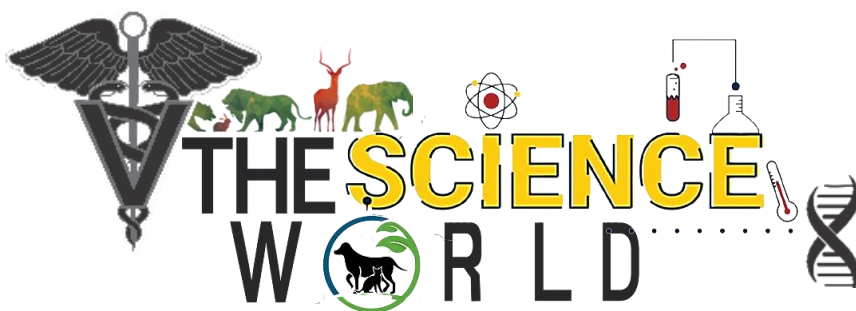




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Popular Article

Biochar for Climate Change Mitigation: Turning Carbon into a Climate Solution

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Introduction

Climate change is no longer a distant threat—it's a present reality, evident in rising global temperatures, increasingly severe weather events, and shifting ecosystems. According to the Intergovernmental Panel on Climate Change (IPCC), the world is on track to exceed a 1.5°C increase in average temperatures by as early as 2030, which could lead to catastrophic consequences for the planet. To mitigate these impacts, we must reduce carbon emissions by nearly half by 2030 and achieve net-zero emissions by 2050. However, meeting these goals requires more than just cutting emissions; we must also explore innovative methods for removing existing carbon from the atmosphere. One promising innovation is biochar—a deceptively simple yet highly effective tool that could play a crucial role in our global strategy to combat climate change. Biochar is a carbon-rich material that resembles charcoal, produced by heating organic matter, such as agricultural waste, wood chips, or plant residues, in an oxygen-limited environment through a process known as pyrolysis. This process converts biomass into a stable form of carbon that can be stored in the soil for long periods, effectively sequestering carbon dioxide (CO₂) that would otherwise be released into the atmosphere during decomposition.

The term "biochar" is derived from the Greek words "bios" (life) and "char" (charcoal), reflecting its origins as a product of biomass carbonization. Coined by Peter Read, a proponent of biochar, the term encompasses a blend of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash in varying amounts rather than pure carbon. Biochar's primary appeal as a soil amendment lies in its highly porous structure, which enhances soil surface area and water retention capacity. It is



important to note that while biochar and charcoal share similarities, they are produced through different methods. Charcoal can be made at high temperatures in regulated environments, often for uses like activated carbon. In contrast, traditional methods of charcoal production, such as using clay kilns, operate at lower temperatures and involve processes like "carbonization," where biomass is smothered with soil before ignition or burned while still wet. "Torrefaction," another method, involves drying and roasting biomass at even lower temperatures. Biochar's key properties, such as its soil conditioning effects and extended residence time in the soil, are comparable to those of ordinary charcoal and char. Research on biochar-rich dark earths in the Amazon, known as *terra preta*, has expanded our understanding of biochar's unique qualities and its potential as a soil enhancer.

History: The Origins and Traditional Uses of Biochar

While the concept of biochar has ancient roots, the term itself was only coined recently. Evidence suggests that biochar has been used in agriculture for millennia, as seen in the Amazon Basin. In this region, soils up to two meters deep are known as *terra preta*, or "dark earth." These soils are highly fertile, dark in colour, and have supported agricultural activities for centuries. The fertility of *terra preta* is attributed to its high organic matter content, including char, which contributes to its neutral pH and excellent nutrient retention—qualities that make it more productive than neighbouring soils. The proximity of *terra preta* to human settlements suggests it was human-made. Various theories explain the formation of *terra preta*. One popular theory suggests that ancient people practiced a "slash-and-char" technique, similar to slash-and-burn agriculture. Instead of fully burning vegetation, this method involved smoldering biomass and burying the remains under soil, which over time led to the creation of fertile, carbon-rich soils. Modern biochar production methods are thought to have evolved from these ancient slash-and-char practices.

Production: How biochar is made

Biochar is produced through a process called pyrolysis, which involves heating organic material in the absence or near-absence of oxygen. This process can occur at varying temperatures, typically between 300°C and 700°C, depending on the desired characteristics of the biochar. During pyrolysis, the organic material undergoes thermal decomposition, breaking down into three primary products: biochar (solid carbon-rich material), syngas (a mixture of gases like hydrogen and carbon monoxide), and bio-oil (a liquid that can be used as a renewable fuel). The specific proportions of these products depend on the temperature and duration of the pyrolysis process.

