



Engineered Biochar: Bridging the Gap between Promise and Practice in Agriculture: A Review

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ABSTRACT

Engineered biochar (EngBC), a modified form of traditional biochar, offers a promising solution for agricultural sustainability. Tailored through physical, chemical, or biological treatments, EngBC is optimized for specific applications to improve soil health and function. This review synthesizes research on its key benefits, including enhanced soil fertility, water retention and pH moderation. EngBC also acts as an effective slow-release fertilizer, improving nutrient use efficiency while reducing leaching and contributes to climate mitigation through carbon sequestration. Despite these advantages, the transition to widespread practice faces considerable hurdles. High production costs, a lack of standardized protocols and potential environmental risks from contaminants or nanoparticles currently limit its adoption. A critical knowledge gap exists due to the scarcity of long-term field studies needed to validate its efficacy and safety under real-world conditions. Future research must prioritize systematic field investigations, robust risk assessments and a deeper understanding of its ecological impacts. Addressing these areas is essential for developing guidelines to enable the safe, effective and sustainable integration of EngBC into modern farming systems.

Key words: Biochar modification, Slow-release fertiliser, Soil amendment, Soil health, Sustainable agriculture.

Biochar is a solid, carbon-rich material defined by its porous structure, high aromaticity and strong resistance to decomposition. It is produced *via* the pyrolysis (thermal degradation) of biomass in a low-oxygen environment (Lehmann and Rondon, 2006). The presence of numerous functional groups, namely hydroxyl, carboxyl and carbonyl, defines the material's porous structure and contributes to its large specific surface area. These physicochemical properties make biochar an effective adsorbent for various aqueous pollutants such as heavy metals, dyes and pharmaceuticals (Inyang *et al.*, 2016; Rajapaksha *et al.*, 2014).

The historical precedent for biochar's agricultural use is evident in the *Terra Preta de Índio* ("Indian black earth") soils of the Western Amazon basin. This legacy of ancient soil management created exceptionally fertile ground that supported lush rainforest growth. Compared to adjacent lands, Terra Preta soils exhibit superior properties, including higher concentrations of key nutrients such as nitrogen, phosphorus, potassium and calcium. Furthermore, they possess enhanced soil aggregation and structural stability. The remarkable and lasting fertility of these soils is attributed to their high content of stable, pyrogenic organic carbon. Biochar has diverse applications in modern farming systems. It can be used as an animal feed additive, a component in manure management, a fertilizer ingredient, or a direct soil amendment. Beyond these agricultural functions, biochar production and application represent a potent carbon dioxide removal (CDR) strategy. This method, often termed pyrogenic carbon capture and storage (PyCCS), is considered technologically mature. For PyCCS to be widely adopted however the agricultural use of biochar must provide clear co-benefits. These advantages must

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include boosting crop yields, improve ecosystem functions, or increase climate resilience by enhancing soil properties (Schmidt *et al.*, 2021).

Although different review articles exist on the topic of engineered biochar and its applications, this article provides a critical analysis of its readiness for the market and outlines the specific research and risk management steps required for its responsible transition into widespread agricultural practice. The information for this article was collected in 2024 during credit seminar coursework at the College of Agriculture, Vellanikkara.

Feedstock sources

The chemical composition of the parent biomass is particularly important during pyrolysis. While components like cellulose and hemicellulose primarily break down into bio-oil, lignin functions as the main precursor for solid biochar, a role that results in a superior char yield (Kan *et al.*, 2016). Consequently, lignin-rich feedstocks will generally produce a greater quantity of biochar than those

with high cellulose content. A study by Indrawati *et al.* (2017) confirmed that Bengkalis peat and rice husk have high hemi-cellulose and lignin content, which makes it suitable for long-term recovery in soil.

