Science Societies

Biochar: A promising tool for soil health and nutrient efficiency in sustainable agriculture

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Biochar has emerged as a promising soil amendment that improves soil health and nutrient efficiency. Photo courtesy of Adobe Stock/Phoebe.

Modern agriculture faces a growing challenge: producing more food while protecting the soil and water resources that sustain it. As the global population continues to rise, food production will need to increase by nearly 50% by 2050, but achieving this goal cannot come at the expense of the natural resources that agriculture depends on (FAO, 2026).

To conserve agriculture's most important natural resource (soil), we must prevent soil erosion and degradation, which is already a serious global concern. Nearly one-third of the world's soils are moderately to highly degraded due to erosion, nutrient depletion, and poor management practices, threatening long-term agricultural productivity.

In addition to the soil loss, nutrient management adds an additional layer to this challenge. While fertilizers are essential for crop production, the amount applied often does not match what the plant can take up. For example, some crops take up only 30–50% of applied nitrogen (N), and the remaining N is lost through microbial processes, volatilization, leaching, and runoff. Similarly, phosphorus (P) and potassium (K) face similar limitations, often becoming unavailable in the soil.

In this context, fertilizer losses carry real consequences: nutrients escaping fields can pollute waterways, fuel harmful algal blooms, and degrade aquatic ecosystems while N losses to the atmosphere contribute to nitrous oxide (N_2O), a potent greenhouse gas. At the same time, farmers are paying for these added inputs that are not fully utilized, reducing both efficiency and profitability.

These interconnected challenges highlight the need for more sustainable and efficient soil and nutrient management strategies. Approaches such as conservation agriculture, improved soil management, efficient irrigation, and nutrient recycling can help address these issues. Among these strategies, increasing attention is being given to practices that rebuild soil organic matter and enhance nutrient retention. Biochar has emerged as a promising soil amendment that improves soil health and nutrient efficiency while potentially mitigating greenhouse gas emissions and contributing to soil and environmental quality. For this article, we will focus on the soil nutrient and health aspects, where biochar can contribute by enhancing soil structure, increasing water-holding capacity, retaining nutrients, and offering a pathway toward more resilient and sustainable agricultural systems.

What is biochar?

Definition of biochar

Biochar is a carbon-rich, stable material produced by burning organic biomass under limited or no oxygen conditions, a process known as “pyrolysis.” During pyrolysis, organic residues are thermally decomposed, leaving behind a porous charcoal-like substance. Unlike charcoal, which is used as fuel, biochar is primarily applied to soil as an amendment to improve soil health and environmental sustainability.

Sources

Common sources for producing biochar include crop residues such as rice husk (Figure 1), wheat straw, corn stover, sugarcane bagasse, etc., which are readily available after crop harvest and processing. Wood-based materials, such as sawdust, wood chips, and forestry residues, are also widely used due to their high carbon content. In addition, animal manures (e.g., poultry, cattle, and swine manure) can be converted into nutrient-rich biochar. Other agricultural by-products, including nut shells, fruit peels, and food-processing residues (e.g. apple/grape pomace), also serve as suitable feedstocks. Utilizing these waste materials for biochar production not only converts biomass into a valuable soil amendment, but also helps reduce agricultural waste and environmental pollution, therefore promoting a circular economy.

Figure 1. *Rice husk (**left**) and forest wood (**right**) residues converted into biochar using a small-scale gasifier on a farm in Colombia. Photos by Gustavo Roa and Jaya Nepal.*

Important properties of biochar

Biochar is a unique, carbon-rich material made from plant residues that has the power to transform soils and support a more sustainable future. With its sponge-like structure and vast surface area (Figure 2), biochar helps soils hold onto water and nutrients more effectively, reducing waste and improving plant growth. It also creates safe, protective spaces for beneficial microbes, which play a key role in nutrient cycling and soil health.