Steps in Biochar Production:

1. **Feedstock Selection:** The process begins with the selection of organic feedstock, which can include agricultural residues (e.g., crop waste, rice husks), forestry residues (e.g., wood chips, sawdust), or even urban waste (e.g., green waste, paper). The choice of feedstock influences the properties of the resulting biochar, including its carbon content and nutrient levels.



2. **Pyrolysis Process:** The feedstock is then subjected to pyrolysis in specialized equipment such as kilns or reactors. During pyrolysis, the material is heated in a low-oxygen environment, which prevents combustion and instead promotes the breakdown of organic molecules into solid carbon (biochar), gases (syngas), and liquid bio-oil. The lack of oxygen is crucial, as it allows the carbon to be stabilized rather than released as CO₂.
3. **Biochar Recovery:** Once the pyrolysis process is complete, the solid biochar is collected, cooled, and the biochar is then crushed or ground to a fine powder, depending on its intended use. Whereas, the syngas and bio-oil can be captured and used as renewable energy sources, making the process energy-efficient and sustainable.



Fig. 1 Systematic representation of synthesis and application of biochar

Biochar production methods vary in efficiency and biochar yield:

1. **Slow Pyrolysis:** Biomass is slowly heated at 400–600°C. This method produces high biochar yields, typically 30–50% of the original biomass.
2. **Fast Pyrolysis:** Biomass is rapidly heated to 400–550°C, with biochar yields around 10–20%, as the process focuses more on bio-oil production.
3. **Gasification:** At very high temperatures (700–1000°C) and limited oxygen, gasification produces biochar as a by-product, with yields of around 5–10%.
4. **Hydrothermal Carbonization:** Involves heating biomass in water at 180–250°C under pressure, yielding biochar at rates of 35–50%.

These processes differ in biochar recovery depending on the temperature and reaction speed.

Biochar production can be done on various scales, from small, low-tech kilns used by farmers to large, industrial-scale pyrolysis plants. The scalability and flexibility of biochar production make it



an appealing option for both smallholders and commercial enterprises looking to improve soil health and sequester carbon. However, the efficiency of biochar production and its environmental benefits can vary depending on the feedstock used, the conditions of pyrolysis, and how the biochar is applied. However, the basic process remains the same: converting organic material into a stable form of carbon that can provide long-term benefits for both the soil and the atmosphere.

Properties of biochar

The characteristics of biochar are significantly affected by the type of feedstock and the pyrolysis conditions used. Wood-based biochar typically has high carbon content, low ash, and lower levels of nutrients such as nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, aluminium, sodium, and copper. It also has lower cation exchange capacity (CEC) and fewer exchangeable cations compared to biochar from manure. Higher pyrolysis temperatures result in increased ash content, higher pH, greater surface basicity, and reduced surface acidity. In fast pyrolysis, biomass is quickly heated to 400–550 °C, producing mainly bio-oil, while in slow pyrolysis, the biomass is gradually heated, yielding biochar and syngas. Key physicochemical properties of biochar include a high surface area, greater porosity, low bulk density, higher CEC, neutral to high pH, and high carbon content. It also contains essential plant nutrients like nitrogen, phosphorus, calcium, magnesium, and potassium. Low-temperature pyrolysis produces more biochar, while higher temperatures yield biochar with greater carbon content, surface area, porosity, and adsorption capacity, along with more stable carbon. At temperatures above 600 °C, functional groups diminish, resulting in highly condensed, recalcitrant structures with polycyclic aromatic compounds. The long-term stability of biochar, which can persist in soil for hundreds to thousands of years, is attributed to its high proportion of aromatic structures, making it resistant to chemical and biological degradation. For plant-based biochar, carbon and nitrogen concentrations rise with increasing pyrolysis temperature, whereas in mineral-rich feedstock, these concentrations decrease as pyrolysis temperature increases.

Biochar for mitigating climate change

I. Carbon sequestration: Storing carbon and preventing emissions

Biochar is a potent tool for carbon sequestration because it captures carbon that would otherwise be released into the atmosphere as carbon dioxide (CO₂). The process of pyrolysis converts organic material into a stable form of carbon that is resistant to decomposition. When biochar is applied to soil, it effectively locks this carbon away, preventing it from being re-emitted as CO₂ for potentially hundreds to thousands of years.

Mechanism of Carbon Sequestration: During the pyrolysis process, the carbon in organic material is transformed into a highly stable form of charcoal. Unlike uncharred organic material, which typically decomposes within a few years and releases its carbon content as CO₂, biochar resists breakdown due



to its molecular structure. This stability means that the carbon remains sequestered in the soil for extended periods, making biochar an effective long-term carbon sink.

According to estimates, the global implementation of biochar could sequester between 0.3 to 2 gigatons of CO₂ equivalent per year by 2050, depending on the scale of adoption and the types of feedstocks used. This significant potential, places biochar alongside other carbon capture and storage (CCS) technologies as a critical component of climate change mitigation strategies.

