

BIOCHAR: DEFINITION, PROPERTIES, PRODUCTION METHODS, AND ENVIRONMENTAL APPLICATIONS IN ROMANIA

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RESEARCH ARTICLE

Abstract

Biochar is a stable, carbon-rich material produced through the thermochemical conversion of biomass in oxygen-limited conditions. Its scientific relevance has grown due to its dual capacity to enhance soil quality and retain carbon in long-lasting forms. This paper provides an integrated overview of biochar, outlining its definition, production pathways, key biomass feedstocks, and the physicochemical properties that determine its environmental functionality. Typical characteristics such as high aromatic carbon content, porous structure, and alkaline pH support improvements in soil structure, nutrient retention, and crop performance, while also enabling the adsorption of pollutants in contaminated environments. Given Romania's substantial agricultural and forestry sectors, the country generates large quantities of residual biomass suitable for biochar production. This positions Romania favourably for developing biochar-based strategies within circular economy frameworks and national climate objectives. The article examines the main application areas relevant to Romania, including agricultural soil amendment, environmental remediation, renewable energy integration through pyrolysis co-products, and long-term carbon sequestration. Representative examples of Romanian feedstocks and expected biochar yields are outlined, together with an assessment of the potential CO₂ removal associated with biochar use. Overall, this study highlights the relevance of biochar as a multifunctional tool for sustainable resource management and environmental protection in Romania.

Keywords: Biochar; Pyrolysis; Biomass Feedstocks; Soil Amendment; Carbon Sequestration.

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INTRODUCTION

Over the last two decades, biochar has emerged as one of the most promising tools in environmental protection and sustainable land management. Its scientific relevance derives from the wide range of functions it can perform in soils and ecosystems, far beyond its origin as a thermochemically converted biomass. Numerous studies demonstrate that biochar can substantially influence soil physical, chemical, and biological processes by improving structure, enhancing nutrient retention, increasing water-holding capacity, and supporting microbial activity (Lehmann & Joseph, 2015; Jeffery et al., 2017). These effects contribute to more resilient and productive soils across diverse climatic conditions, including those affected by drought, erosion, or nutrient depletion (Mandal et al., 2023).

Modern interest in biochar is rooted in historical observations of the Amazonian *terra preta* soils, where char-enriched anthropogenic horizons remained fertile for centuries,

illustrating the long-term stability and agronomic potential of carbonized biomass (Glaser et al., 2001). Today, controlled pyrolysis technologies allow the conversion of a wide variety of agricultural, forestry, and organic residues into stable carbon-rich materials with well-defined physicochemical characteristics (Tripathi et al., 2016). Depending on the feedstock and production parameters, biochar can function as a soil amendment, pollutant adsorbent, remediation tool, or long-lasting carbon sink with measurable climate benefits (Ahmad et al., 2014; Beesley et al., 2011).

Romania offers a particularly relevant context for biochar development due to its substantial biomass resource base and its environmental challenges. More than half of the country's land area is used for agriculture, and nearly one-third is covered by forests, generating large quantities of biomass residues from cereal cropping, maize cultivation, viticulture, horticulture, livestock systems, and wood processing (Eurostat, 2023). Many of these residues remain underutilized or are managed in ways that contribute to carbon

losses and local pollution (Figure 1). Converting them into biochar provides a strategic opportunity to integrate waste valorization with soil restoration, circular economy objectives, and national climate mitigation efforts. Research from Eastern Europe also supports the effectiveness of biochar in improving degraded soils, reducing nutrient leaching, and immobilizing contaminants in post-industrial landscapes (Gheorghe-Bulmău et al., 2022).

Considering these scientific, environmental, and regional factors, biochar emerges as a versatile and impactful solution for Romania. The present paper examines biochar from a comprehensive perspective, detailing its production methods, biomass feedstocks, physicochemical properties, and major environmental applications, with particular emphasis on its potential contribution to sustainable agriculture and environmental protection in Romania.