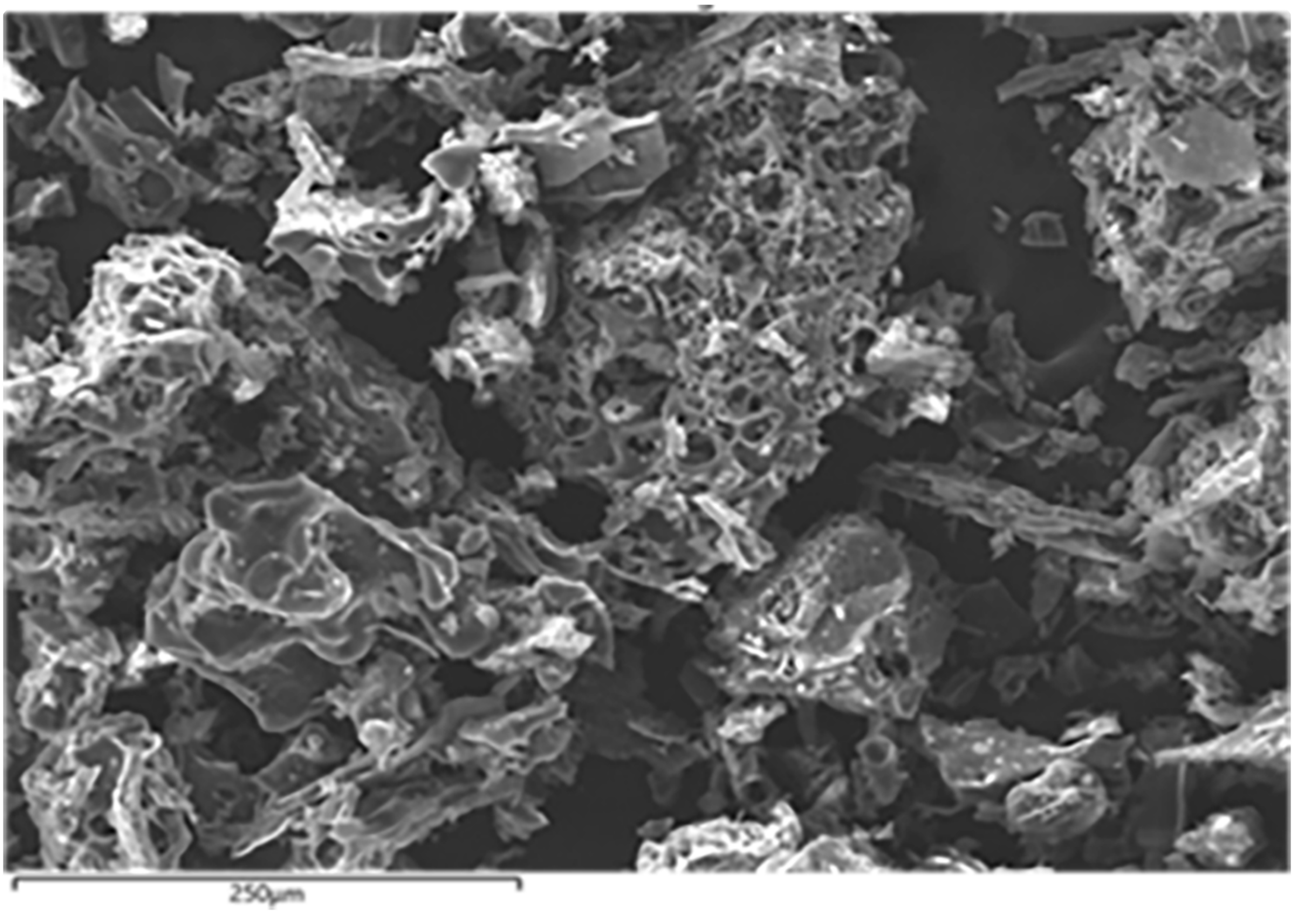

Figure 2. *Scanning electron microscopy (SEM) image of biochar showing its highly porous structure and irregular surface morphology. The presence of interconnected pores and surface cavities highlights the large surface area of biochar, which contributes to its capacity for water retention and nutrient adsorption. Photo by Gutierrez & Hettiarachchi, 2026.*

What makes biochar especially remarkable is its stability. It can remain in soil for decades or even centuries, locking away carbon that would otherwise return to the atmosphere. Together, these properties make biochar a promising tool for building healthier soils, improving crop productivity, and helping mitigate climate change (Table 1).

Table 1. Key properties of biochar and its role on the soil–environment continuum.

