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Review Article

Feedstock selection in biochar production: Implications for properties and application performance

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ABSTRACT

Biochar - a porous, carbon-rich material produced through thermochemical conversion of organic biomass under oxygen-limited conditions - is increasingly applied in soil amendment, environmental remediation, and climate change mitigation. Its properties, and ultimately its utility across these contexts, are determined by the feedstock from which it is produced. This review examines how feedstock classification and compositional characteristics shape biochar properties including yield, elemental composition, surface area, porosity, pH, cation exchange capacity, and contaminant content, drawing on proximate and ultimate analysis, FTIR, BET, and SEM evidence. Seven major feedstock categories are evaluated: Agricultural residues, woody biomass, herbaceous and energy crops, animal manures, slaughterhouse wastes, sewage sludge, and algal biomass. Lignocellulosic feedstocks - particularly wood and crop residues-consistently produce biochars with high carbon stability and well-developed surface area, whereas manure- and sludge-derived biochars are nutrient-rich and strongly alkaline but carry elevated risks of heavy metal accumulation and organic contaminant transfer. Pyrolysis temperature modifies but does not override feedstock-driven property differences: High temperatures raise aromaticity and surface area yet suppress cation exchange capacity and nutrient retention - a trade-off central to rational biochar product design. Application-specific performance in soil amendment, carbon sequestration, heavy metal immobilization, and water remediation is reviewed with feedstock-specific examples, revealing that the optimal feedstock is application-dependent and cannot be determined without reference to the target system.

Keywords: Biochar, Feedstock, Pyrolysis, Physicochemical properties, Soil amendment, Carbon sequestration, Heavy metal remediation

INTRODUCTION

Biochar is produced by the thermal decomposition of organic biomass under oxygen-limited conditions, a process broadly termed pyrolysis, and is distinguished from conventional charcoal by its intended use in soil or environmental applications rather than combustion for energy (Lehmann & Joseph, 2015). Its conceptual roots lie in the terra preta soils of the pre-Columbian Amazon, where deliberate charcoal and organic waste incorporation created anthropogenic dark earths of exceptional fertility that persist to the present - a historical precedent suggesting that pyrogenic carbon can remain stable in soil on millennial timescales. Contemporary interest in biochar reflects several converging pressures: Declining soil organic matter under intensive agriculture, the global imperative to manage mounting volumes of organic waste, and the search for scalable negative emissions technologies. Estimates suggest that sustainable biochar deployment could sequester between 0.7 and 1.8 Pg CO_2 equivalent annually by mid-century, placing it among the more credible carbon dioxide removal strategies under active consideration for climate policy (Lehmann & Joseph, 2015; Lehmann et al., 2006).

Pyrolysis is broadly classified by heating rate and residence time. Slow pyrolysis - low heating rates, residence times of hours, temperatures of 300-600°C - maximizes biochar yield at 25-40% of dry feedstock mass and is the mode most relevant to soil-

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targeted production. Fast pyrolysis favors bio-oil, yielding only 10-25% biochar, while gasification at temperatures above 700°C prioritizes syngas with biochar as a residual (You et al., 2017). Recent progress in optimizing pyrolysis conditions across lignocellulosic feedstock types has further refined understanding of these production pathways (Chen et al., 2024). Each pathway interacts with feedstock composition differently. This interaction is the central concern of the present review, because among all variables governing biochar quality, feedstock type is arguably the most important and most frequently underweighted. A wood-derived biochar and a poultry manure-derived biochar produced under identical conditions can differ by orders of magnitude in surface area, pH, cation exchange capacity, and heavy metal content (Tomczyk et al., 2020; Dukanović et al., 2023). Understanding these feedstock-driven differences is the practical foundation for matching a biochar product to a target application, and this review is structured around that principle - addressing feedstock classification and composition, mechanisms by which feedstock governs biochar properties, the modifying effect of pyrolysis temperature, and application-specific performance.