MATERIALS AND METHODS

Biomass Feedstocks Considered

This study evaluates a broad range of biomass feedstocks suitable for biochar production in Romania, reflecting the extensive diversity documented in international biochar standards and scientific literature. More than 60 distinct feedstock categories are recognized in biochar research, particularly within the European Biochar Certificate and EU renewable energy classification systems (Lehmann & Joseph, 2015; EBC, 2022). These categories include agricultural, forestry, agro-industrial, municipal, and animal-derived materials, many of which are widely available across Romania. Major agricultural feedstocks include cereal straws (wheat, barley, rye, oats), corn stover, maize cobs, sunflower husks, rapeseed straw, soybean residues, and biomass from vegetable and horticultural production. These residues represent some of the most abundant lignocellulosic feedstocks in Romania and have been widely described as suitable substrates for slow pyrolysis (Tripathi et al., 2016; Mandal et al., 2023).

Permanent crop systems contribute significant quantities of pruned biomass from vineyards, orchards, and berry plantations, all listed among recommended biochar feedstocks due to their favourable carbon content and low contamination risk (Ahmad et al., 2014). Forestry related materials such as hardwood and softwood chips, sawdust, bark, and thinning

residues remain among the most important and stable sources for high-quality biochar with high fixed carbon content (Beesley et al., 2011).

Additional feedstock classes include agro-industrial residues (grain-processing by-products, oilseed husks, fruit pomace, winery and stillery waste), livestock derived feedstocks (manure, poultry litter, digestate solids), and municipal bio-waste, all recognized as viable in international research frameworks (Sohi et al., 2010; EBC, 2022).

According to European agricultural statistics, Romania produces one of the largest biomass surpluses in Eastern Europe, offering a feedstock portfolio that spans nearly all major categories listed in EU directives (Eurostat, 2023). The conceptual feedstock distribution relevant to Romania is illustrated in Figure 1.

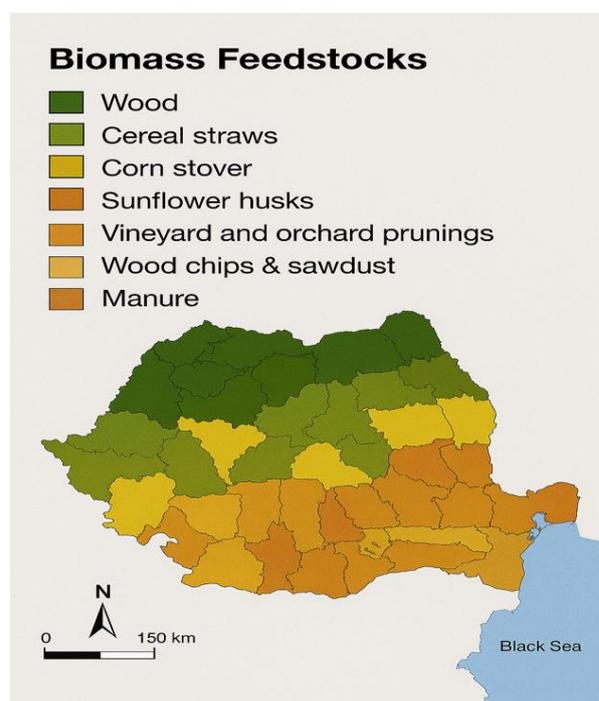


Figure 1. Biomass feedstock distribution across Romania (author's own contribution, 2025).

During autothermal slow pyrolysis, biomass is typically heated to 400–550°C, where lignocellulosic components (cellulose, hemicellulose, lignin) undergo sequential thermal decomposition. This process yields three main product fractions: solid biochar, condensable vapors (bio-oil/tars), and non-condensable gases (Li et al., 2023). The proportion of these outputs depends on temperature, heating rate, residence time, and feedstock type, with higher lignin content generally enhancing biochar aromaticity and stability (Wang et al., 2022). The reactor

configuration illustrated in **Figure 2** (author's own contribution, 2025) represents a typical modern autothermal unit

Biomass residues enter the system, where controlled partial oxidation reactions generate hot gases that circulate internally to maintain reactor temperature. A portion of these gases passes through a flue-gas heat exchanger, producing useful heat for external applications such as drying or low-temperature industrial processes (Singh et al., 2024). The remaining exhaust stream is directed through a filtration unit before release, ensuring minimal particulate emissions and compliance with current environmental standards (Zhao et al., 2023).

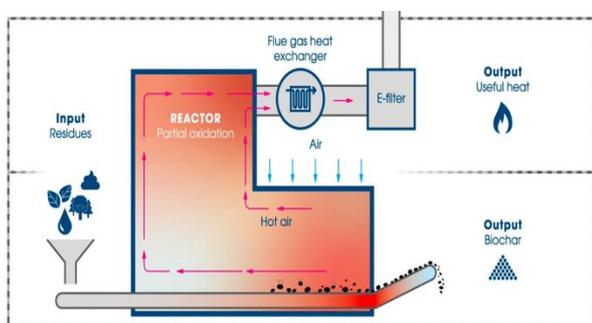


Figure 2. Autothermal slow-pyrolysis reactor schematic (author's own contribution, 2025).