Property	Description	Typical range	Soil function	Environmental benefit
Carbon content	Carbon-rich, stable SOM	50–90% C by feedstock/temperature	Long-term organic matter pool; modulate C:N ratio	Carbon sequestration; GHG mitigation
Porosity	Highly porous structure	30–80% total pore volume	Enhances water and nutrient retention; improves aeration	Reduces leaching; microbial habitats
Surface area	Very high specific surface area	100-300 $m^2\ g^{-1}$ (typical range)	Adsorbs nutrients/pollutants; supports microbes	Pollutant immobilization
Stability	Biochemically resistant carbon	Persists for decades/centuries	Maintains soil structure; long-lasting amendment	Long-term carbon storage
Microbial habitat	Provides protected microenvironments	Not fully understood	Promotes beneficial microbial activity	Supports biodiversity, nutrient cycling

Note: SOM, soil organic matter; GHG, greenhouse gas.

Biochar effects on soil health indicators

Biochar has gained increasing attention as a sustainable amendment for agricultural systems due to its potential to improve soil health. Biochar can modify key soil physicochemical properties, thereby improving overall soil health and creating favorable conditions for plant growth (Figure 3).

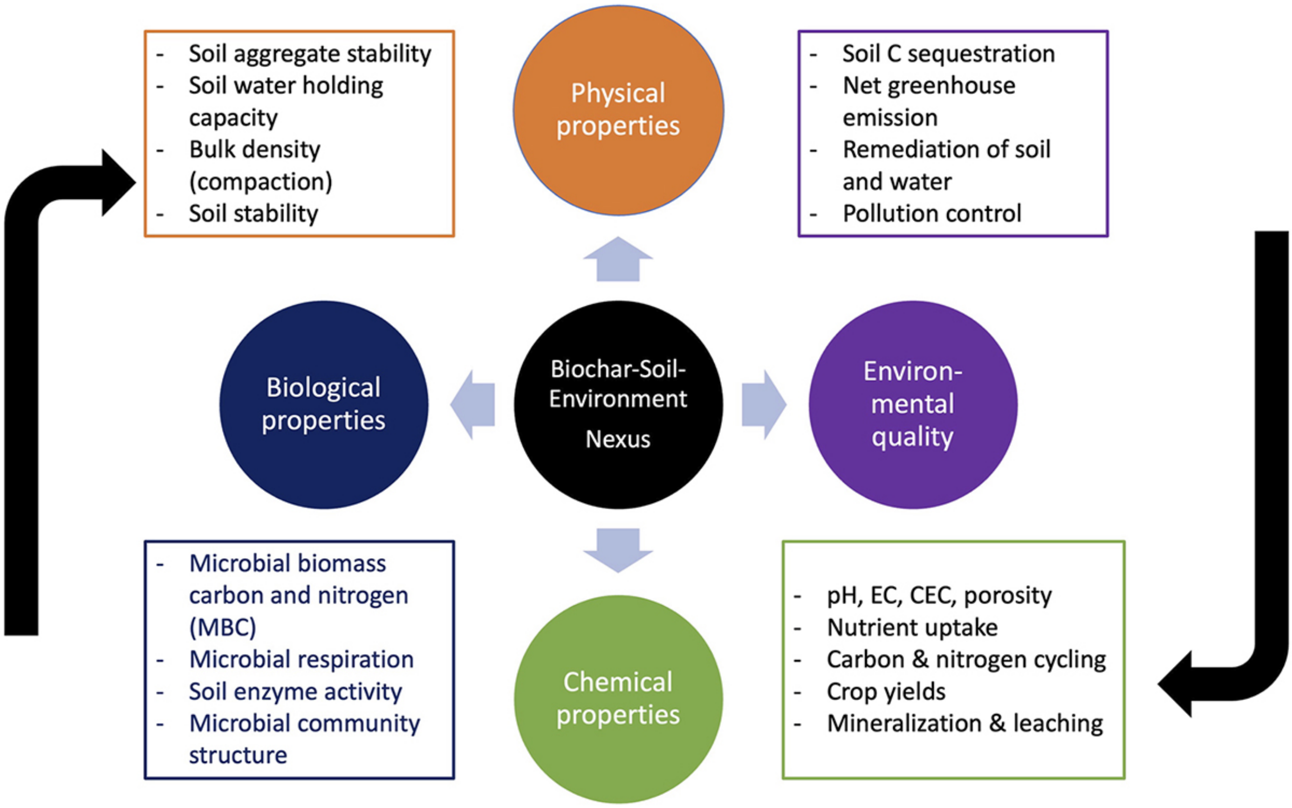

Figure 3. *Biochar role in soil physical-chemical properties and environmental applications (Nepal et al., 2023).*