FEEDSTOCK CLASSIFICATION AND COMPOSITIONAL CHARACTERISTICS

The three structural polymers of plant biomass-cellulose (typically 30-50%), hemicellulose (20-35%), and lignin (15-35%) - decompose at distinct temperatures during pyrolysis and contribute differently to the solid char residue. High-lignin feedstocks yield thermally stable, aromatic biochars because lignin's complex phenylpropanoid structure undergoes extensive polycondensation rather than clean volatilization. Feedstocks dominated by cellulose and hemicellulose produce more volatile-rich chars with lower aromaticity at equivalent temperatures. Non-lignocellulosic feedstocks - manures, sludges, algae - introduce substantial inorganic mineral matrices that alter product chemistry in ways that no pyrolysis adjustment can fully compensate for (Chun et al., 2021; Tomczyk et al., 2020). Table 1 summarizes the compositional characteristics of the principal feedstock categories discussed below.

Agricultural residues

Cereal straws, husks, maize stover, sugarcane bagasse, and cotton stalks are among the most globally abundant and geographically dispersed biochar feedstocks. Their wide availability and negligible cost make them attractive at scale, though seasonal availability and competition with alternative uses - animal fodder, direct incorporation - create logistical constraints (Duku et al., 2011). Rice straw is notable for its unusually high silica content (SiO_2 up to 20% of ash), which imparts an inorganic character to the resulting biochar and partially limits pore development (Jaiswal et al., 2021). Wheat straw and maize stover biochars typically exhibit moderate surface areas (5–50 m^2/g), mildly alkaline pH, and carbon contents of 40–65% under slow pyrolysis at 400–550°C (Dukanović et al., 2023; Uzoma et al., 2016). Despite their moderate individual property profiles, agricultural residue biochars have demonstrated consistent benefits for soil organic carbon accumulation and N_2O emission reduction in multiple review assessments (Harisa et al., 2024).

Woody and forestry biomass

Wood-derived feedstocks-hardwoods, softwoods, bark, and nut shells - produce biochars with consistently high carbon content, well-developed microporous structure, and strong thermal stability. This reflects the characteristically high lignin content of woody biomass (25-35%), which drives extensive polycondensation to form stable aromatic carbon frameworks (Tomczyk et al., 2020). BET surface areas for wood biochars commonly exceed 100-400 m^2/g at temperatures above 500°C, and carbon content routinely reaches 65-85%. Hardwoods generally yield slightly more biochar than softwoods owing to their greater lignin proportion and denser cell walls. Forestry residues - sawdust, bark, processing off-cuts - represent significant and readily accessible waste streams with established supply chains and low moisture content, making them among the most straightforward materials to process at commercial scale (Ahmed et al., 2024).

Herbaceous and energy crops

Dedicated energy crops–switchgrass, Miscanthus, and herbaceous species such as goldenrod - are increasingly considered as purpose-grown biochar feedstocks on marginal land. Łapczyńska-Kordon et al., (2021) characterized goldenrod-derived biochar and reported moderate surface area values (28-75 m^2/g) and mildly alkaline pH, with mineral nutrient content exceeding that of typical wood biochars. Switchgrass produces biochars with carbon content of approximately 55-65% and has been studied in life cycle contexts given the US interest in dedicated bioenergy crops (Lehmann et al., 2006). Land-use competition with food production and the risk of indirect land-use change emissions are persistent concerns - factors that can erode or reverse apparent climate benefits when accounted for in full life cycle calculations.

Animal manures

Cattle, swine, poultry, and more specialized manure feedstocks such as yak dung are characterized by high ash contents (30-60%), elevated phosphorus, potassium, and nitrogen concentrations, and - in intensively managed systems - the potential presence of veterinary antibiotics and antibiotic resistance genes (Rathnayake et al., 2023). These properties produce strongly alkaline biochars (pH 9-12), moderate CEC, and comparatively low surface areas, with mineral ash physically limiting pore development even at high pyrolysis temperatures. Sarfaraz et al., (2020) demonstrated measurable differences in carbon mineralization rates between poultry manure and cattle dung biochars, with poultry-derived material mineralizing faster - an important distinction where long-term carbon stability is the objective. Zhang et al., (2019) found that increasing pyrolysis temperature from 300°C to 600°C in yak manure biochar systematically raised pH and fixed carbon content while reducing water-soluble nutrient fractions, highlighting the inherent tension between stability and nutrient availability that characterizes this feedstock class.