Pyrolysis Process Description

Autothermal slow pyrolysis has become the technological pathway for biochar production in recent years due to its high carbon-retention efficiency, reduced external energy demand, and significantly improved environmental performance. Modern systems operate under partial oxidation, a controlled sub-stoichiometric air supply that provides just enough oxygen to sustain internal heating reactions without fully combusting the biomass (Zhang et al., 2023; Yu & Chen, 2022). This approach enables “self-sustaining” thermochemical conversion, eliminating the need for external fuel inputs and increasing overall system efficiency.

Heating rates in slow pyrolysis are intentionally maintained at low to moderate levels (5–15°C/min) to favour secondary carbonisation reactions and promote the formation of highly aromatic, recalcitrant carbon structures (Li et al., 2022). Under optimized conditions, autothermal systems typically generate 25–35% biochar on a dry-feedstock basis, making them particularly suitable for climate-positive applications where carbon permanence is essential. Overall,

autothermal slow pyrolysis combines stable biochar production with renewable heat generation, offering a highly efficient route for converting Romania's diverse biomass resources into carbon-negative materials.

Biochar Characterisation Framework

The characterisation of biochar is essential for understanding its environmental behaviour and functional performance in soils. Recent analytical approaches focus on physicochemical parameters that influence nutrient dynamics, sorption capacity, carbon stability, and broader agroecosystem benefits (Zhang et al., 2023; Li et al., 2022). The properties examined in this study were selected based on the most recent literature and current standardisation guidelines.

Carbon content and elemental composition. Carbon concentration remains the principal indicator of biochar stability and long-term persistence. Contemporary studies report that biochars produced from lignin-rich feedstocks under slow-pyrolysis conditions often contain 70–80% carbon on a dry basis, reflecting a high degree of aromatic condensation (Wang et al., 2022). Elemental ratios (H/C and O/C) were used as proxies for aromaticity, structural order, and carbon permanence.

Ash content and mineral composition. Ash represents the inorganic fraction of biochar and varies substantially with feedstock origin. Current analyses highlight the relevance of mineral constituents such as Ca, K, Mg, P, and Si, which can contribute to nutrient supply and pH buffering in soils (Yu & Chen, 2022). High-ash biochars derived from manure, digestate, or crop residues often exhibit liming effects, particularly in acidic soils common in several Romanian regions.

Surface area and porosity. Pore architecture strongly influences water retention, microbial habitat formation, and pollutant adsorption. Recent characterisation studies employing N₂-BET analysis and mercury porosimetry show that wood-derived biochars typically exhibit well-developed micro- and mesopores, whereas agricultural-residue biochars present broader pore distributions due to their more heterogeneous structures (Zhao et al., 2023). A conceptual representation of these features is shown in **Figure 3 (author's own contribution, 2025)**.

pH and cation exchange capacity (CEC). Biochars produced at moderate

temperatures generally display alkaline pH values, largely due to the presence of basic oxides and carbonates. This alkalinity can help correct soil acidity and improve nutrient retention. CEC gradually increases as biochar oxidises in soil, enhancing its ability to retain cations and interact with dissolved nutrients (Mandal et al., 2023).

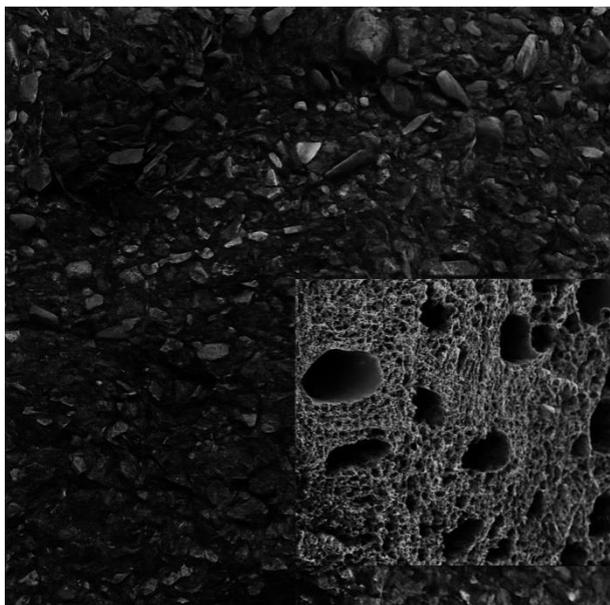


Figure 3. SEM microstructure of biochar showing the characteristic porous network (author's own contribution, 2025).