Physical improvements

Biochar has been widely recognized for its ability to improve key physical properties of soils. Its porous structure and low density contribute to enhanced soil aggregation and a reduction in bulk density, which facilitates root growth and improves soil aeration. Additionally, biochar can significantly increase water-holding capacity, particularly in coarse-textured soils, by enhancing pore space and water retention at field capacity.

Similarly, biochar applications have been shown to increase soil organic carbon (SOC) by providing a direct input of stable, recalcitrant carbon that resists physical and biochemical decomposition. Field studies have reported consistent increases in SOC following biochar application by approximately 1.43-fold relative to the control after nine years with single and repeated application showing significant effects, highlighting its potential as a strategy to improve soil health and carbon sequestration under different management systems. Overall, the incorporation of biochar can lead to more stable soil structure and improved physical conditions for plant development

Chemical improvements

The chemical properties of biochar depend largely on the feedstock used and the production conditions. For example, biochar pH depends mainly on how it is produced and the type of raw material used. Biochar produced at higher temperatures (600–700 °C) is generally more alkaline while lower-temperature biochar (300–400 °C) tends to have a lower pH.

Feedstock plays an important role as biochar made from manure or nutrient-rich materials is typically more alkaline than that produced from wood or crop residues. Because of these differences, selecting the right biochar depends on both its production conditions and the specific needs of the soil.

The application of biochar can increase soil cation exchange capacity (CEC) and improve nutrient retention. This is mainly due to its large surface area and the presence of functional groups that can hold and exchange nutrients such as Ca, Mg, P, and K. As a result, biochar helps reduce nutrient losses through leaching and makes nutrients more available for plant uptake over time. These benefits are particularly important in low-fertility or sandy soils where nutrient retention is often limited.

Biological improvements

One of the main concerns regarding biochar application is its impact on soil microbial communities, particularly under long-term conditions. While some studies have reported positive effects, such as increased microbial activity, enhanced N-fixing populations, and improved habitat for beneficial microorganisms, others have shown neutral or even negative responses, including no changes or reductions in microbial biomass and mycorrhizal abundance.

These contrasting results suggest that the effects of biochar on soil microbial communities are highly variable and depend on factors such as soil type, biochar properties, and management practices. Therefore, based on current evidence, the overall impact of biochar on soil microbial communities remains unclear and requires further in-depth and long-term investigation.

Biochar and nutrient management

Biochar and fertilizers are best viewed as partners, not competitors. Fertilizers remain the main nutrient source for crops while biochar can influence how nutrients are retained, released, and lost after application. Its value is therefore less about supplying nutrients directly and more about helping soils use applied nutrients more efficiently.

Nitrogen: help keeping N in the field

Nitrogen is often the nutrient that is the costliest and most prone to loss in crop production. Much of the N applied can be lost through leaching, volatilization, or gaseous emissions before crops use it, and biochar can influence several steps in this process.

- Reducing nitrate leaching: By improving water retention and slowing water movement, biochar can help reduce nitrate leaching and keep more N in the root zone. This effect is especially relevant in sandy soils, under high rainfall or irrigation, and where nitrate commonly moves below the rooting depth.

- Retaining ammonium: Biochar can often have a charged surface that can temporarily hold ammonium, reducing rapid losses after fertilizer application. This retention appears to be electrostatic and pH dependent with stronger ammonium sorption often reported for lower-temperature biochar under near-neutral conditions.

- Influencing N transformations: Biochar can also alter soil pH, aeration, and microbial activity, which may affect nitrification and denitrification. In some systems, this has been associated with lower nitrous oxide emissions and slower conversion of fertilizer N into forms more prone to loss, especially in wet or poorly aerated soils.

Phosphorus: holding P without locking it up

Phosphorus presents a different challenge. Unlike N, P is less likely to be lost, but it can become tied up in soil or be transported in runoff, reducing fertilizer efficiency and water quality. Biochar can influence both P retention and P availability although the outcome depends strongly on the biochar and the soil. A meta-analysis by Glaser & Lehr (2019) found that biochar generally increased plant-available P in agricultural soils with stronger effects in acidic and neutral soils and with lower-temperature biochar applied at higher rates.