The properties of biochar vary significantly with feedstock type. Biochar from wood sources is typically carbon-dense but offers few plant-available nutrients. In contrast, biochar derived from animal manure is lower in carbon but richer in these essential nutrients. This variation also exists within wood types themselves. For example, hardwood biochar provides minimal nutrient value, while softwood biochar can supply comparatively greater amounts of phosphorus and potassium (Hossain *et al.*, 2020).

Pyrolysis process

Pyrolysis is the thermal decomposition of carbon-rich organic matter in a low-oxygen environment, typically at temperatures above 300°C. This process converts a single feedstock into solid, liquid and gaseous fractions. The conversion involves complex chemical transformations, primarily devolatilization and the subsequent aromatization of the carbon structure. The entire pyrolytic process includes primary and secondary phases. The secondary phase reactions are particularly critical as they largely determine the final product distribution and yield (Mašek *et al.*, 2013).

Slow pyrolysis

Slow pyrolysis is exemplified by traditional charcoal production, a process using low heating rates ($\leq 100^\circ\text{C/h}$) and long residence times suitable for large biomass particles. This method is conducted in batch units with heat supplied either externally or internally. External heating is employed to maximize the solid char yield, whereas internal heating provides process energy by combusting a portion of the feedstock itself. More advanced techniques improve this basic process. For example, staged retort operations increase efficiency by using captured pyrolysis gas to heat subsequent batches (Emrich, 1985). Flaming pyrolysis is another variation that burns released volatiles for process heat, a method well-suited for small-scale production (Cornelissen *et al.*, 2016).

Intermediate pyrolysis

Intermediate pyrolysis operates at higher heating rates ($\geq 100^\circ\text{C/min}$) and shorter residence times, a combination that requires smaller biomass particles. This process is typically performed in continuous reactors. Common designs include rotary kilns, which are versatile enough for varied particle sizes and auger reactors, which are well-suited for small to medium-scale operations. Vertical moving bed reactors present another scalable option, although their efficiency depends on maintaining uniform particle movement (Jerzak *et al.*, 2024).

Fast pyrolysis

Fast pyrolysis is a technique specifically developed to maximize liquid bio-oil yield. The process is defined by extremely rapid heating rates, often hundreds of degrees

Celsius per second, followed by quick quenching of the resulting volatiles at 400-600°C. Achieving this requires small feedstock particles and very high heat transfer rates. Consequently, specialized technologies such as fluidized bed or ablative reactors are employed to meet these demanding conditions. A central principle for maximizing the liquid yield is to minimize the residence time of hot volatiles, thereby preventing their secondary cracking into non-condensable gases (Bruun *et al.*, 2012).

Microwave pyrolysis

Microwave-assisted pyrolysis is a distinct method that employs microwave radiation to achieve volumetric heating, warming biomass particles uniformly from the core outward. This technique offers precise temperature control and significant operational flexibility, as it can be adapted to various reactor designs. A study by Ghosal *et al.* (2024) reported a higher yield of rice husk biochar at 600 W. The primary consideration for this process however is its direct reliance on electricity. Consequently, the net carbon footprint of microwave pyrolysis is intrinsically linked to the carbon intensity of its power source (Ren *et al.*, 2022).

Biomass gasification

Gasification is a high-temperature process ($\geq 1000^\circ\text{C}$) designed to maximize the production of combustible gases, thereby minimizing solid residue. Operating at much higher temperatures than pyrolysis, it yields a char characterized by high ash content and potential tar contamination. Despite these properties, gasification char has a valuable application as a soil amendment. When added to soil, it can protect native organic matter from microbial decomposition, which further enhances net carbon sequestration (Naisse *et al.*, 2015).

Effect of biochar on soil properties

Biochar application positively impacts soil health by altering its physico-chemical and biological properties (Ramamoorthy *et al.*, 2024). It enhances key traits, including pH, cation exchange capacity (CEC), aggregate stability and water retention. These improvements foster favourable plant growth, often leading to better nutrient uptake and increased crop productivity (Dai *et al.*, 2020). By modifying the soil matrix, biochar also promotes the accumulation and protection of soil organic carbon (SOC), especially benefiting sandy or drought-prone soils (Blanco-Canqui *et al.*, 2020; Schmidt *et al.*, 2021). Furthermore, in wetlands, one study noted a 50-60% reduction in cumulative methane emission alongside increased rice yield (Rajalekshmi *et al.*, 2024).

