

Biochar: The black gold of sustainable agriculture

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Biochar is a carbon-rich material produced by heating biomass with limited oxygen. It is increasingly seen as a practical tool for environmental sustainability in agriculture and other sectors. It helps soil regeneration by enhancing nutrient retention, water-holding capacity, and biological activity, while also enabling long-term carbon storage that aids climate mitigation. Recent innovations are speeding up adoption which includes energy-efficient production methods like microwave-assisted pyrolysis and automation for real time monitoring and consistent quality. By turning organic wastes into valuable products, biochar boosts circular economy pathways and supports multiple Sustainable Development Goals (SDG), especially SDG 2, 6, 12, 13, and 15.

Keywords: Carbon sequestration, Environmental sustainability, Innovative green technologies, Sustainable development goals

BIOCHAR, a charcoal-like material produced by heating plant biomass in low-oxygen conditions, is increasingly seen as a promising tool for tackling global environmental issues. Although its origin goes back thousands of years to the 'Terra Preta' soils of the Amazon, modern science is rediscovering biochar through new technologies, innovative uses, and climate-focused solutions. The environmental crises i.e. rising pollution, soil degradation, declining freshwater supplies, climate change, etc. highlight the urgent need for multifunctional, nature-based solutions. A recent scientific review notes that about two billion people currently lack access to safe drinking water; and soil degradation is a major threat to agricultural productivity in many areas. These challenges emphasise the importance of materials like biochar which can improve soil health, filter water pollutants, increase carbon storage, and support sustainable development. Biochar's relevance goes well beyond agriculture. It is now being integrated into climate policies, green-building strategies, renewable energy technologies, and circular-economy initiatives. Its alignment with the United Nations' Sustainable Development Goals (SDG), especially those related to food security (SDG 2), clean water (SDG 6), responsible consumption (SDG 12), climate action (SDG 13), and ecosystem restoration (SDG 15), makes it an influential material in efforts to create a more resilient and environment sustainable world.

The need for biochar comes from many interconnected environmental pressures. Around

the world, soils are losing fertility due to nutrient mining, erosion, pollution, and declines in soil organic matter. Degraded soils decrease crop yields, weaken ecosystems, and threaten food security. Biochar provides a solution because its stable carbon structure improves nutrient retention, boosts soil organic matter, and supports soil microbial life. These benefits can help reverse decades of soil decline and promote long-term agricultural productivity. Besides soil health, biochar also plays a key role in removing carbon. By stabilising carbon in a form that remains in soils for centuries, biochar prevents carbon dioxide from re-entering the atmosphere. Recently, it has been highlighted that traditional measures of biochar durability often underestimate its long-term carbon storage ability because they mainly depend on the hydrogen-to-carbon ratio without considering environmental factors or feedstock differences. Now, more advanced frameworks are structured that account for soil type, climate, and biomass source when assessing carbon permanence. This better understanding strengthens biochar's role as a dependable strategy for climate change mitigation.

Breakthrough innovations in biochar technologies

Advancements in production technologies: Recent years have seen notable progress in how biochar is produced. One key development is microwave-assisted pyrolysis, a technique that heats biomass quickly and evenly. This method lowers energy use, boosts efficiency, and creates high-quality biochar with better

environmental advantages. A 2024–2025 scientific review highlights that microwave-assisted pyrolysis is becoming a vital tool for developing energy-efficient pathways for biochar composites. Another important trend is the growth of low-temperature pyrolysis and advanced gasification methods. These techniques help manufacturers customise biochar properties for specific uses, whether for soil improvement, carbon sequestration, water purification, or building materials. The integration of automation and digital monitoring systems in production facilities is also transforming biochar manufacturing. These smart systems enable real-time monitoring of temperature, gas composition, and energy consumption, leading to more efficient processes and better product consistency.