Slaughterhouse waste and animal bones

Slaughterhouse residues - blood meal, meat and bone meal, and raw bone - are chemically distinct from other manure-class feedstocks. Nega et al., (2022) demonstrated that slaughterhouse waste biochar carries elevated nitrogen and phosphorus concentrations, positioning it as a slow-release fertilizer candidate in nutrient-depleted soils. Bone-derived biochars are particularly notable for their high hydroxyapatite content, which drives exceptional phosphate retention capacity and makes them well-matched to phosphorus-contaminated water treatment applications (Koron et al., 2016). Azeem et al., (2022) documented substantial shifts in bacterial community composition and microbial biomass in smelter-contaminated soils following cow bone biochar application, attributed to the distinct mineral chemistry and strong liming effect of this feedstock class.

Sewage sludge

Sewage sludge is simultaneously nutrient-rich, abundantly available as a municipal wastewater by-product, and problematic as a biochar feedstock. Sludge biochars frequently contain elevated concentrations of zinc, copper, cadmium, lead, and nickel, alongside Polycyclic Aromatic Hydrocarbons (PAHs) and micropollutants that restrict land application without extensive quality verification (Agrafioti et al., 2013; Noor et al., 2023). Heavy metals are concentrated rather than destroyed during pyrolysis, and PAHs can form newly through volatile condensation at char surfaces. Co-pyrolysis of sludge with lignocellulosic biomass has been reported to reduce heavy metal mobility in the resulting biochar by up to 93% in some cases, representing a promising route to safer sludge utilization, though regulatory acceptance remains inconsistent across jurisdictions (Noor et al., 2023).

Algae and aquatic biomass

Algal and aquatic biomass feedstocks are characterized by near-absence of lignin, high protein content, and elevated mineral concentrations including potassium, calcium, and magnesium. These properties translate into biochars with high CEC and strong alkalinity but modest surface areas, constrained by the absence of a structured lignocellulosic pore network (Chun et al., 2021). A recent meta-analysis found that aquatic biomass-derived biochars exhibited the highest mean CEC across all feedstock categories, though this was accompanied by elevated electrical conductivity that may pose salinity risks under intensive soil application (Thompson et al., 2025). Interest in algal biochar is growing particularly in the context of wastewater-grown microalgae, where nutrients removed during cultivation are partially recovered through subsequent pyrolysis - a coupling that aligns with circular nutrient management principles (Table 1).

Table 1. Feedstock classification and key compositional characteristics for biochar production.

Feedstock category	Examples	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture (%)	Ash (%)	Biochar C content (%)	Key references
Agricultural residues	Rice straw, wheat straw, maize stover	30-45	20-30	10-20	8-15	10-25	40-65	Harisa et al. (2024)
Woody biomass	Oak, pine, bamboo, sawdust, nut shells	40-50	20-35	25-35	10-20	1-5	65-85	Tomczyk et al. (2020); Ahmed et al. (2024)
Herbaceous/ Energy crops	Switchgrass, Miscanthus, goldenrod	35-45	25-35	15-25	8-14	3-10	55-70	Łapczyńska-Kordon et al. (2021)
Animal manure	Cattle, poultry, swine, yak dung	8-20	5-15	5-15	50-80	30-60	25-50	Rathnayake et al. (2023); Zhang et al. (2019)
Slaughterhouse waste/bones	Meat and bone meal, blood meal, raw bone	-	-	-	30-60	40-70	20-45	Nega et al. (2022); Koron et al. (2016)
Sewage sludge	Municipal wastewater treatment sludge	5-15	3-10	3-8	60-85	30-55	15-35	Agrafioti et al. (2013)
Algae/Aquatic biomass	Microalgae, macroalgae, duckweed	<5	<5	<2	80-90	10-30	25-45	Chun et al. (2021); Thompson et al. (2025)

Note: Ranges compiled from multiple studies; values represent typical reported ranges and may vary with geographic origin, seasonal variation, processing history, and measurement method. '-' = not applicable or negligible.

INFLUENCE OF FEEDSTOCK ON BIOCHAR PROPERTIES

The transformation of raw biomass into biochar involves dehydration, depolymerization, aromatization, and condensation reactions whose extent and products are tightly linked to initial feedstock composition. The following subsections trace how feedstock type shapes each major biochar property, drawing on proximate and ultimate analysis, FTIR spectroscopy, BET surface analysis, and SEM characterization.