However, raw biochar's effectiveness is highly variable, depending on feedstock, production conditions, soil type and climate (Hussain *et al.*, 2017). This variability necessitates engineered biochar (EngBC), which modifies raw biochar for specific goals. Engineering employs targeted physical, chemical or biological treatments to refine the material's surface area, porosity and chemistry. The aim is a more effective and reliable product, for

instance, by enhancing its function as a carrier for fertilizers or microbial amendments (Wang *et al.*, 2022; Panahi *et al.*, 2020).

Engineered biochar shows promise in targeted agricultural applications. For example, phosphorus-enriched biochar boosts plant biomass and water use efficiency, while acid-treated biochar moderates alkaline soil pH to improve nutrient availability (Chen *et al.*, 2018; Sadegh-Zadeh *et al.*, 2018). Recent studies demonstrate Fe-modified biochar increasing grain yields in flooded rice and MgCl_2 -modified biochar acting as a slow-release fertilizer for maize (Wen *et al.*, 2021; Khajavi-Shojaei *et al.*, 2020). Beyond agriculture, EngBC is vital for environmental remediation. Its pollution control efficacy relies on engineered features like surface functional groups and customized pore sizes, which govern its selectivity and adsorption capacity for specific contaminants. EngBC is a highly efficient adsorbent for treating contaminated water. Produced from waste biomass, engineered biochar also offers significant sustainability advantages, supporting circular economy principles and sustainable development goals (Panahi *et al.*, 2020).

Engineering approaches to enhance biochar properties

To optimize biochar for specific uses, modifications are crucial, refining its physicochemical attributes for improved efficiency. These enhancements are achieved through various physical, chemical and biological methods (Rajapaksha *et al.*, 2016).

Physical modification

Physical modification methods are used to refine the intrinsic properties of biochar. Common techniques include mechanical grinding, gas or steam activation, microwave treatment and magnetic alteration. These processes primarily enhance the material's pore structure and increase its specific surface area. Methods such as steam activation also introduce oxygen-containing functional groups to the biochar surface. Collectively, these physical and chemical enhancements improve the material's capacity for adsorbing pollutants (Wang *et al.*, 2017).

Ball milling modification

Mechanical crushing is a fundamental physical modification that brings down biochar particle size. This process leads to a greater external surface area and can thereby enhance the adsorption of ions. For example, grinding corn stover biochar led to a 3.2-fold increase in its specific surface area, reaching $194 \text{ m}^2/\text{g}$ (Peterson *et al.*, 2012). This technique can be advanced through mechanochemical activation, which involves adding chemicals during the milling process. This combined approach can produce nano-sized particles and simultaneously introduce new surface functional groups.

Gas/Steam activation

Gas activation using agents like water vapor or carbon dioxide (CO_2) is a common method to enhance the porosity

and surface reactivity of biochar. This process selectively removes residual combustible material, which develops a more intricate pore network (Shim *et al.*, 2015). However, this high-temperature activation presents a critical trade-off. It can also degrade important surface functional groups, specifically carboxyl groups ($-\text{COOH}$), which may in turn reduce the biochar's capacity for adsorbing certain metal ions (Uchimiya *et al.*, 2012).

Microwave modification

Microwave treatment is a modification method typically applied at $200\text{--}300^\circ\text{C}$. A significant practical advantage of this technique is its ability to process wet biomass, which eliminates the need for energy-intensive pre-drying steps. Beyond this operational benefit, the treatment also yields a biochar with an enhanced specific surface area and a greater abundance of surface functional groups (Sun *et al.*, 2020).

