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Transforming crop residue into fertile soils: A comprehensive review on biochar application and future directions

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Abstract
The escalation of agricultural activities globally generates immense volumes of crop residues. Burning or improper disposal of these residues exacerbates environmental degradation and greenhouse gas emissions. Converting this surplus biomass into biochar via pyrolysis offers a sustainable, closed-loop solution to enhance soil health and mitigate climate change. This review comprehensively synthesizes recent advancements in biochar technology. It evaluates how diverse biomass feedstocks and pyrolysis engineering dictate the final physicochemical architecture of biochar. Furthermore, it details the mechanisms through which biochar alters soil physical structures, chemical dynamics, and biological networks. Special emphasis is placed on biochar's performance in stressed environments, contaminant immobilization, and its next-generation modifications like engineered biochars and biochar-based fertilizers (BCBFs). Finally, we address economic viability, life cycle impacts, knowledge gaps, and smart policy integration necessary for large-scale field adoption.

Keywords: Biochar, Crop residue, pyrolysis, soil fertility, carbon sequestration, sustainable agriculture

Introduction

Global agriculture generates billions of tons of crop residues annually. Managing this massive biomass output poses severe logistical and ecological challenges. In many developing economies, on-field burning remains the cheapest and fastest method to clear fields for subsequent planting cycles [1]. However, this practice releases colossal amounts of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and particulate matter ($PM_{2.5}$ and (PM_{10}) into the atmosphere, causing dense smog and respiratory crises [2]. Alternatively, leaving raw residues on fields can impede tillage machinery, lock up soil nitrogen temporarily, and shelter crop pathogens that damage the next harvest [3]. Therefore, transitioning from hazardous residue disposal to value-added utilization is imperative for modern sustainable farming. The biochar paradigm offers a viable solution to the crop residue dilemma by converting waste biomass into a stable, carbon-rich material. Generated through the thermal degradation of organic matter under oxygen-limited or anaerobic conditions [4], biochar converts volatile, easily degradable carbon components into highly aromatic, recalcitrant ring structures. This molecular architecture makes it resistant to microbial degradation, allowing it to persist in soils for hundreds to thousands of years [5]. Applying biochar to agricultural soils shifts carbon cycling from a rapid, carbon-positive loop into a long-term, carbon-negative sink. Beyond carbon sequestration, biochar's highly porous structure, large specific surface area, and abundant surface functional groups make it an excellent soil conditioner. It acts as a permanent structural anchor within the soil matrix, altering bulk density, enhancing water holding capacity, holds plant nutrients, and creating a porous habitat for beneficial soil microbes. By redirecting agricultural waste streams into pyrolytic processing, farming systems can reduce reliance on fossil-fuel-derived inputs, lower greenhouse gas emissions, and establish a circular bioeconomy.

Biomass Feedstock and Pyrolysis Engineering

Feedstock Diversity

The properties of biochar depend heavily on the inherent characteristics of the source biomass. Common residues like wheat straw, rice husk, corn stover, and cotton stalks exhibit drastically different ratios of cellulose, hemicellulose, and lignin [6]. High-lignin feedstocks (e.g., nutshells) degrade slowly across a wide temperature range 250ºC to 900ºC, producing dense, mechanically strong biochars with high fixed carbon. Conversely, herbaceous residues (e.g., rice and wheat straw) are rich in cellulose and hemicellulose. These components decompose rapidly at lower temperatures 200ºC to 400ºC, yielding less carbon but creating highly developed macroporous networks. Additionally, straw and husk derived biochars feature higher ash content, which helpfully concentrates essential inorganic plant nutrients like potassium, silicon, phosphorus, calcium, and magnesium within the carbon matrix [7]. However, excessive ash content can sometimes clog micro and mesopores, which ultimately reduces the biochar's total specific surface area.

