

Biochar: A Traditional Material with Modern Environmental Applications

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At first glance, biochar looks like ordinary charcoal: black, lightweight and easy to crumble. Its real value, however, lies in what cannot be seen. Inside each particle is a network of pores and chemically active surfaces capable of holding water, retaining nutrients, storing carbon and binding certain pollutants. This simple-looking material is therefore receiving renewed attention as agriculture and environmental management search for practical ways to deal with biomass waste, declining soil quality and climate change.

From crop residue to carbon-rich material

Biochar can be produced from crop residues, wood waste, animal manure and other forms of biomass. These materials are heated under oxygen-limited conditions through a process known as pyrolysis. Because oxygen is restricted, the biomass does not burn completely. Instead, part of its carbon is converted into a relatively stable solid.

The temperature and method used during pyrolysis determine the qualities of the final product. A biochar produced at a lower temperature may contain more readily available compounds and oxygen-containing functional groups. Higher temperatures generally produce a material with greater carbon stability, aromaticity, alkalinity and surface area. The original feedstock matters too. Manure-based biochars are often richer in nutrients and ash, whereas biochars made from woody or other lignocellulosic residues usually contain more stable carbon and may have greater porosity. In other words, biochar is not a single, uniform product; its performance depends on how and from what it is made (Rasool et al., 2026).

This conversion process offers a useful route for managing agricultural residues. Materials that might otherwise be dumped, openly burned or allowed to decompose rapidly can be converted into a product with potential agricultural and environmental value. Bio-oil and gases generated during pyrolysis may also be recovered as energy products, improving the overall usefulness of the process.

A helping hand for tired soils

One of the most familiar uses of biochar is as a soil amendment. Its porous structure can reduce soil bulk density, improve aeration and create spaces where water and dissolved nutrients are retained. These properties can be particularly valuable in coarse-textured or degraded soils that lose water and nutrients quickly.

Biochar may also improve cation exchange capacity, which represents the soil's ability to hold positively charged nutrients such as potassium, calcium and magnesium. Depending on its properties and the condition of the soil, it can reduce nutrient losses and gradually improve nutrient availability. Its pores may provide protected microsites for soil microorganisms, including some bacteria and fungi associated with nutrient cycling and plant growth.

These changes do not automatically guarantee a higher crop yield. Biochar is most useful when it addresses an existing limitation such as acidity, poor water retention, low organic carbon or nutrient loss. A review of Mediterranean farming systems found that crop responses were more favourable in degraded and coarse-textured soils and under drought or salinity stress. Responses were less predictable where soil fertility, moisture and other growing conditions were already adequate (Borgatti et al., 2026).

This is an important lesson for farmers: biochar should not be treated as a universal fertilizer. It usually contains less immediately available nutrition than compost or manure and may perform better when combined with these materials. Co-composting or blending biochar with nutrient-rich organic amendments can fill its pores with nutrients and reduce the possibility of nutrient immobilisation after application.

Keeping carbon in the ground

Plants absorb carbon dioxide from the atmosphere and use it to build their tissues. When crop residues are burned or allowed to decompose, much of this carbon eventually returns to the atmosphere. Pyrolysis alters this pathway by converting some of the plant carbon into chemically stable forms that resist rapid microbial decomposition.

Once incorporated into soil, part of this carbon may remain there for centuries or even longer. Biochar therefore links agricultural waste management with carbon sequestration. It does not merely avoid residue disposal; it turns short-lived plant material into a more persistent carbon pool.

The possible climate benefit extends beyond carbon storage. Biochar can influence emissions of carbon dioxide, methane and nitrous oxide from soil, although these effects vary with soil properties, temperature, rainfall, crop type and management. Using global field data and machine-learning models, Lu et al. (2026) estimated that an optimised biochar

strategy could offset approximately 1.08 Pg of carbon dioxide equivalent annually while increasing global staple-crop production by about 15 million tonnes. These values represent modelled potential rather than results that can be expected uniformly on every farm.

A porous trap for pollutants

The same pores and surface groups that retain nutrients can also capture contaminants. Biochar is being investigated for the treatment of polluted soils and water containing metals, pesticides, dyes, pharmaceutical residues and other organic chemicals.

Pollutant removal is not based on one process alone. Some contaminants become trapped inside pores, while others attach to the surface through electrostatic attraction, ion exchange or chemical complex formation. Aromatic compounds may interact with the carbon-rich surfaces, and certain metals can be immobilised through precipitation or reduction reactions. Researchers are also examining biochar for capturing emerging contaminants such as microplastics and per- and polyfluoroalkyl substances, commonly called PFAS.

For specialised treatment, biochar can be activated or combined with minerals, metals, hydrogels and magnetic materials. Magnetic biochar, for example, may be separated from treated water more easily than loose powdered material. Microwave-assisted pyrolysis is another developing approach. It can provide rapid and relatively uniform heating and may produce biochars with favourable pore structures and surface properties for pollutant removal. Nevertheless, higher equipment costs and limited experience at the industrial scale currently restrict its widespread application (Rasool et al., 2026).

Useful—but not risk-free

The growing enthusiasm surrounding biochar should be balanced with careful production and use. An unsuitable feedstock or poorly controlled pyrolysis process can introduce undesirable substances, including heavy metals or polycyclic aromatic hydrocarbons. Very alkaline biochar may disturb nutrient availability in soils that already have a high pH. Fine biochar dust can create handling difficulties, while excessive application may alter water movement or produce nutrient imbalances.

Even its effects on greenhouse gases are not always positive. Biochar commonly reduces nitrous oxide emissions under suitable conditions, but methane production may increase in warm, waterlogged soils if its pores encourage the formation of oxygen-deficient microsites. Field evidence therefore supports moderate, site-specific application rather

than the assumption that adding more biochar will always produce greater benefits (Borgatti et al., 2026).

Before agricultural use, the feedstock source, production temperature, pH, salt content, nutrient composition and possible contaminants should be assessed. Small field trials are advisable before large-scale application. The soil type, crop, rainfall pattern and purpose of application must also be considered when deciding the rate and method of use.

A place in the circular economy

Biochar is helpful because it can perform several roles at once. It can convert locally available biomass residues into a useful material, retain carbon, improve certain soils and help remove contaminants. It may also be used in composting, wastewater treatment, construction materials, catalysts and energy-storage systems.

However, biochar is a tool rather than a complete solution. Its environmental value depends on responsible sourcing of biomass, efficient production, safe product quality and appropriate use. Transporting bulky feedstock over long distances or using excessive fossil energy during pyrolysis could reduce its climate benefits. Equally, applying an unsuitable biochar without understanding the soil may create new problems instead of solving existing ones.

The most promising future for biochar is therefore likely to be local and purpose-driven: crop residues converted near their source, the product tested for quality, and its application matched to a clearly identified need. When used in this way, a charcoal-like material rooted in a simple principle can become part of modern approaches to soil restoration, pollution control, resource recovery and climate-resilient agriculture.

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