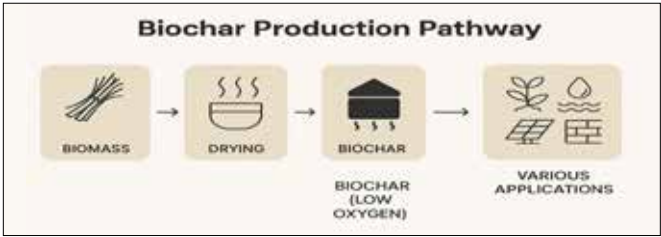


Table 1. Major biochar innovations and their environmental benefits

Innovation / Technology	Description	Environmental benefits
Microwave-assisted pyrolysis	Energy-efficient, uniform biomass heating	Lower emissions, high-quality biochar
Low-temperature pyrolysis	Controlled, feedstock-specific production	Tailored properties for specific uses
Gasification technologies	Produces biochar + syngas	Cleaner energy + carbon-rich residues
Digital/Automated production	Real-time system monitoring	Consistent quality, optimised energy use
Biochar composites	Biochar + material combinations	Pollutant removal, soil and energy applications

Biochar composites: One of the most exciting areas of innovation involves biochar composites which combine biochar with other materials to improve or alter its functionality. Studies shows that biochar composites produced through methods such as pyrolysis, ball milling, and co-precipitation can remove over 98% of toxic metals like chromium (Cr VI) and lead (Pb II) from contaminated water. These composites also boost soil fertility by increasing nutrient retention and show strong potential in energy storage applications, such as improving supercapacitor and lithium-ion battery performance. The development of these composites marks a major shift in how biochar is viewed. It is no longer just a soil amendment but a multifunctional material relevant to engineering, water treatment, renewable energy, and environmental cleanup.

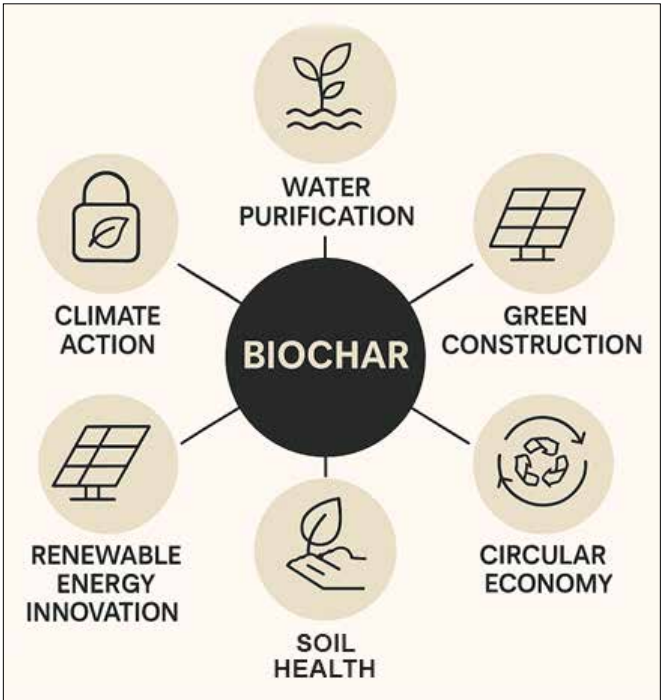
Applications of biochar across sectors

Regenerative agriculture and soil health: One of the most well-known uses of biochar is in farming,

where it helps improve soil structure, retain nutrients, and increase water holding capacity. Its porous nature allows soils to hold more water, which is especially helpful in drought-prone areas. Additionally, biochar boosts microbial diversity and raises soil organic carbon levels. These benefits result in healthier soils and higher crop yields, supporting efforts to achieve SDG 2 (Zero Hunger) and restore damaged ecosystems under SDG 15 (Life on Land). Biochar’s ability to support long-term soil restoration also makes it an affordable option for low-income farmers, particularly in regions where chemical fertilisers are expensive or hard to find. By naturally improving soil health, biochar helps farming communities rely less on external inputs while boosting productivity.

Water purification and access to clean water: Biochar’s porous structure makes it an effective medium for filtration and purification. Studies show that biochar composites can remove over 98% of heavy metals and other toxic substances from polluted water. This makes biochar an affordable and scalable solution for communities facing water pollution and scarcity. Additionally, biochar-based filters can help eliminate agricultural runoff, antibiotics, pesticides, and organic pollutants from drinking water and natural water bodies. These uses directly support SDG 6 (Clean Water and Sanitation).