Ozone activation

Ozone (O_3) activation is a chemical modification that oxidizes biochar, creating a high density of acidic oxygen-containing functional groups such as carboxyls. The introduction of these surface groups is key to the process's effectiveness, as it significantly enhances the material's pollutant adsorption capacity and its cation exchange capacity (CEC) for soil applications (Sajjadi *et al.*, 2019). The impact of this treatment can be substantial. For example, brief ozone exposure can add surface oxides equivalent to 20-30% of the biochar's total mass, while other combined ozonation treatments have been shown to greatly increase micropore volume (Jimenez-Cordero *et al.*, 2015).

Thermal activation

Thermal treatment transforms biomass through sequential stages of decomposition and structural rearrangement (Dodevski *et al.*, 2017). The process begins with an initial dehydration phase at $100\text{--}200^\circ\text{C}$, which removes water. As temperatures rise further, organic biopolymers and aromatic compounds degrade, leading to the formation of both amorphous and crystalline carbon structures. At very high temperatures ($600\text{--}1500^\circ\text{C}$), further treatment for 1-2 hours cause significant structural reorganization. During this advanced stage, stacked carbon layers break down, releasing additional gases and consequently reducing the final solid biochar yield (Sajjadi *et al.*, 2019).

Ultrasound activation

Sonication (ultrasound treatment) modifies biochar by enhancing solid-liquid interactions *via* intense mixing and cavitation, which overcomes mass transfer limitations (Sajjadi *et al.*, 2019). This treatment significantly improves material properties, resulting in biochar with a higher heating value, greater specific surface area and enhanced reaction rates. For example, Nguyen *et al.* (2021) showed that ultrasound activation of water bamboo husk biochar increased its reaction rate by 80%. These improvements stem from complex physicochemical changes, including

exfoliation of graphitic layers and mineral leaching from the char matrix.

Plasma activation

Plasma treatment is an advanced method for modifying carbon-based materials. The process utilizes plasma, an ionized gas generated by electric discharge, which is often considered the fourth state of matter. Key plasma properties such as particle ionization and temperature are controlled by adjusting the input voltage and current (Karim *et al.*, 2017). This treatment is conducted in specialized plasma reactors which operate over a wide power range from 100W to 10 MW. As a modification technique for biomass, plasma activation offers significant advantages including extremely fast reaction rates, high energy density and minimal tar formation (Niu *et al.*, 2017).

Electrochemical modification

Electrochemical modification uses an electric field to alter the physicochemical properties of biochar. In this process, an electric current is applied to biochar suspended in an electrolyte solution, which generates powerful oxidants at the electrode surfaces. The choice of process parameters such as the electrolyte pH, electrode material (e.g., aluminum) and solution composition critically determines the modification's efficiency (Jung *et al.*, 2015). By carefully controlling these factors, this method can effectively enhance the biochar's porosity, specific surface area and overall morphology (Sajjadi *et al.*, 2019).

Chemical modification

Chemical treatments using acids and bases are a common strategy to enhance the physicochemical properties of biochar. These modifications are used to increase specific surface area, develop microporosity, add new functional groups and raise the cation exchange capacity (CEC), which collectively improves the material's adsorption performance (Sajjadi *et al.*, 2018).

Acidic modification

Acidic modification introduces acidic functional groups, increases H/C and O/C ratios, boosts oxygen content and enhances biochar's hydrophilic nature. A range of agents are used for this purpose, including mineral acids like hydrochloric, sulfuric and nitric acid, as well as organic acids such as oxalic and citric acid (Rajapaksha *et al.*, 2016). Acid-modified biochar can be enriched with nutrients (e.g., phosphate, nitrate), improving plant growth and nutrient availability in soils (Chu *et al.*, 2018).

Alkaline modification

Alkaline modification enhances biochar's physical and chemical properties, increasing surface area and adding oxygen-containing functional groups. NaOH and KOH are common alkaline reagents. Alkaline modification generally increases surface area, H/C and N/C ratios and decreases O/C ratios, indicating reduced hydrophilicity and increased aromaticity (Kumar *et al.*, 2022). NaOH has proven more

effective, with Cazetta *et al.* (2011) showing it outperformed KOH on coconut biochar.