Biochar yield

Biochar yield - expressed as mass of char per unit mass of dry feedstock - varies considerably across feedstock types. At slow pyrolysis temperatures of 400-550°C, wood-derived biochars typically achieve yields of 25-35%, while manure and sludge-derived materials yield 35-55%, primarily because their high mineral ash content does not volatilize during pyrolysis (Rathnayake et al., 2023; Tomczyk et al., 2020). High-lignin feedstocks produce greater yields than cellulose-rich materials because lignin decomposes more gradually, contributing disproportionately to the solid char residue. Yield decreases with increasing temperature across all feedstock types, though the rate of decline is steeper for low-lignin materials where the volatile fraction is larger and lost more completely at higher temperatures (Li et al., 2023). This yield trade-off has practical relevance for system economics: High-ash feedstocks like manure and sludge produce more biochar per ton of input, but much of that mass is inorganic and contributes little to carbon sequestration or sorption capacity.

Elemental composition and carbon stability

Carbon content in biochar ranges from approximately 15% in sewage sludge biochars to over 85% in wood chars produced at high temperatures (Dukanović et al., 2023). The H/C and O/C molar ratios - proxies for aromaticity and polarity, respectively - are used to assess carbon stability and classify biochars under frameworks such as those of the International Biochar Initiative, which recommends H/C below 0.7 and O/C below 0.4 for stable carbon storage grades. Wood and crop residue biochars readily meet these thresholds at temperatures above 450°C, whereas manure-derived biochars often display elevated O/C ratios even at higher temperatures, attributable to the persistence of inorganic oxygenated mineral phases (Tomczyk et al., 2020). Nitrogen content shows the reverse trend: manure, sludge, and bone biochars contain considerably more nitrogen (often 2-6%) than lignocellulosic counterparts (<1%), with implications for nitrogen cycling, the risk of N_2O emissions from amended soils, and fertilizer value. Ultimate analysis of diverse feedstocks confirms that carbon, hydrogen, nitrogen, and oxygen proportions in the parent material are reliably predictive of their distribution in the resulting biochar, underscoring the primacy of feedstock selection in any deliberate biochar design process.

Ash content, pH, and liming potential

Ash content directly reflects the inorganic mineral fraction of the feedstock and ranges from 1-5% in wood biochars to 30-60% in manure and sludge-derived chars, driven by mineral-rich diets and the concentration of inorganics during wastewater treatment (Agrafioti et al., 2013). Proximate analysis confirms that fixed carbon and volatile matter are inversely related to ash content across feedstock categories. High ash content confers strongly alkaline pH (typically 8-12) through the abundance of calcium, magnesium, and potassium carbonates and oxides - a property that makes high-ash biochars particularly valuable as liming agents in acidic soils (Hoque et al., 2023). A contradictory effect is that high mineral content can impede pore development, as inorganic particles partially block the char matrix, reducing surface area relative to lignocellulosic counterparts at equivalent temperatures. The liming capacity of manure-derived biochars has been consistently reported as substantially greater than that of wood or straw biochars applied at equivalent rates - a practical advantage in the management of acid agricultural soils common across humid tropical regions.

Surface area, porosity, and pore structure

The BET surface area and pore architecture of biochar govern its sorption capacity, water retention, and suitability as a microbial habitat - properties of direct relevance to both soil amendment and remediation applications. Lignocellulosic biochars - particularly those from wood, nut shells, and bamboo - exhibit the highest surface areas, commonly reaching 200-600 m^2/g at temperatures above 600°C, reflecting the well-defined vascular pore network of woody tissues that is progressively opened as volatile matter is expelled (Xiao et al., 2018). Agricultural residue biochars show intermediate values (5-100 m^2/g), while manure, sludge, and algal biochars consistently fall below 20 m^2/g, with mineral blockage being the principal constraint (Tomczyk et al., 2020). SEM imaging confirms that manure biochars display irregular, partially occluded pore architectures compared to the ordered, open channel structures of wood-derived chars. Mesopores (2-50 nm) predominate in agricultural and wood biochars, favouring adsorption of mid-molecular-weight organic contaminants, while macropores in manure biochars may better accommodate microbial colonization and soil aggregate formation.