- Improving P retention: Biochar can help retain phosphate on soil and biochar surfaces, which may reduce P losses in runoff or leachate, especially in soils vulnerable to off-field P movement.

- Altering P availability: In many acidic soils, biochar raises pH and can reduce P fixation by aluminum and iron, increasing P availability to plants. Some manurederived biochar may also contribute to P directly. In other cases, however, biochar can temporarily reduce available P, particularly when sorption is strong or when the biochar raises soil pH too much. For this reason, biochar should not be treated as a universal P fertilizer replacement.

Other nutrients and nutrient buffering

Beyond N and P, biochar can also influence how soils retain other nutrients, including K, Ca, and Mg. This can be especially useful in sandy or low-organic-matter soils where nutrient retention is limited. In some cases, biochar may also directly supply K, Ca, and Mg through its ash fraction.

Together, these effects can improve nutrient retention and support soil fertility, although the size of the benefit varies widely with biochar type and soil conditions. Biochar may also help buffer nutrient availability across changing moisture conditions, but this effect is inconsistent and should not be assumed in all systems. General review evidence suggests that biochar tends to be more effective in acidic and degraded soils than in alkaline or calcareous soils. In practice, some types of biochar contribute meaningful nutrients while others mainly improve retention rather than supply.

Biochar–fertilizer management strategies

This is where biochar connects directly to fertilizer decisions in practice. Table 2 summarizes the main ways to integrate biochar with fertilizers and the situations where each strategy is most likely to make sense.

Table 2. Ways to integrate biochar with fertilizers.

Strategy	What it is	Nutrient benefits	When it makes sense

Co application with mineral NPK	Apply biochar separately alongside usual NPK rates	Better retention of N, P, and K, often improving nutrient use efficiency and yield stability	A practical first step for on-farm testing, especially in degraded, sandy, or acidic soils
Biochar based or coated fertilizers	Fertilizer granules mixed with or coated on biochar	Slower N release, reduced leaching, higher N uptake, and sometimes lower gaseous N losses	High-value crops, high-rainfall environments, or sandy soils where nutrient loss is a major concern
Nutrient enriched biochar	Biochar pre-loaded with manure, compost, or fertilizer solutions before application	Reduces short-term nutrient tie-up and allows nutrients to be released more gradually	Organic and mixed systems using manures or composts, especially where nutrient stabilization is desired
Partial fertilizer substitution	Biochar used together with reduced fertilizer rates	In some systems may maintain yield with lower fertilizer inputs although responses are variable	Long-term soil health programs or areas with high fertilizer cost or environmental limits, but only after local testing

Taken together, biochar is best viewed as a complement to fertilizer strategies with the greatest potential to improve nutrient retention and nutrient use efficiency under specific soil and management conditions. In practice, the most reliable approach is to begin with co-application at realistic rates, monitor crop and soil responses locally, and consider partial fertilizer substitution only where evidence supports it.

Benefits and limitations of biochar in nutrient management

The strongest and most consistent evidence generally supports using biochar together with fertilizers, rather than relying on biochar alone. Positive responses are most common in acidic, degraded, or leaching-prone soils while benefits are often smaller or less consistent in already fertile, well-managed fields. There are also clear limits. Very high biochar rates can cause short-term nutrient tie-up, excessive pH increases, or reduced early growth. In addition, biochar varies widely in feedstock, pyrolysis conditions, and particle size, so results from one material or site may not transfer directly to another. As a result, broad rules such as automatically reducing fertilizer rates by a fixed percentage are not reliable.

Economic returns are another practical consideration. Producing, transporting, and applying biochar adds cost, and nutrient management benefits alone may not always justify that investment. In many systems, the case for biochar becomes stronger when nutrient efficiency gains are combined with other benefits, such as improved soil function, carbon storage, or reduced nutrient losses.

Biochar in cropping systems

Biochar is not a silver bullet, but it can be a useful tool when matched carefully to soil, climate, and cropping systems. The key is to think of biochar as a long-lasting soil sponge and soil-health management tool, not as a stand-alone amendment or fertilizer.