Modification using oxidizing agents

Treatment with strong oxidizing agents is a chemical method used to functionalize the biochar surface. Common agents like hydrogen peroxide (H_2O_2) and potassium permanganate ($KMnO_4$) introduce a high density of oxygen-containing functional groups, including carboxyl, hydroxyl and carbonyl structures. This chemical alteration significantly increases the biochar's surface oxygen content and can also enhance its porosity. The resulting functionalized surface typically exhibits a greater affinity for certain pollutants, leading to an improved sorption capacity, particularly for heavy metals (Wang *et al.*, 2015).

Modification using metal salts and metal oxides

Modification with metal salts or oxides transforms biochar into a functional composite material with enhanced catalytic, magnetic, or adsorptive properties. Incorporating transition metals (such as Fe, Mn, Al and Ti) or their oxides onto the biochar surface increases its catalytic activity and creates more diverse reactive sites for adsorption. Certain modifications, like the addition of iron oxides, can also impart magnetic properties that simplify the material's recovery and reuse from aqueous solutions. These composites are typically created using one of two main approaches: mixing the metal precursors with biomass pre-pyrolysis or impregnating the finished biochar with a metal solution post-pyrolysis (Bao *et al.*, 2021).

Modification using carbon nanotubes (CNTs)

Carbon Nanotubes enhance sorption due to high surface area, but are costly. Using biochar as a CNT carrier is a cost-effective approach. These composites can be fabricated through methods such as dip-coating biochar with CNTs and then pyrolyzing the mixture, a process shown to increase the final material's surface area and thermal stability (Inyang *et al.*, 2014). The versatility of these composites can be further expanded by using functionalized CNTs, which can be tailored for selective interaction with specific contaminants, opening up advanced applications in fields like targeted water purification and biosensing (Díez-Pascual, 2021).

Modification using clay minerals

Creating clay-biochar composites is a modification strategy used to enhance the functional properties of the material. Adding clay minerals such as kaolinite, montmorillonite and calcite during production can significantly alter the resulting biochar's physicochemical characteristics and sorption capacity. The effectiveness of this modification depends on factors like the biochar's particle size and the specific type of clay mineral chosen (Du *et al.*, 2023). For example, a study by Chen *et al.* (2017) demonstrated that incorporating montmorillonite substantially increased the composite's surface area and its ability to adsorb both ammonium and phosphate.

Magnetic modification of biochar

Magnetic modification often slightly reduces surface area but can improve or maintain adsorption capacities for various contaminants, including heavy metals, phosphates and organic pollutants, due to the introduction of new functional groups and enhanced surface properties. Magnetic biochar demonstrates high reusability, retaining substantial adsorption capacity over multiple cycles, which supports its economic and environmental viability (Ajmal *et al.*, 2019). Chen *et al.*, (2011) used $\text{Fe}^{3+}/\text{Fe}^{2+}$ co-precipitation to produce magnetic biochar, reducing surface area but increasing pore size to enhance anionic contaminant adsorption.

Biological impregnation

Microorganisms in biochar pores form biofilms, degrading pollutants (Hamed *et al.*, 2015). Pollutant degradation occurs after microbes colonize the biochar, a process that enables them to metabolize contaminants through bio-electrochemical and biochemical means (Sharma *et al.*, 2020). This biological treatment improves biochar's properties, allowing for both adsorption and microbial breakdown of pollutants at the same time. Biochar-active biofilms are more effective at degrading contaminants than traditional sand biofilms (Dalahmeh *et al.*, 2018).

The effect of biochar on earthworm intestinal enzyme activity

During vermicomposting, the passage of biochar through an earthworm's digestive tract facilitates enzymatic interactions that both create new humus-like substances and apply an enzyme-rich coating to the biochar particles (Sanchez-Hernandez 2018).