Aromaticity and stability indicators. Aromatic carbon structures are central to biochar's long-term carbon sequestration potential. Current standards classify biochars with H/C ratios below 0.4 and O/C ratios below 0.6 as highly stable materials capable of persisting in soils for decades to centuries (EBC, 2022). These indices are widely used to assess suitability for carbon removal initiatives and climate-oriented applications.

Together, these physicochemical parameters define the functional profile of biochar and guide its selection for specific environmental applications, including soil amendment, contaminant immobilisation, and carbon sequestration. Representative values from recent studies are summarised in the Results and Discussion section.

Analytical Approach

The analytical approach used in this study follows a structured methodology designed to integrate recent scientific evidence with the Romanian environmental context. The selection of biomass feedstocks was based on current European and national resource assessments, which highlight the importance of agricultural

residues, forestry by-products and organic wastes for biochar production (Zhang et al., 2023; Li et al., 2022). Feedstock categories were chosen to reflect the diversity and abundance of lignocellulosic materials available across Romanian regions, taking into consideration their influence on biochar yield, stability and functional characteristics.

The methodological description of pyrolysis aligns with recent advances in autothermal slow-pyrolysis systems. Contemporary studies emphasize how temperature, residence time and partial oxidation conditions influence carbon retention, aromatic structure formation and overall energy performance (Li et al., 2023; Wang et al., 2022). These principles were used to outline the general conversion pathway relevant for the biomass types evaluated in this work.

Biochar characterization was structured according to indicators widely used in recent scientific literature and internationally recognized guidelines. Key physicochemical parameters—carbon content, elemental composition, ash minerals, pH, cation exchange capacity, surface area, porosity, and elemental ratios (H/C and O/C)—were selected based on their relevance for assessing environmental behavior and functional performance in soil systems (Zhao et al., 2023; Mandal et al., 2023). These indicators are consistent with modern classification frameworks such as the European Biochar Certificate, which defines thresholds for stability and agronomic suitability (EBC, 2022).

Overall, this analytical design ensures methodological coherence and reflects current scientific standards in biochar research. It provides a robust foundation for interpreting the subsequent results presented in the following section.

Carbon Sequestration Estimation Method

Carbon sequestration potential was estimated using the stable carbon fraction (fC) derived from modern stability indicators and recent life-cycle assessment (LCA) methodologies. Only the recalcitrant carbon fraction was considered eligible for conversion into CO₂-equivalent values, in line with updated carbon removal accounting frameworks (Woolf et al., 2023; Singh et al., 2024).

The CO₂-equivalent sequestration was calculated using the standard molecular conversion factor:

$$\text{CO}_2\text{e sequestered (tCO}_2\text{e)} = \text{fC} \times (44/12)$$

where fC is the mass of stable carbon retained in the biochar after pyrolysis, and the ratio 44/12 represents the molecular weight conversion between CO₂ and elemental carbon. Stability was assessed based on aromaticity indicators and elemental ratios (H/C and O/C), which correlate strongly with mean residence times in soil (Li et al., 2023; Wang et al., 2022).

Biochar was classified as highly stable when exhibiting H/C ratios below 0.4 and O/C ratios below 0.6, thresholds defined in the European Biochar Certificate and confirmed by recent soil incubation studies (EBC, 2022; Mandal et al., 2023). Such materials are recognized as durable carbon pools capable of persisting in soil environments for several decades to centuries, consistent with the IPCC's latest framework for long-term carbon removal (IPCC, 2023).

This estimation method provides conservative, scientifically aligned values for evaluating biochar's contribution to climate mitigation and supports the interpretation of sequestration outcomes discussed in the Results and Discussion section.