How much and how often?

Most field studies that report consistent agronomic benefits use moderate biochar rates, typically about 5 to 15 tons per hectare, rather than the very high rates sometimes used in research trials. At these realistic rates, biochar often reduces bulk density, increases porosity and water-holding capacity, and improves nutrient retention, especially in coarse‑textured or degraded soils. Because biochar carbon is stable for decades or longer, it is not something that needs to be applied every year; a single, well‑timed application can gradually enhance soil properties over multiple rotations. In practice, many programs and field trials are converging on an approach where 10–15 tons per hectare are applied once and then revisited after several years based on soil tests and crop response rather than on a fixed calendar.

How to apply biochar?

Broadcasting and incorporating biochar with tillage is still the most common method in row‑crop systems because it distributes the material through the rooting zone and reduces dust and wind loss. Where tillage is limited, banding or strip‑placing biochar in the crop row concentrates where roots are most active and can lower the total amount needed per hectare (Figure 4). Mixing biochar with manure or compost before application can be especially effective. In small-scale trials with corn–soybean systems, manure–biochar mixtures have been shown to increase soil organic matter and N, P, and K while reducing nutrient losses in leachates compared with manure alone. Co‑

Figure 4. *Biochar in crop row application as a soil amendment for field corn in sandy soils at Fort Pierce, FL. Photo by Jaya Nepal.*

composted or manure-enriched biochar also tends to have higher nutrient content and can improve soil enzyme activity and microbial processes more than raw biochar by itself.

Which soils and which crops?

Biochar consistently performs best where soils are inherently poor—think of soils that are sandy, acidic, saline, or low in organic matter. In coarse-textured, low-CEC soils, adding 5–10 tons per hectare of biochar in the rooting zone can sharply improve water retention, cut nitrate leaching, and enhance CEC, which in turn helps crops like corn and soybean make better use of applied N, P, K, Ca, and Mg.

In acidic, highly weathered soils, biochar made from manures or crop residues at moderate to high temperatures can raise pH, reduce soluble aluminum, and improve P availability, which has translated into higher maize and wheat yields in long-term field trials. On fertile temperate silt loams or clays, yield gains are less consistent; here, the main rationale is often nutrient use efficiency, erosion control, or carbon sequestration rather than a large jump in yield.

How does biochar fit with fertilizers?

Biochar and fertilizers should be managed as complementary tools. Biochar provides extra storage sites for nutrients and water in the soil while mineral fertilizer and organic amendments supply the nutrients themselves. Studies combining biochar with manure or mineral N and P show that biochar can reduce nitrate leaching, sorb ammonium, and moderate processes like nitrification and denitrification, often lowering nitrous oxide emissions and improving N recovery by crops. For P, some biochar (especially those richer in Ca, Mg, or Fe) can increase P retention yet maintain plant availability, which is useful in P-vulnerable watersheds. In practice, this means farmers can often maintain or slightly reduce fertilizer rates while improving nutrient use efficiency, rather than expecting biochar to replace fertilizer entirely.

Practical guidelines for farmers:

- **Match the biochar to your goal and soil.** Nutrient-rich manure or compost-based biochar make sense for nutrient-poor or acidic soils while high-carbon wood or crop-residue biochar are better suited for building soil carbon and water-holding capacity.
- **Start with moderate rates.** For most field situations, 5–10 tons per hectare on trial strips or fields is a reasonable starting point, ideally integrated with manure, compost, or existing fertilizer programs rather than applied alone.
- **Use soil tests to guide reapplication.** Because biochar is persistent, any reapplication should be based on changes in pH, CEC, organic matter, and crop response over several years, not on an annual schedule.
- **Target the fields where it matters most.** The strongest agronomic and environmental returns are likely on sandy or marginal soils, fields with persistent nutrient losses, and systems where you are already investing in practices like cover crops and reduced tillage to protect soil structure.

Other opportunities

As agriculture faces increasing pressure to enhance productivity while reducing environmental impacts, biochar offers a versatile platform for advancing soil and environmental management. Emerging research highlights its potential to function not only as a soil amendment, but also as an integrative tool that works synergistically with biological, chemical, and physical soil management strategies.