Cation exchange capacity and surface functional groups

Cation exchange capacity quantifies biochar's ability to retain and exchange positively charged nutrient ions, a property of direct agronomic significance. CEC is primarily associated with carboxylic, phenolic, and carbonyl surface groups detectable by FTIR as absorption bands near 1700-1720 cm^{-1} (C=O stretch) and 3300-3500 cm^{-1} (O-H stretch). Notably, CEC is inversely related to pyrolysis temperature and tends to be higher in manure and aquatic biomass biochars than in wood chairs, because low-temperature biochars retain a greater density of oxygenated functional groups on their surfaces (Thompson et al., 2025; Tomczyk et al., 2020). Gaskin et al., (2008) found significantly higher CEC for poultry litter biochar (38.3 cmol/kg) than for peanut hull (4.6 cmol/kg) and pine chip (5.0 cmol/kg) biochars produced at 500°C, with the superior CEC of manure-derived chars attributed to a greater abundance of oxygenated surface functional groups - a finding with practical implications for nutrient retention in sandy or leaching-prone soils where surface charge is the primary mechanism retaining ammonium and potassium against rainfall-driven loss (Tomczyk et al., 2020).

Heavy metals and organic contaminants

From a regulatory and risk perspective, the contaminant profile of biochar is the most consequential feedstock-dependent property. Sewage sludge biochars routinely contain elevated zinc, copper, cadmium, lead, and nickel concentrations, reflecting industrial and household inputs to wastewater streams (Agrafioti et al., 2013). Pyrolysis reduces the bio-accessibility of heavy metals by converting them from soluble to more stable mineral phases, but total metal concentrations remain elevated and can re-mobilize under acidic soil conditions. PAHs can form de novo during pyrolysis through condensation of volatile hydrocarbons at char surfaces, with concentrations peaking at intermediate temperatures (400-600°C) and highest in feedstocks with high volatile matter content (Noor et al., 2023). Animal manure biochars may carry residual veterinary antibiotics, though most compounds are effectively degraded at temperatures above 400°C. Wang et al. (2020) reviewed long-term heavy metal immobilization by biochar across multiple soil types and documented a consistent risk: Soil acidification over time progressively weakens initial immobilization gains, with this temporal de-stabilization more pronounced for lower-buffering-capacity wood biochars than for self-liming manure or bone chars. This finding underlines the need to match not only the biochar type to the application, but to account for the evolving chemistry of the receiving soil environment.

Nutrient content

While biochar is not conventionally classified as a fertilizer, feedstock type strongly determines its direct nutrient contribution to amended soils. Bone and slaughterhouse biochars are distinguished by high phosphorus content (5-15% P_2O_5), primarily as hydroxyapatite, which releases phosphate slowly under field conditions and is less susceptible to leaching than soluble inorganic fertilizers (Nega et al., 2022). Poultry manure biochars carry the highest nitrogen concentrations among common feedstocks (2-5% N), and their application has produced measurable plant nitrogen benefits in short-term crop experiments (Sarfaraz et al., 2020). Wood and straw biochars contribute negligible direct nutrient supply but improve nutrient retention capacity through their sorption properties and soil physical improvements - a distinction that matters for long-term fertility management but is often lost in studies that measure only short-term crop responses (Table 2).

Table 2. Comparative biochar properties by feedstock type (Slow pyrolysis, 400-600°C).

Feedstock	Yield (%)	C content (%)	H/C molar ratio	pH	BET surface area (m^2/g)	CEC (cmol/kg)	Ash (%)
Woody biomass	25-35	65-85	0.3-0.5	7.5-9.5	100-400	5-20	1-5
Agricultural residues	28-38	40-65	0.4-0.7	7.0-10.0	5-80	10-35	10-25
Herbaceous/ energy crops	27-36	50-70	0.4-0.6	7.5-9.5	10-100	8-30	5-15
Poultry manure	40-55	30-50	0.5-0.8	9.0-11.5	2-15	35-80	35-55
Cattle/swine manure	35-50	25-45	0.6-0.9	8.5-11.0	1-12	30-70	30-50
Slaughterhouse /bone	35-50	20-45	0.4-0.7	9.5-12.5	2-25	20-50	40-70
Sewage sludge	35-55	15-35	0.5-0.9	7.0-9.5	1-20	15-40	30-55
Algae/Aquatic biomass	30-45	25-45	0.5-0.9	8.5-11.0	1-15	40-90	10-30

Sources: Tomczyk et al. (2020); Gaffar et al. (2021); Rathnayake et al. (2023); Sarfaraz et al. (2020); Zhang et al. (2019); Gunamantha & Widana (2021); Agrafioti et al. (2013); Thompson et al. (2025); Łapczyńska-Kordon et al. (2021).
Note: Values represent typical ranges and vary with specific pyrolysis conditions, feedstock origin, and measurement protocols.