II. Soil health: Enhancing soil fertility, moisture retention, and crop yield

Beyond carbon sequestration, biochar offers substantial benefits for soil health, which in turn can contribute to reducing greenhouse gas emissions. When added to soil, biochar improves its physical, chemical, and biological properties, leading to better crop yields and reduced reliance on synthetic fertilizers.

1. **Soil Fertility:** Biochar enhances soil fertility by increasing the soil's cation exchange capacity (CEC), which is a measure of how well soil can retain and supply nutrients to plants. This is particularly important in tropical and subtropical regions where soils are often acidic and nutrient-poor. By improving nutrient retention, biochar reduces the need for chemical fertilizers, which are a major source of nitrous oxide (N₂O) emissions—a potent greenhouse gas.
2. **Moisture Retention:** Biochar's porous structure also improves the soil's ability to retain moisture. This is especially beneficial in arid and semi-arid regions where water scarcity is a critical issue. By enhancing water retention, biochar helps plants survive during dry periods, reduces the need for irrigation, and improves overall crop resilience. A study found that biochar application can increase soil water retention by up to 18%, depending on the soil type and biochar properties.
3. **Rehabilitate contaminated soil:** Biochar has the potential to rehabilitate contaminated soils and brownfield sites. Its adsorptive qualities can immobilize and neutralize pollutants, decreasing their mobility and availability. Biochar amendments have been applied to clean up contaminated areas and restore soil health.
4. **Crop Yields:** Improved soil fertility and moisture retention naturally lead to higher crop yields. Increased crop productivity can reduce the need to convert additional land for agriculture, thereby helping to preserve forests and other natural ecosystems that act as carbon sinks. Additionally, better crop yields can reduce the amount of agricultural inputs required, further decreasing the environmental footprint of farming practices.

III. Other Environmental Benefits:

Biochar's benefits extend beyond carbon sequestration and soil health. It also plays a role in reducing methane emissions from agriculture, improving water quality, and managing waste.



1. **Reducing Methane Emissions:** Methane (CH₄) is a powerful greenhouse gas, with a global warming potential more than 25 times that of CO₂ over a 100-year period. Agriculture, particularly rice paddies and livestock manure management, is a significant source of methane emissions. Biochar can mitigate methane emissions by altering the microbial processes in soil that produce methane. For example, when biochar is applied to rice paddies, it changes the soil's redox potential, making conditions less favorable for methane-producing bacteria. Similarly, when mixed with manure, biochar can absorb and stabilize nitrogen, reducing the release of methane and ammonia. A study reported that the application of biochar to rice fields could reduce methane emissions by 12% to 50%, depending on the specific conditions and biochar used.
2. **Renewable Energy:** Biochar production generates byproducts like bio-oil and syngas, which can serve as renewable energy sources. Bio-oil can be converted into biofuels or used for generating heat and power, while syngas can be employed in gasification processes to produce energy and heat.
3. **Improving Water Quality:** Biochar also has the ability to filter and retain nutrients, such as nitrogen and phosphorus, which can otherwise leach into waterways and cause eutrophication—a process that depletes oxygen in water bodies, leading to dead zones and loss of aquatic life. By retaining these nutrients in the soil, biochar helps to improve water quality downstream and reduce the environmental impact of agriculture on rivers, lakes, and coastal areas.
4. **Construction and Building Materials:** Biochar can be incorporated into construction materials like concrete and cement to enhance their strength, durability, and thermal insulation. This application helps reduce the environmental impact of construction materials and supports sustainable building practices.
5. **Managing Waste:** Biochar production provides a sustainable way to manage organic waste, turning materials that would otherwise decompose and emit greenhouse gases into a valuable product. This not only reduces the volume of waste sent to landfills but also converts waste into a form of carbon that can be safely stored in the soil. The use of biochar in waste management is particularly relevant in developing countries where organic waste often contributes significantly to urban pollution and greenhouse gas emissions.