[Biomass Feedstock Type] ⟶ [Lignin vs. Cellulose Ratio] ⟶ [Biochar Surface Properties]
(e.g., Straws vs. Shells) (Thermal Degradation Path) (Porosity & Surface Charge)

Pyrolysis Technologies

Pyrolysis systems are classified into slow, fast, and gasification regimes based on heating rates, residence times, and maximum temperatures (T_{max}). Each regime shifts the distribution of solid (biochar), liquid (bio-oil), and gaseous (syngas) products. Slow pyrolysis operates at low heating rates (1-10ºC per minute) with long residence times, maximizing biochar yields up to 35–50% by weight [8]. Conversely, fast pyrolysis uses rapid heating rates and very short residence times to maximize liquid bio-oil production, leaving minimal biochar behind. Pyrolysis temperature is the dominant process parameter governing biochar behavior. Increasing the process temperature from (500–700ºC) induces the following profound structural transformations [9].

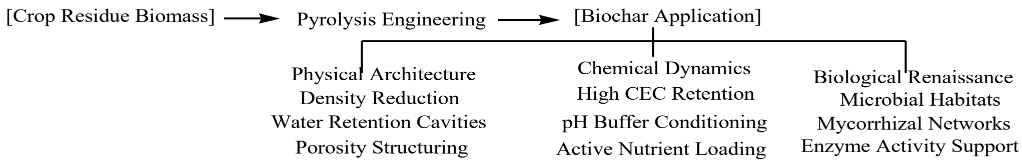
- Volatile matter is progressively driven off, raising the relative proportion of fixed carbon.
- Total specific surface area expands dramatically as micro and mesopores clear out.
- Hydrophobic aliphatic compounds break down, leaving a hydrophilic, highly aromatic structure.
- High temperatures accelerate the loss of acidic surface functional groups, increasing biochar pH due to the concentration of alkaline earth metals in the ash fraction.

Physicochemical Tailoring

By fine-tuning operational parameters like highest treatment temperature, residence time, and sweep gas flow, engineers can customize biochar for specific applications. Low-temperature biochars (300–400ºC) retain volatile fatty acids and oxygenated functional groups like –COOH and -OH groups, making them excellent for correcting nutrient retention issues in sandy soils [10]. High-temperature biochars (>600ºC) exhibit superior electrical conductivity and internal surface areas, which are ideal for capturing heavy metals or promoting electron transfer among soil bacteria.

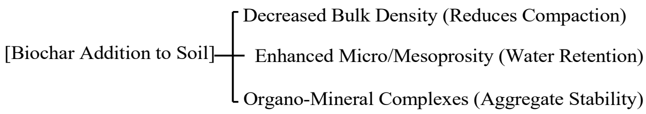
Mechanism of Soil Fertility Enhancement

Based on the structural pillars of biochar science, the mechanisms of soil fertility enhancement operate across three primary dimensions. Soil Physical Architecture, Chemical Dynamics and Biological Renaissance.



Soil Physical Architecture

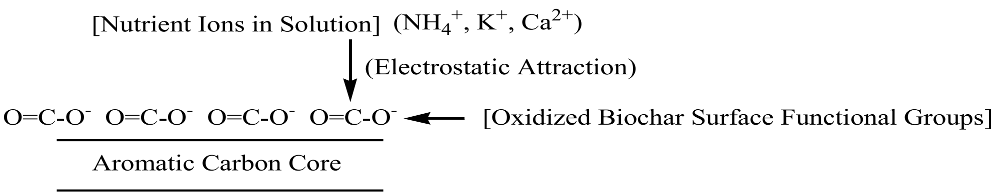
Adding biochar significantly modifies the physical architecture of the soil profile. Because biochar has a much lower bulk density than mineral soils, mixing it into compressed soils decreases overall bulk density, reduces compaction, and increases total porosity.