EFFECT OF PYROLYSIS TEMPERATURE ON FEEDSTOCK-DERIVED BIOCHARS

Pyrolysis temperature modifies - but does not override - the property differences established by feedstock composition. As temperature rises from 300°C to 700°C, virtually all biochars exhibit increasing carbon content, pH, surface area, and aromatic ring condensation, alongside decreasing yield, volatile matter, H/C ratio, O/C ratio, and CEC (Tomczyk et al., 2020; Li et al., 2023). The direction of these trends is broadly consistent across feedstock categories; the magnitude is not.

In wood-derived biochars, the temperature-driven expansion of surface area is the most dramatic: A wood biochar produced at 700°C may exhibit surface area ten to twenty times greater than one produced at 300°C, reflecting the progressive opening and coalescence of micropores as volatile organic matter is expelled (Li et al., 2023; Zhu et al., 2024). For manure-derived biochars, this gain is substantially more modest - inorganic mineral phases constrain pore development regardless of how high the pyrolysis temperature is set (Tomczyk et al., 2020). Khan et al., (2022) observed that the pH of manure biochars reaches a plateau at lower temperatures than crop residue biochars, likely because inorganic carbonate decomposition - the primary alkalinity driver in mineral-rich feedstocks - occurs at lower temperatures than the surface de-protonation reactions that govern pH development in lignocellulosic chars.

A persistent debate in the literature concerns whether temperature or feedstock type is the stronger driver of final biochar properties. Meta-analytical evidence suggests a context-dependent hierarchy: Below approximately 400°C, feedstock composition dominates CEC, nutrient content, and pH responses; above 600°C, temperature becomes the stronger predictor of surface area and carbon stability, yet feedstock continues to govern ash loading, heavy metal concentrations, and the pH ceiling that temperature can reach (Thompson et al., 2025; Li et al., 2023). The practical implication is that optimizing biochar for a specific application requires treating feedstock selection and pyrolysis temperature as interdependent design variables rather than independent choices. Selecting a high-lignin feedstock and processing it at high temperature targets carbon sequestration and sorption applications; selecting a nutrient-rich manure and pyrolysing at moderate temperature preserves CEC and nutrient availability for soil amendment goals - choices that cannot be made from pyrolysis conditions alone.

BIOCHAR PERFORMANCE ACROSS ENVIRONMENTAL APPLICATIONS

Biochar performance is always mediated by the characteristics of the receiving system - soil texture, pH, climate, contaminant chemistry - so cross-study generalizations require caution. Nonetheless, coherent feedstock-dependent patterns emerge from the accumulated evidence and are reviewed here across four major application domains.

Soil amendment and crop productivity

Soil amendment is the most widely studied biochar application, and the variability of crop yield responses-ranging from significant gains to occasional penalties-is substantially explained by feedstock type. Manure-derived biochars, with their high nutrient loads and strong liming effect, tend to produce the greatest yield improvements in acidic, nutrient-depleted soils (Rathnayake et al., 2023; Sapkota et al., 2022). Wood and straw-derived biochars show more modest and less consistent direct yield effects in already-fertile soils, but reliably improve soil physical properties - bulk density, water holding capacity, aggregate stability - with benefits that may compound over multiple growing seasons (Siedt et al., 2021; Hoque et al., 2023).

Rajkovich et al. (2012) evaluated biochars from hardwood, corn stover, food waste, and manure applied to a temperate soil and found that manure-derived biochar significantly enhanced plant nitrogen uptake, while hardwood biochar improved water retention with negligible nitrogen benefit - a divergence that maps directly onto the property differences documented. Abideen et al., (2020) demonstrated improved photosynthetic efficiency and antioxidant defence in Phragmites karka under drought stress following biochar application, with the physiological benefit attributable to improved soil water retention and altered root zone chemistry. Harisa et al., (2024) reviewed agricultural waste biochars and concluded that rice straw and sugarcane bagasse biochars provided consistent benefits to soil organic carbon accumulation and N_2O emission reduction, though effect magnitude varied considerably with soil type and application rate - a reminder that feedstock-specific benefits are not uniformly transferable across pedo-climatic contexts.