Climate action and carbon sequestration: Biochar is becoming increasingly vital in global climate strategies. When added to soil, it can lock away carbon in stable chemical forms for hundreds of years. When properly evaluated and applied, biochar is one of the most durable and measurable options for removing carbon dioxide (CO₂). In addition to carbon sequestration, biochar can reduce emissions of nitrous oxide and methane from agricultural systems. These gases are much stronger than CO₂, so reducing them provides a significant climate benefit.



Benefits of biochar in agriculture

Sustainable construction and green materials: Innovation in green building materials has positioned biochar as a leading eco-building solution. Recent advances show that biochar can be used as an additive in concrete, plaster, insulation, and composite panels. Incorporating biochar into construction materials lowers their carbon footprint, enhances insulation, improves moisture control, and aids in sequestering carbon directly within structures. This trend supports global efforts to cut emissions from the construction industry and advances the development of carbon-neutral buildings.

Energy storage and clean technology: Biochar-based composites are also being used in the renewable energy industry. Recent studies show that these materials can greatly enhance the performance of supercapacitors and lithium-ion batteries, offering a sustainable alternative to traditional carbon electrodes. This expansion of biochar into electronics and the clean energy sector demonstrates its increasing importance in green technology and modern innovation.

Table 2. Biochar applications mapped to SDGs

Application area	Biochar impact	Relevant SDGs
Soil fertility and regenerative agriculture	Improves soil carbon, microbial activity	SDG 12, SDG 15
Water purification	Removes heavy metals and pollutants	SDG 6
Climate mitigation	Sequesters carbon in long-term	SDG 13
Circular economy and waste management	Converts biomass waste to products	SDG 12
Green construction	Reduces carbon footprint of buildings	SDG 9, SDG 11

The innovation boom: Trends to watch

Biochar technology is advancing quickly. A major trend is the development of standardised certification frameworks to ensure consistent quality in carbon market use. Recent research focuses on improving durability metrics to better evaluate long-term carbon storage potential. Another emerging trend involves smart biochar factories that use real-time sensors, automated controls, and data analytics to optimise production. These facilities enhance efficiency and reduce emissions by adjusting key variables such as temperature and feedstock composition. Additional notable trends

include the rise of customised, application-specific biochar products, the expansion of biochar use in urban infrastructure, such as stormwater management, and new circular-economy models that turn waste biomass into valuable biochar-based products. Moreover, integrating biochar into energy-storage systems further highlights its potential to support a cleaner energy future.

Challenges and the future road ahead

Despite increasing popularity, biochar still faces challenges that must be addressed to realise its full potential. Variations in feedstocks, production temperatures and processing methods can cause inconsistencies in biochar quality. Production costs remain a major obstacle, especially for small-scale producers and developing regions. It is also seen that biochar’s effectiveness can differ based on local soil types, climatic conditions, and agricultural systems, highlighting the need for region-specific studies. Additionally, supportive policy frameworks are needed to promote sustainable production, regulate quality, and expand market access. Governments and scientific institutions can help overcome these barriers by investing in research, offering incentives for carbon-negative technologies, and establishing clear guidelines for biochar use.

SUMMARY

Biochar is shifting from a traditional soil enhancer to a versatile platform for climate and materials innovation. Its capacity to lock carbon in stable forms and enhance soil health makes it a strong option for climate action and resilient farming, while improved durability assessment frameworks can boost the credibility of biochar's carbon removal claims. Technological progress, such as microwave-assisted pyrolysis and smarter, automated production is increasing efficiency and consistency which are crucial for scaling up. Meanwhile, next-generation biochar composites are broadening their impact into water purification and clean energy technologies, showing high removal rates for toxic metals and promising performance in energy storage systems. With better standards, regional validation, and supportive policies, biochar could become a key solution connecting circular economy practices with SDG progress.

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