This structural adjustment reduces mechanical resistance to root elongation [11], allowing crops to build deeper and more expansive root networks. Biochar's internal porosity significantly boosts soil water-holding capacity (WHC), especially in coarse-textured sandy soils. Its capillary pores act as internal reservoirs that capture and hold water during rainfall or irrigation, then slowly release it to plant roots during dry periods. This helps crops survive prolonged droughts [12]. Furthermore, biochar promotes the formation of stable soil aggregates. Highly reactive biochar surfaces bond with fine clay minerals and native organic matter to form durable organo-mineral complexes. These complexes act as structural glues that bind individual soil particles into water-stable macroaggregates, preventing erosion and improving water infiltration rates.

Soil Chemical Dynamics

Biochar alters soil chemical dynamics through its high surface charge, mineral content, and redox capabilities. Its primary chemical benefit is increasing the soil's Cation Exchange Capacity (CEC). As biochar ages, its surface oxidizes, creating oxygen containing functional groups like carboxylic (-COOH), phenolic (-OH), and carbonyl (>C=O) groups. These groups deprotonate under typical soil pH conditions, generating negative surface charges that electrostatically attract and hold essential plant nutrients like ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}). This retention reduces nutrient leaching into groundwater [13].



Biochar also acts as a sustainable liming agent, particularly in acidic soils. Pyrogenic carbonates, oxides, and hydroxides within the ash fraction dissolve in the soil solution to consume hydrogen ions (H^+), raising the soil pH. This neutralization alleviates aluminum and manganese toxicities while increasing the bioavailability of phosphorus, which is typically immobilized as insoluble iron and aluminum phosphates in acidic soils [14]. Additionally, the aromatic carbon core serves as an electron conduit, facilitating biogeochemical redox transformations that keep nutrients in plant-available forms.

Soil Biological Renaissance

Biochar revitalizes the soil biology by altering the physical habitat and chemical balance of the rhizosphere. Its intricate network of macropores provides a protected refuge for beneficial soil microorganisms, shielding bacteria and mycorrhizal fungi from larger protozoan predators and desiccation stress [15]. By improving aeration, balancing pH, and increasing moisture retention, biochar creates ideal microenvironments that stimulate microbial reproduction and metabolic activity. This biological shift alters the structure of the soil microbial community, often increasing the abundance of plant growth promoting rhizobacteria (PGPR), nitrogen fixing taxa, and arbuscular mycorrhizal fungi (AMF). These fungi extend their hyphae directly into biochar pores to access stored phosphorus and water. Furthermore, biochar adsorbs root-exuded signaling compounds and microbial pheromones onto its surfaces. This concentration of biochemical signals facilitates quorum sensing and speeds up the colonization of plant roots by beneficial microbes. Increased microbial biomass accelerates the cycling of organic matter, leading to greater enzyme production such as urease, phosphatase, and glucosidase that unlocks locked-up organic nutrients for plant uptake [16].

Biochar in Stress Environment Remediation: [i] Degraded and Marginal Soils

Degraded and marginal agricultural soils such as those affected by extreme salinity, sodicity, alkalinity or severe nutrient depletion benefit significantly from biochar applications. In salt-affected, arid soils, high electrical conductivity and osmotic pressure restrict water uptake, causing severe physiological stress in crops. Biochar mitigates salinity stress through its high transient ion-adsorption capacity. It temporarily binds sodium (Na^{+}) and chloride (Cl^{-}) ions within its pore structures and on its surface exchange sites, reducing their concentration in the soil solution and lowering osmotic pressure around root zones.

[Saline Soil Solution] → Biochar Sorbs Excess Na^{+} Ions → Lowers Root Osmotic Stress

↓

Releases K^{+}, $Ca2^{+}$, and Mg^{2+} → Restores Nutrient Balance

Simultaneously, biochar releases soluble nutrients like potassium (K^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) into the soil. This lowers the sodium adsorption ratio (SAR) and corrects nutrient imbalances [17]. In highly alkaline or sodic soils, applying acidic or low-ash biochars neutralizes hydroxyl ions (OH^{-}), improving soil structure and preventing the dispersion of clay particles. For highly weathered, nutrient-depleted tropical soils, biochar acts as a stable structural foundation that stops nutrient leaching, traps organic carbon, and prevents the rapid loss of added chemical fertilizers.