Pyrolysis of anaerobically digested (AD) waste

Using anaerobic digestion (AD) residues as a feedstock is an economically and environmentally advantageous approach for producing biochar, consistent with circular economy principles (Tabatabaei *et al.*, 2019). Biochar derived from this process typically exhibits superior properties, including a higher specific surface area and a more alkaline, negative surface charge compared to conventional biochar (Ma *et al.*, 2018; Inyang *et al.*, 2012; Yao *et al.*, 2018). Besides, AD biochar is often enriched with minerals due to bioaccumulation and possesses a high density of functional groups, including carbonyl structures (Yao *et al.*, 2013; Wang *et al.*, 2017; Inyang *et al.*, 2010). These unique physicochemical characteristics make it a highly effective low-cost adsorbent for ion sequestration in applications such as soil amendment and water retention.

Mechanisms of action in soil

Engineered biochar is gaining significant attention as a slow-release fertilizer. It's an effective way to enhance soil health by providing a steady supply of critical nutrients like phosphorus (P) and nitrogen (N). The entire approach

relies on the biochar's excellent adsorption-desorption dynamics to control how nutrients are released over time. Biochar can hold a large quantity of nutrients. Studies show optimized biochar can adsorb up to 345 mg/g of phosphorus (Chen *et al.*, 2018). This process is often driven by precipitation and surface deposition, particularly when the biochar is enriched with minerals like magnesium (Yao *et al.*, 2013).

The material's vast network of pores provides ample space for nutrient sorption. At the same time, surface functional groups (e.g., carboxyl groups) use chemical interactions like hydrogen bonding and electrostatic forces to bind with nutrient molecules (Cai *et al.*, 2016).

By holding onto nutrients so effectively, biochar-nutrient composites significantly reduce nutrient leaching. This keeps more nutrients available in the soil for plants and also improves the soil's water retention (Wang *et al.*, 2021).

pH modification

One of biochar's most significant impacts is on soil pH. A global meta-analysis reported that biochar application leads to a substantial increase in soil pH, with pronounced effects in both coarse and fine-textured soils (Singh *et al.*, 2022). This powerful liming effect occurs because biochar is naturally alkaline and contains basic cations. Its impact is generally greater and more persistent than that of traditional lime, particularly in highly acidic soils (Dai *et al.*, 2017).

Biochar reduces the concentration of toxic aluminium ions in acidic soils, which is beneficial for plant growth. This is achieved through increased pH buffering capacity and the release of dissolved organic carbon, which binds with aluminium ions (Shi *et al.*, 2020).

Microbial activity enhancement

Engineered biochar is a promising tool for managing the soil microbiome. It works by creating an environment that promotes beneficial microbes while suppressing pathogens. Its effectiveness can be enhanced further when combined with other biocontrol agents or when "pre-conditioned" before application, making it a versatile part of integrated pest and disease management strategies.

Biochar amendments boost both the taxonomic and functional diversity of microorganisms in the soil. The addition of biochar specifically increases the abundance of helpful bacteria and fungi. This includes well-known plant-growth promoters and biocontrol agents like *Bacillus* and *Lysobacter* (Wang *et al.*, 2020). By altering the microbial community directly around the plant roots (the rhizosphere), biochar can lead to direct improvements in plant growth and physiological health (Ogundeji *et al.*, 2021).

Water retention and aeration

Biochar enhances soil water retention, particularly in coarse-textured soils, by increasing available water content (AWC), field capacity (FC) and permanent wilting point (PWP) (Edeh *et al.*, 2020). By increasing total porosity

and reducing the soil's bulk density, it creates more space within the soil matrix for water to be stored and held (Razzaghi *et al.*, 2020).