Biochar–microbe synergy

One promising direction is the integration of biochar with biofertilizers. Biochar can serve as an effective carrier for beneficial microorganisms, providing a protective habitat that enhances microbial survival and activity in the soil. This improved microbial establishment can promote nutrient cycling, increase plant nutrient availability, and ultimately support plant growth and resilience under stress conditions. Research highlights that the intricate pore structure of biochar provides microenvironments that help microorganisms better cope with environmental stress, thus stimulating microbial growth and survival (Graziano, 2025). These microbial communities play a critical role in regulating soil nutrients. For example, studies in tomato cultivation have shown that biochar can enhance N transformation by regulating N cycling related microbes, leading to increased inorganic N availability in the plant roots, reduced N lost by leaching, and greater N uptake efficiency.

Biochar for carbon sequestration and storage

Biochar is gaining attention as a powerful tool for carbon sequestration, offering a simple yet effective way to store carbon in soils for long periods. Produced from plant materials, biochar converts organic carbon into a highly stable form that resists decomposition, allowing it to remain in the soil for decades or even centuries. Instead of returning quickly to the atmosphere as carbon dioxide, this carbon is effectively “locked away,” helping reduce greenhouse gas emissions. Beyond its direct role in carbon storage, biochar also improves soil conditions (enhanced structure, water retention, and microbial activity), which can further support the buildup of soil organic carbon. As highlighted by Shyam et al. (2025), these combined benefits make biochar more than just a soil amendment (Figure 5); it represents a promising, nature-based solution that connects soil health with climate resilience and long-term carbon management.