Contaminant Immobilization

Cultivating crops on land contaminated with toxic heavy metals or persistent organic pollutants (POPs) poses serious food safety and ecological risks. Biochar serves as an effective, in-situ remediation agent by binding these pollutants and reducing their bioavailability to crops. Heavy metals like lead (Pb^{2+}), cadmium (Cd^{2+}), Arsenic (As^{3+}), copper (Cu^{2+}), and chromium (Cr^{3+}, Cr^{6+}) are immobilized through several complementary mechanisms [18]:

- Surface complexation with oxygenated functional groups.
- Cation exchange with naturally adsorbed minerals.
- Electrostatic attraction to negatively charged surfaces.
- Direct precipitation as insoluble mineral complexes (e.g., metal carbonates or phosphates) within the ash layer.

[Toxic Heavy Metals] (e.g., Pb^{2+}, Cd^{2+}, Cu^{2+})
- Surface Complexation (Binding with -COOH and -OH)
- Precipitation (Forming insoluble metal carbonates/phosphates)
- Pore Entrapment (Physical immobilization in micropores)

For organic pollutants like pesticides, herbicides, polycyclic aromatic hydrocarbons (PAHs), and emerging microplastics, biochar's highly aromatic carbon sheets offer strong adsorption sites driven by hydrophobic interactions and π-π electron donor-acceptor dynamics. Immobilizing these contaminants within biochar's micropores prevents them from crossing root membranes, protecting food crops from contaminant accumulation.

Climate Change Mitigation

Biochar applications help mitigate global climate change through three main pathways: direct carbon storage, reduced nitrous oxide (N_2O) emissions, and suppressed methane (CH_4) release. Unlike raw crop residues, which rot quickly and return carbon to the atmosphere as (CO_2) within months, biochar locks carbon into a highly stable form. This pyrogenic carbon resists microbial decomposition, allowing it to store carbon for centuries and effectively remove carbon dioxide from the atmosphere.

[Biochar Climate Benefits]
- Direct Carbon Storage (Centuries of Recalcitrant Sequestration)
- Suppressed N_2O Emissions (Alters Denitrification Pathways)
- Reduced CH_4 Flux (Boosts Methanotrophic Activity in Soils)

Furthermore, adding biochar to soil consistently reduces emissions of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential nearly 300 times greater than (CO_2) [19]. It lowers (N_2O) emissions by:

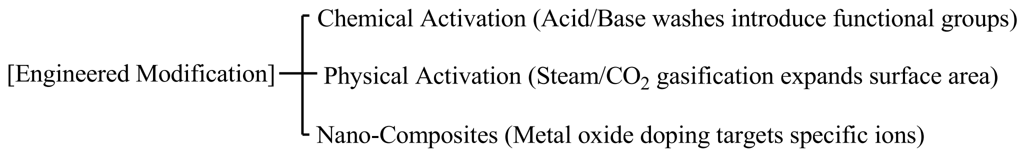
- Improving soil aeration, which prevents the formation of anaerobic pockets that trigger denitrification.
- Promoting the activity of nitrous oxide reductase enzymes, which convert hazardous (N_2O) into harmless atmospheric nitrogen nitrogen gas (N_2) [20].
- Adsorbing excess nitrate (NO_3^-) ions, making them less available to denitrifying bacteria.

In waterlogged environments like rice paddies, biochar reduces methane (CH_4) emissions by improving soil structure and boosting the population of methanotrophic bacteria, which consume methane before it escapes into the atmosphere.