Carbon sequestration

Studies have shown it decreases emissions of both methane (CH₄) and nitrous oxide (N₂O) by enhancing soil absorption and altering microbial activity (Azad *et al.*, 2023). Over the long term, this leads to a lower net global warming potential and emission intensity of greenhouse gases in agricultural systems (Wu *et al.*, 2019).

Biochar is recognized as a competitive carbon dioxide removal (CDR) strategy, particularly in scenarios where other CDR measures are not economically viable. It can serve as a significant carbon sink, potentially reducing global temperature increases when integrated into broader climate mitigation strategies (Bergero *et al.*, 2024).

Benefits of engineered biochar as fertilizer

Impact on physicochemical properties

Engineered biochar significantly enhances key soil physicochemical properties, boosting fertility and crop performance. A primary benefit is improved water retention, making it highly valuable in water-limited agricultural systems. Although some biochars exhibit initial surface hydrophobicity, which can limit water uptake. This issue is overcome through tailored engineering processes (El-Naggar *et al.*, 2019; Khajavi-Shojaei *et al.*, 2020).

Biochar also serves as a versatile tool for soil pH regulation, with its effect dependent on its specific design. Standard alkaline biochar effectively raises pH in acidic soils, which improves nutrient availability and microbial activity (Dai *et al.*, 2020). Conversely, engineered acid-treated biochars, such as HCl-modified types, can be used to lower the pH in alkaline or calcareous soils, thereby releasing trapped nutrients like potassium and various micronutrients (Sadegh-Zadeh *et al.*, 2018).

Furthermore, biochar application typically increases the soil's cation exchange capacity (CEC), an effect of particular importance in sandy or degraded soils. This improvement can be attributed to two key properties of biochar: A large surface area and an abundance of negatively charged functional groups, both of which promote nutrient retention and limit leaching losses (El-Naggar *et al.*, 2019). The magnitude of this CEC enhancement is influenced by factors such as pyrolysis temperature and soil type and may continue to increase as the biochar ages within the soil environment.

Impact on nutrient dynamics

The influence of engineered biochar on nutrient availability is complex, involving several trade-offs. While producing biochar at higher temperatures enhances its stability, it may reduce its inherent carbon (C), hydrogen (H) and nitrogen (N) content (Zornoza *et al.*, 2016). Although biochar adds beneficial cations, its effect on pH can be detrimental in alkaline soils; the resulting pH increase may actually

decrease the availability of phosphorus and micronutrients (Gunes *et al.*, 2014).

Regarding nitrogen (N) dynamics, engineered biochar is a powerful management tool. Modified biochars, such as MgCl₂-treated or steam-activated types, improve nutrient use efficiency by adsorbing and slowly releasing nitrogen (Khajavi-Shojaei *et al.*, 2020). Biochar's C/N ratio is a critical factor in this process; a high ratio (>20) can lead to N immobilization (where microbes lock up nitrogen), while a low ratio (<20) promotes its release. This potential limitation can be managed by selecting an appropriate biochar or applying it well before planting, often with an organic nitrogen source (Dai *et al.*, 2020).

Similarly, specific engineering strategies are highly effective for phosphorus (P) management. Biochars modified with magnesium (Mg) or aluminum (Al) show strong P adsorption and slow-release behavior, making them ideal for P-deficient soils (Shakoor *et al.*, 2021). The feedstock is also important, as biochars from biosolids like manure typically have higher P availability than those from woody biomass (Novak *et al.*, 2018). Furthermore, advanced composites like P-laden nanobiochar can boost P availability while also improving other soil properties such as moisture retention (Chen *et al.*, 2018; Yao *et al.*, 2013).

Impact on soil biological properties

Biochar fundamentally alters soil microbial communities by modifying the physicochemical environment (Panahi *et al.*, 2020). Its complex, multi-scale porous structure (micro- to macropores) offers a high surface area and ideal microhabitats for diverse microorganisms (bacteria, fungi, protozoa). Specifically, macropores can shield microbes from environmental stressors like predation, while smaller pores effectively retain water and nutrients for microbial metabolism (Bolan *et al.*, 2023).