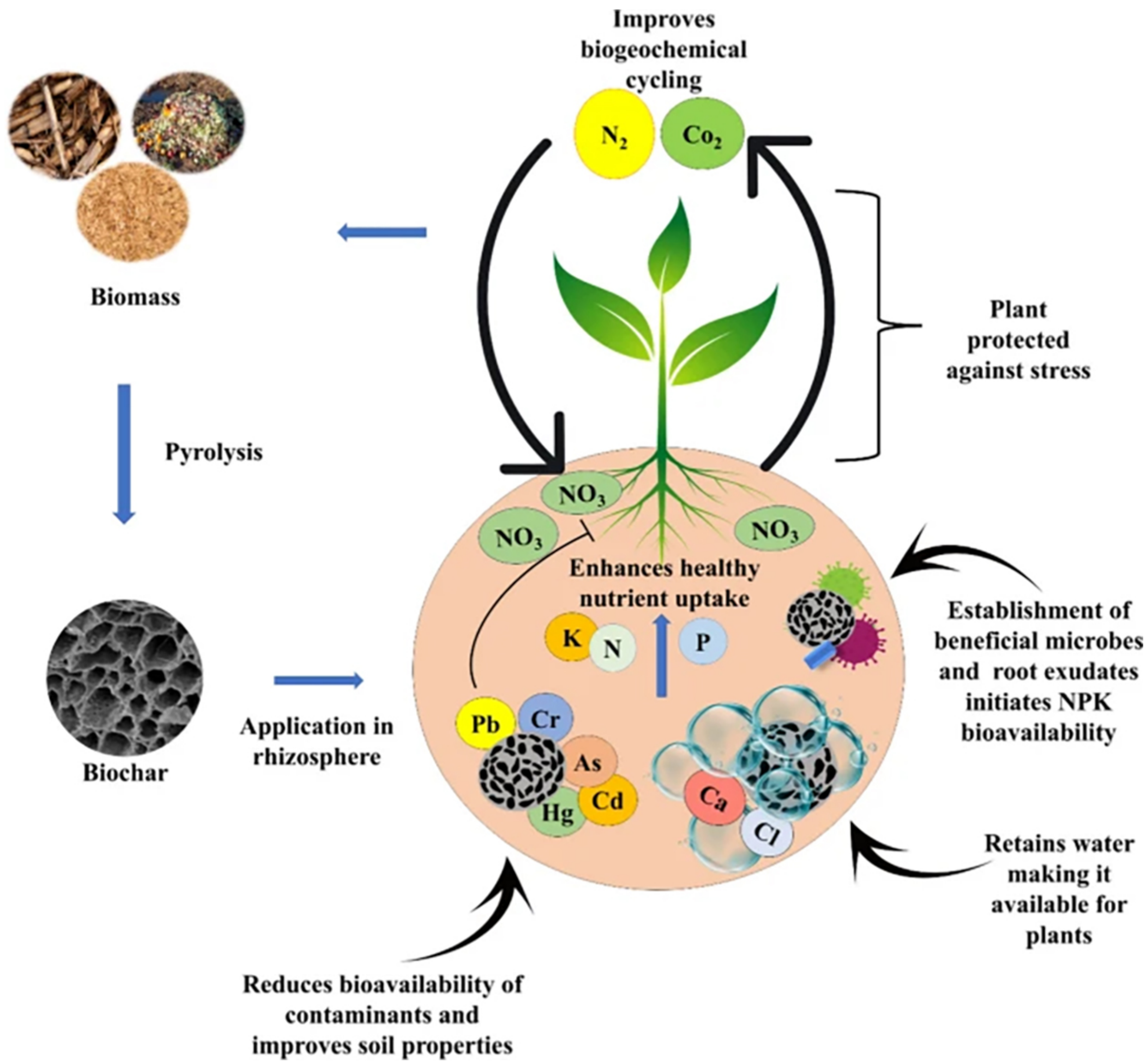

Figure 5. *Biochar as a climate-smart soil amendment: pathways for carbon sequestration and soil health improvement. Illustration republished from Shyam et al. (2025).*

Biochar for heavy metal immobilization

Biochar is increasingly recognized as an effective soil amendment for immobilizing heavy metals and reducing their environmental risk. Its high surface area, porous structure, and abundance of functional groups (e.g., carboxyl, hydroxyl) enable strong adsorption and complexation of metal ions such as cadmium (Cd), lead (Pb), and copper (Cu). In addition, biochar can increase soil pH and cation exchange capacity, promoting the precipitation and stabilization of metals into less bioavailable forms. For example, in research conducted in urban soil contaminated with lead (Pb) with a total Pb concentration of ~ 860 mg kg^{-1}, biochar showed a reduction in desorbable Pb around 54% relative to the control (Figure 6). Biosolids, in contrast, primarily promoted organic complexation and surface sorption through stable organic carbon and reactive binding sites that retain Pb (Gutierrez & Hettiarachchi, 2026).

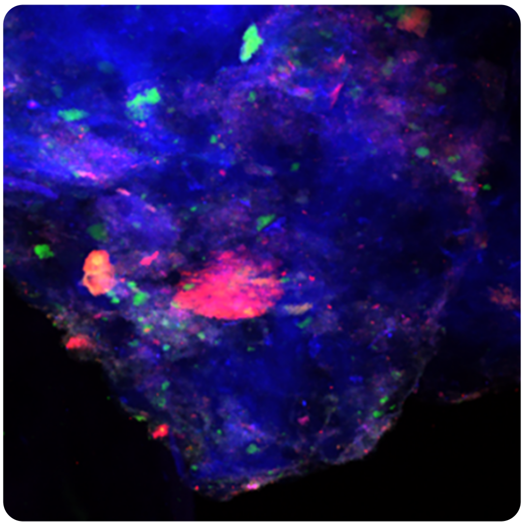

Figure 6. Micro–X-ray fluorescence (μ-XRF) map showing the spatial distribution of Pb (red), Fe (green), and Zn (blue) in a biochar particle collected from field soil three months after application. The map (1 × 1 mm) was obtained from intact biochar fragments. Color intensity is relative within the map. Data were collected at the X-ray microprobe beamline (13-ID-E) of the GeoSoilEnviro Consortium for Advanced Radiation Sources (GSECARS) at the Advanced Photon Source, Argonne National Laboratory. Photo by Gutierrez & Hettiarachchi (2026).

Take-home message

Biochar is more than a soil amendment, it is a multifunctional tool that can enhance nutrient efficiency, support beneficial microbes, improve water retention, and contribute to long-term carbon storage. When strategically integrated with fertilizers and biological inputs, biochar can play a key role in building resilient, climate-smart agricultural systems.

Looking ahead, the integration of biochar into climate-smart agriculture will depend on continued interdisciplinary research, field-scale validation, and the development of region-specific management practices. By bridging soil health, nutrient efficiency, and environmental sustainability, biochar holds significant promise as a cornerstone technology for the future of resilient agricultural systems.

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