Advanced Biochar Systems-Next Generation Modifications

1. Engineered or Modified Biochars

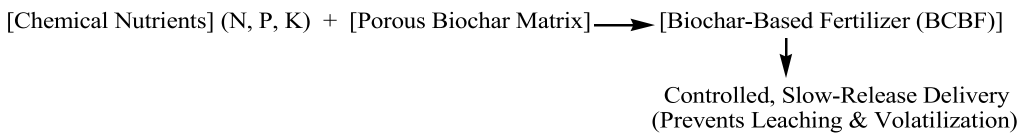
Raw biochar sometimes lacks the surface functionality or structural properties needed to solve complex environmental issues. To overcome these limitations, researchers are developing next-generation engineered or modified biochars using physical, chemical, or biological alterations [21]. Chemical modification involves treating biochar with acidic or basic solutions such as H_3PO_4, HNO_3, or KOH to add specific surface oxygen complexes, expanding its nutrient binding capacity.



Physical activation uses gas streams like steam or CO_2 at high temperatures (>700 ºC) to burn away trapped tars. This process creates an ultra-porous structure with an exceptionally high specific surface area. Additionally, doping biochars with metal oxides or engineered nanoparticles like iron oxides, aluminum oxides, or layered double hydroxides creates specialized magnetic carbon nanocomposites. These materials are highly effective at capturing anionic pollutants like arsenate, chromate, and phosphate from soil solutions, opening up new possibilities for targeted soil remediation.

Biochar-Based Fertilizers (BCBFs)

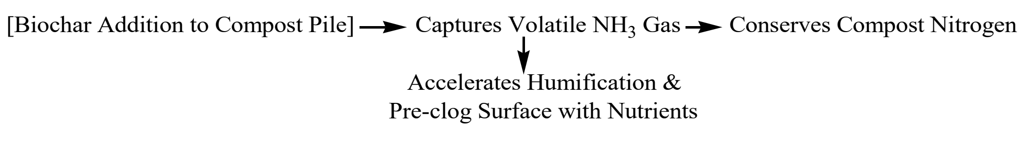
Biochar-Based Fertilizers (BCBFs) are created by blending raw biochar directly with liquid mineral fertilizers or nutrient rich waste streams. The porous carbon matrix absorbs these highly soluble chemical nutrients, turning them into a slow-release format [22]. Instead of dissolving instantly and washing away, nutrients leach out gradually to match the natural growth rate of plant roots. This significantly boosts nutrient use efficiency (NUE) and cuts fertilizer costs for farmers. While raw biochar can store nutrients, it contains few highly bioavailable nutrients itself. To address this, Biochar-Based Fertilizers (BCBFs) are engineered by blending mineral fertilizers with the porous structure of biochar. This process infuses chemical nutrients like nitrogen, phosphorus, and potassium directly into the biochar matrix. The porous carbon framework slowly releases these nutrients over time, matching the uptake rates of growing plants (22). This controlled release improves nutrient use efficiency (NUE) and minimizes losses from nitrate leaching or ammonia volatilization.



Furthermore, BCBFs protect fragile root systems from the fertilizer burn often caused by highly concentrated chemical inputs. By delivering nutrients alongside a stable carbon carrier, BCBFs restore soil carbon levels while supplying necessary plant nutrition, allowing farmers to reduce total mineral fertilizer applications without sacrificing crop yields.

Composting and Co-composting

Adding biochar into organic composting systems provides significant mutual benefits, improving both the composting process and the final product. Adding biochar 5% - 15% by weight to raw composting feedstocks improves pile structure and aeration, preventing compaction and maintaining aerobic conditions [23]. Its high moisture-retention and gas-adsorption capacities capture volatile ammonia (NH_3) and hydrogen sulfide (H_2S) gases, reducing odor issues and conserving valuable nitrogen within the organic compost matrix and accelerates the humification process, resulting in an exceptionally rich organic compost product [24].



Biochar also accelerates the composting process by stimulating microbial metabolism, which shortens the thermophilic phase and speeds up humification. During this co-composting process, the biochar undergoes accelerated "aging." Its surfaces become coated with nutrient-rich organic compounds, humic acids, and beneficial microbes. This pre-conditioning pre-clogs the biochar's binding sites, ensuring that when it is applied to fields, it immediately supports soil fertility rather than temporarily drawing nutrients away from crops.

