. Field trials in Tamil Nadu, Maharashtra, and Karnataka have shown:

- 10–20% yield increase
- Reduced fertilizer input by 15–30%
- Improved SOC levels by 0.2–0.5%

Co-benefits and Economic Impacts

Biochar not only contributes to soil restoration and carbon removal but also delivers tangible co-benefits and economic value to farming communities. When applied systematically, biochar reduces costs, increases resilience, and creates new revenue streams for farmers, making it a cornerstone of sustainable rural development.

Reduction in Agricultural Inputs

- Due to improved nutrient retention, biochar reduces the frequency and volume of fertilizer applications.
- Enhanced microbial activity supports natural nutrient cycling, further lowering chemical dependency.
- Improved water retention leads to a 25–30% reduction in irrigation needs, especially in drought-prone regions.

Crop Yield and Quality Improvement

- Field trials indicate consistent 10–20% yield increases across crops like vegetables, pulses, and sugarcane.
- Enhanced soil health leads to better root development and resilience to environmental stress.
- Farmers also report improved produce quality, shelf life, and market value.

Carbon Credit Revenue

- Carbon Fresh enables the generation of verified carbon credits through MRV-aligned projects.
- Each tonne of biochar can sequester approximately 2.2–3.0 tonnes of CO₂e.
- Participation in carbon markets offers an additional income stream, supporting inclusive climate finance.

Socioeconomic Benefits

- Localized biochar production creates rural employment opportunities.
- Utilization of crop residues minimizes waste and improves sanitation in rural areas.
- Enhanced land productivity supports long-term food security and sustainable livelihoods.

Challenges and Considerations

Despite its potential, biochar implementation in regenerative agriculture presents several challenges that require strategic planning, stakeholder coordination, and investment.

Farmer Awareness and Training

- Limited awareness among farmers regarding biochar benefits and application methods.
- Need for extension services, capacity-building programs, and demonstrative pilots.

Variability in Soil Response

- Biochar performance varies based on soil type, biochar quality, crop, and climate.
- Site-specific trials are essential to customize dosage and blending techniques.

Quality Assurance and Standardization

- Lack of standardized guidelines in India for biochar properties and application protocols.
- Ensuring consistent biochar quality is critical for scaling carbon credit systems and achieving desired agronomic outcomes.

Future Outlook and Innovations

Biochar technology is evolving rapidly, with increasing integration into climate action and soil regeneration agendas. Carbon Fresh Climate India Pvt Ltd envisions the following pathways to accelerate adoption:

Decentralized Supply Chain Hubs

- Establish localised supply chain units at the village or FPO (Farmer Producer Organization) level.
- Promote community-led production to manage crop waste and distribute biochar locally.

Biochar-Infused Products

- Innovate with biochar-enriched composts, seed coatings, and biofertilizers.
- Develop biochar-integrated soil bricks, mulching products, and livestock bedding.

Policy Partnerships and Climate Finance

- Collaborate with different stakeholders such as state agriculture departments, NABARD, CSR programs, and farmer cooperatives.
- Advocate for incentives, subsidies, and inclusion in national carbon inventories.

Digital MRV and Carbon Platforms

- Enable blockchain-based traceability of carbon credits from soil to market.
- To enable farmers with mobile apps and dashboards for reporting, verification, and benefit tracking.

Summary and Way Forward

Biochar has emerged as a nature-positive, scalable, and scientifically validated solution for India's agricultural and climate challenges. It enables the regeneration of degraded land, reduces emissions, and empowers farmers to be part of the climate solution.

Carbon Fresh Climate India Pvt Ltd is committed to building a future where every farm functions as a carbon sink—enhancing food security while reversing climate change. Through innovation, education, and partnerships, we aim to scale the impact of biochar and transform Indian agriculture into a regenerative, resilient, and economically inclusive system.

*** The End ***