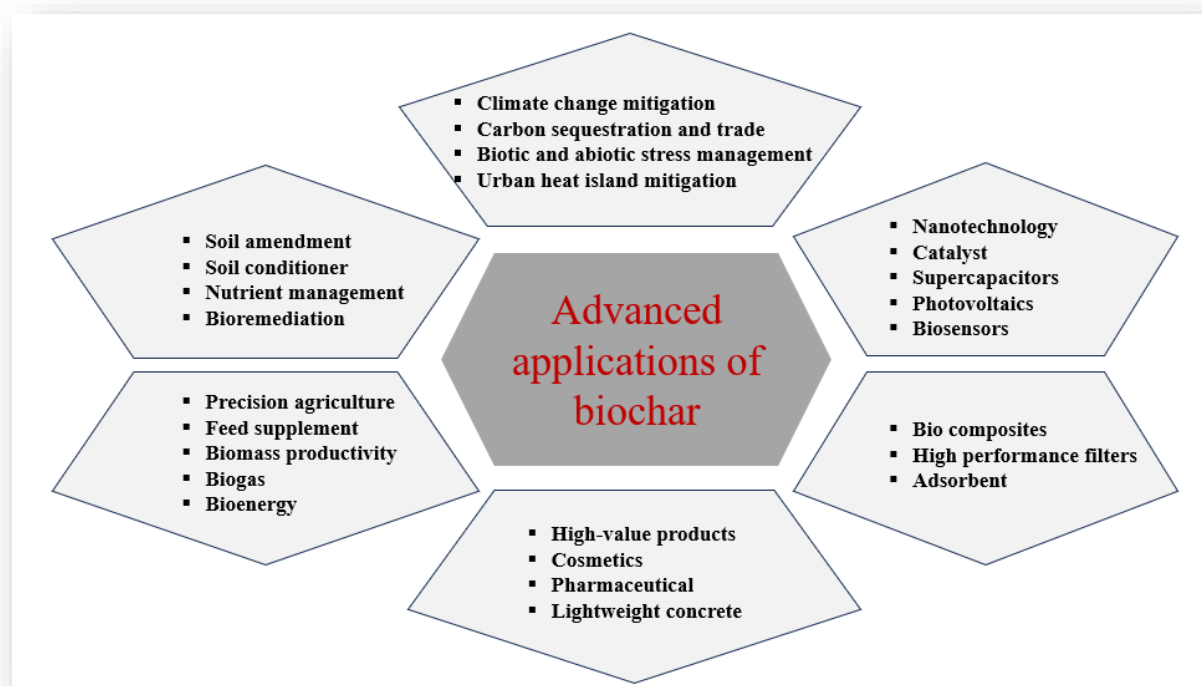


Fig. 2 Advanced application of biochar

Challenges and Considerations

Scalability: Scaling up biochar production and application faces several challenges. Producing biochar requires a consistent supply of organic feedstock, which can be variable and compete with other uses. Large-scale production also demands significant infrastructure and investment, and managing the energy required for pyrolysis while ensuring carbon neutrality is crucial. On the application side, transporting and integrating biochar into soil can be costly and complex, with effectiveness varying based on soil type and climate.

Economic Viability: Biochar's initial costs for production, transportation, and application can be high, particularly for small-scale operations. However, it offers long-term benefits like reduced need for fertilizers and improved soil health. Economic incentives, such as subsidies, carbon credits, and developing markets for biochar products, could improve its viability and encourage adoption.

Research and Development: Ongoing research is vital for optimizing biochar production and application. Key areas include understanding the best feedstocks, biochar characteristics, and long-term impacts on soil and crops. Economic models and policies supporting biochar's use are also crucial. Collaborative efforts across disciplines and sectors are needed to advance biochar technology and maximize its benefits.

Future prospects

New technologies are making biochar production more efficient and scalable. Innovations like 'continuous pyrolysis systems' and 'mobile pyrolysis units' allow for more efficient and flexible production, even in remote areas. Some technologies combine biochar production with bioenergy



generation, using pyrolysis heat to produce electricity or heat. This creates a closed-loop system that minimizes waste and maximizes resource use. These advancements can help overcome logistical challenges and reduce production costs, making biochar more accessible. On the other hand, government policies and financial incentives are crucial for scaling biochar use. By including biochar in carbon credit markets, offering subsidies or grants, and implementing supportive regulations, governments can encourage widespread adoption. The biochar sequestered carbon acts as carbon credits and can be sold to companies or governments for emissions offset, creating a new revenue stream and encouraging biochar production. Educational programs and outreach can further promote biochar's benefits, helping farmers and businesses integrate it into their practices. If widely adopted, biochar could significantly mitigate climate change by sequestering large amounts of CO₂. It could also improve soil health, boost agricultural productivity, and contribute to food security, especially in developing regions. Additionally, biochar could play a key role in waste management and the circular economy, turning organic waste into a valuable resource while reducing greenhouse gas emissions.

Conclusion

In conclusion, while challenges remain, the future of biochar is promising. By sequestering carbon, enhancing soil health, and supporting sustainable agriculture, biochar can play a significant role in global climate mitigation strategies. With continued innovation, supportive policies, and widespread adoption, biochar could become a key tool in the global effort to combat climate change, enhance food security, and promote sustainable development. Looking ahead, widespread adoption of biochar could be instrumental in building a more resilient and sustainable planet, making carbon a valuable ally in our climate solution efforts.

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