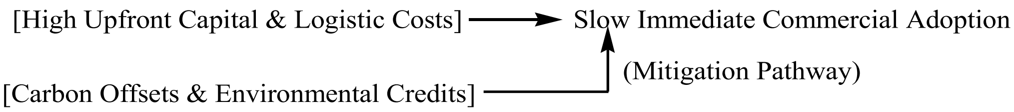
Socio-Economic, Policy, and Field-Scale Challenges

Agronomic Variability

Despite excellent laboratory results, biochar's performance in real-world fields can vary widely. Crop yields may rise dramatically in poor, acidic soils, yet show little to no change in highly fertile, neutral lands [25]. This unpredictability stems from complex interactions between different biochar types, local soil varieties, regional climates, and specific crop choices, making generic, one-size-fits-all recommendations difficult.

Economic Viability

The initial investment required to purchase, transport, and apply biochar remains high for average smallholder farmers. Building industrial pyrolysis plants demands substantial upfront capital, and collecting spread-out crop residues from fields adds high logistical costs [26]. Until supply chains mature and production costs drop, many farmers find it difficult to justify the upfront expense based solely on short-term yield increases.



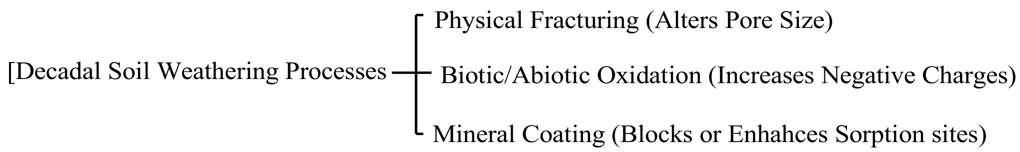
Safety and Life Cycle Assessment

A complete life cycle assessment (LCA) is essential to confirm that biochar production delivers a net environmental benefit. If pyrolysis units lack proper emission controls, they can release volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) into local air supplies [27]. Additionally, handling fine biochar powder can generate dust hazards for workers. These risks highlight the need for standardized safety guidelines and clean, closed-loop production equipment.

Future Directions and Knowledge Gaps

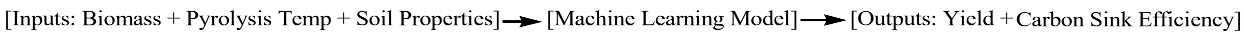
1. Long-Term Aging Effects

Most published research relies on short-term laboratory trials lasting less than three years. We still know very little about industrial pyrolysis plants demands substantial upfront capital, and collecting spread-out crop residues from fields adds high logistical costs [26]. Until supply chains mature and production costs drop, many



Machine Learning and Modeling

The vast diversity of crop residues and pyrolysis combinations makes manual testing slow and expensive. Researchers are beginning to use advanced Machine Learning (ML) models to solve this bottleneck. By feeding algorithms data on feedstock chemistry and pyrolysis temperatures, these models can accurately predict a biochar's final surface area, pH, and nutrient binding capabilities [28]. This allows scientists to design custom biochars for specific soil types digitally before running physical trials.



Smart Policy Integration

To achieve widespread use, biochar needs to be integrated into international carbon trading markets and national farm subsidy programs. Governments can create economic incentives by offering carbon credits to farmers who bury biochar, paying them directly for their carbon storage services. Developing clear certified testing standards for biochar safety and quality will build commercial trust, transforming crop residue recycling from an eco-friendly concept into a routine farming standard.

Conclusion

Converting loose crop residues into engineered biochars offers a powerful, scientifically validated strategy to restore global soil fertility while trapping atmospheric carbon. By shifting from open residue burning to controlled, high efficiency pyrolysis, agriculture can transition toward a sustainable, circular economy. While raw biochar provides reliable physical enhancements, next-generation modifications like BCBFs and co-composted biochars offer targeted solutions for nutrient delivery and contaminant cleanup. Overcoming current adoption barriers will require building efficient biomass supply chains, lowering production costs, and establishing carbon credit frameworks that reward farmers for building healthy, fertile soils.

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