Carbon sequestration

Sequestration efficacy depends primarily on the stability of the aromatic carbon framework, assessed through H/C molar ratio, the recalcitrance index (R_{50}), or mean residence time from incubation and field studies (Harvey et al., 2012; Wang et al., 2016). Woody and nut-shell biochars - with H/C ratios consistently below 0.5 and dominated by fused aromatic ring systems - demonstrate the greatest carbon stability and longest estimated residence times under temperate soil conditions (Xiao et al., 2018; Lehmann & Joseph, 2015). Manure and sludge biochars are generally considered less stable owing to higher aliphatic and oxygenated carbon fractions, though Thompson et al., (2025) noted that the high mineral ash content of manure biochars may physically protect carbon from microbial decomposition - a mechanism that could partially offset their lower intrinsic chemical recalcitrance and challenges the prevailing assumption that lignocellulosic feedstocks are categorically superior for sequestration. Sapkota et al., (2022) provided direct experimental evidence for this contrast, demonstrating that plant-derived biochars showed significantly greater resistance to mineralization over a 12-month incubation than animal residue counterparts under standard soil conditions.

Heavy metal immobilisation in contaminated soils

Biochar reduces heavy metal bioavailability through surface complexation, precipitation as hydroxides or carbonates, electrostatic retention on negatively charged surfaces, and physical occlusion within pores (Amin et al., 2020; Wang et al., 2020). Feedstock determines which of these mechanisms dominates. High-ash, alkaline biochars from manure and bone are most effective in acidic contaminated soils, primarily through pH elevation and metal precipitation (Azeem et al., 2022; Koron et al., 2016). Amin et al., (2020) compared six feedstocks for their capacity to reduce heavy metal uptake by wheat grown in contaminated soil, finding bone meal biochar most effective for cadmium and lead - attributed to hydroxyapatite-mediated phosphate co-precipitation of these metals. Wang et al., (2020) documented that while initial immobilization is high across most feedstocks, soil acidification over time progressively weakens this effect, with the risk more pronounced for lower-buffering-capacity wood biochars. This temporal de-stabilization of remediation performance is a significant gap in multi-year field evidence.

Water and wastewater remediation

In water treatment contexts, surface area, pore volume, and functional group chemistry drive performance. High-surface-area lignocellulosic biochars - particularly activated variants - are among the most effective low-cost adsorbents for organic pollutants including antibiotics, dyes, and herbicides (Xiao et al., 2018). Bone-derived biochars are uniquely effective for phosphate removal from eutrophied water, exploiting their calcium-rich surface chemistry to promote hydroxyapatite nucleation (Koron et al., 2016). Algal and sludge biochars, despite modest surface areas, show promise for nitrogen and phosphorus recovery from wastewater, reflecting their inherent chemical affinity for these elements. The feedstock–application match in water remediation is arguably the most straightforward to predict: Performance can largely be anticipated from the physicochemical properties, often without exhaustive empirical screening of every candidate material.

CONCLUSION

This review has demonstrated, through systematic examination of feedstock composition, biochar property data, and application performance evidence, that feedstock type is one of the most persistent determinant of biochar characteristics - one whose influence cannot be overridden by adjusting pyrolysis conditions alone. Lignocellulosic feedstocks, particularly woody biomass, produce biochars with high carbon stability, large surface areas, and low ash content, making them most suited to carbon sequestration and sorption-based remediation. Manure, bone, and sludge-derived biochars are nutrient-rich and strongly alkaline, positioning them as effective soil amendments in degraded and acidic systems, but their contaminant burdens and lower carbon stability impose constraints that must be explicitly managed and verified.

No single feedstock is universally optimal. The choice is application-specific, and the property trade-offs documented here - surface area versus CEC, carbon stability versus nutrient content, contamination risk versus liming capacity - define a decision space that must be navigated with site-specific knowledge. Pyrolysis temperature is best understood as a supportive tuning parameter operating within the boundaries set by feedstock composition rather than an independent lever capable of compensating for a poorly chosen feedstock. The feedstock-property-application linkages synthesized in this review provide a practical framework for rational biochar selection.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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