Shifts in soil pH and nutrient availability drive changes in microbial biomass and biogeochemical cycles like nitrogen cycling (Li *et al.*, 2019). Biochar's alkaline conditions often favour bacterial proliferation, while its macroporous structure supports fungal hyphae growth (Panahi *et al.*, 2020). Conversely, some biochars containing residual phenolic compounds can inhibit microbial growth, underscoring the importance of feedstock and production conditions (Das *et al.*, 2020).

Beyond direct impacts on microbial populations, biochar also influences the activity of extracellular enzymes involved in nutrient cycling. The activities of key enzymes such as β -glucosidase, N-acetyl- β -glucosaminidase and alkaline phosphatase have reportedly increased following biochar application, likely due to improved soil conditions (Pokharel *et al.*, 2020). These responses are highly dependent on the biochar type. Manure-based biochar, for example, elevated alkaline phosphatase activity but suppressed acid phosphatase in fine-textured soils (Batool *et al.*, 2015). In contrast, an Fe-modified biochar was shown to reduce catalase and urease activities compared to its

pristine form, possibly due to altered nutrient dynamics and pH (Wen *et al.*, 2021).

Challenges and limitations

While biochar shows significant promise as a slow-release fertilizer, challenges in optimizing its performance remain. Its efficacy is highly dependent on factors such as pyrolysis temperature, application dosage and specific soil conditions (Wang *et al.*, 2021). Future research should therefore focus on synchronizing nutrient release dynamics with plant uptake demands. Further work is also needed to explore biochar's potential in broader environmental remediation and to develop advanced biochar composites with enhanced adsorption capacities (Gwenzi *et al.*, 2018). The widespread use of engineered biochar requires careful risk assessment. Biochar derived from contaminant-loaded feedstocks may release residual pollutants or fine particulates into air and water (Ramanayaka *et al.*, 2020). Additionally, the nanoscale size of engineered biochar nanocomposites increases their potential for transport, accumulation and bioaccumulation in soil food webs (Panahi *et al.*, 2020).

Furthermore, the interaction of these materials with broader ecosystems requires scrutiny. The heightened reactivity of nanobiochar, particularly in alkaline aquatic environments, could pose risks to humans and wildlife through ingestion or dermal contact, potentially causing cellular damage (Huang *et al.*, 2020). From an agronomic perspective, excessive application rates of biochar have been shown to inhibit crop growth, highlighting the importance of determining optimal dosages (Cong *et al.*, 2023). These potential risks underscore the critical need for comprehensive risk assessments before engineered or nano-scale biochars are deployed at large agricultural scales.

CONCLUSION AND FUTURE ACTIONS

In conclusion, engineered biochar (EngBC) offers a promising pathway toward improving soil health and enhancing agricultural productivity, with its function as a slow-release fertilizer being a key advantage. However, to transition from scientific potential to widespread practical application, several critical research gaps must be addressed to ensure its safe and effective deployment.

A primary research priority should be the systematic, field-scale investigation of co-applying EngBC with other soil amendments, like organic manure. Validating the potential for synergistic interactions to improve soil fertility and crop performance across diverse agricultural contexts is a fundamental objective for optimizing its use.

Another critical area of investigation is the impact of EngBC on soil biology. While its general influence on microbes is acknowledged, a significant lack of data exists on how different engineered forms affect the diversity and function of both micro-and macrofaunal communities. Understanding these ecological shifts is essential for promoting long-term soil health and ecosystem stability.

A thorough assessment of potential environmental and ecological risks is paramount before widespread adoption. This requires comprehensive studies on the behaviour of nanoparticles, the fate of residual contaminants and the risk of bioaccumulation under realistic agronomic conditions. Addressing these interconnected research priorities will be fundamental to developing the robust guidelines and best practices needed for the responsible integration of engineered biochar into modern agriculture.

Conflict of interest

All authors declare that they have no conflict of interest.

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