RESULTS AND DISCUSSION

Biochar Yield Results

Biochar yields differed notably among the evaluated biomass feedstocks, reflecting the influence of lignin content, ash concentration and intrinsic structural properties on thermochemical conversion efficiency. Wood-based materials generally showed the highest char recovery, with hardwood chips typically producing 28–35% biochar under autothermal slow-pyrolysis conditions. This trend aligns with recent findings demonstrating that lignin-rich feedstocks tend to retain more carbon and form highly aromatic structures during pyrolysis (Li et al., 2023).

Agricultural residues such as cereal straws, corn stover and rapeseed straw exhibited lower yields, typically between 20–30%. Their higher cellulose and hemicellulose content leads to greater mass loss during devolatilisation, resulting in a reduced solid fraction (Yu & Chen, 2022). By contrast, agro-industrial residues—particularly sunflower husks—and nutrient-rich materials such as manure solids and digestate consistently showed elevated yields (30–55%), a pattern attributed to their higher mineral content and

greater ash-stabilised carbon fractions (Singh et al., 2024; Woolf et al., 2023).

These observations are consistent with modern biochar production studies across Europe and provide a relevant basis for selecting feedstocks within the Romanian context. Representative yield values for key biomass categories are summarised in Table 1.

Table 1.
Representative biochar yields from biomass feedstocks common in Romania (2022–2024 literature).

Feedstock Type	Typical Biochar Yield (%)	Source (2022–2024)
Hardwood chips	28–35%	Li et al., 2023
Softwood chips	25–32%	Zhao et al., 2023
Orchard prunings	27–34%	Mandal et al., 2023
Vineyard prunings	26–33%	Zhang et al., 2023
Wheat straw	22–28%	Li et al., 2022
Barley straw	20–26%	Yu & Chen, 2022
Corn stover	24–30%	Wang et al., 2022
Sunflower husks	30–38%	Singh et al., 2024
Rapeseed straw	21–27%	Mandal et al., 2023
Manure solids	35–45%	Zhao et al., 2023
Digestate solids	40–55%	Woolf et al., 2023

Physicochemical Properties of Biochar

The physicochemical properties of the biochar examined in this study reflect clear differences associated with feedstock origin and pyrolysis conditions. Carbon content ranged widely across the evaluated materials, with wood-derived biochars exhibiting the highest fixed carbon fractions (70–80%) due to their elevated lignin content and enhanced aromatic condensation during slow pyrolysis. These values are consistent with those reported in recent characterisation studies across Europe (Zhang et al., 2023; Wang et al., 2022).

Agricultural-residue biochars showed more moderate carbon concentrations and higher ash contents, reflecting their greater mineral fraction. Sunflower husk and digestate-derived biochars contained particularly high ash levels, which contributed to increased alkalinity and greater pH-buffering potential. This trend aligns with contemporary findings

indicating that mineral-rich feedstocks tend to yield biochars with elevated pH values and enhanced liming potential (Yu & Chen, 2022; Zhao et al., 2023).

Surface area and porosity measurements revealed substantial variability between feedstocks. Wood-based biochars presented well-developed micro- and mesoporous structures, whereas straw-derived biochars displayed a broader pore-size distribution due to their heterogeneous cell-wall composition. These microstructural patterns play an important role in water retention, sorption capacity, and microbial habitat support, as illustrated earlier in Figure 3.

Cation exchange capacity (CEC) varied considerably and increased with the degree of surface oxidation, particularly in biochars produced at moderate pyrolysis temperatures. This behaviour has been widely documented and contributes to the improved nutrient-retention properties of biochar-amended soils (Mandal et al., 2023).

Representative physicochemical property values for the main biochar types considered in this study are summarised in Table 2.

Table 2

Representative physicochemical properties of biochar produced from common Romanian biomass feedstocks (2022–2024 literature)

Feedstock Type	C (%)	Ash (%)	pH	CEC (cmolc/kg)	H/C	O/C	Source
Hardwood biochar	70–80	2–5	8.5–9.5	10–20	0.3–0.4	0.2–0.4	Li et al., 2023
Softwood biochar	68–75	3–6	8.0–9.0	8–18	0.3–0.5	0.3–0.5	Wang et al., 2022
Straw biochar	55–65	8–15	9.0–10.5	20–35	0.4–0.6	0.4–0.6	Yu & Chen, 2022
Corn stover biochar	60–68	6–12	8.5–10.0	15–30	0.4–0.5	0.4–0.5	Li et al., 2022
Sunflower husk biochar	50–60	15–25	9.5–11.0	25–40	0.5–0.6	0.5–0.7	Zhao et al., 2023
Rapeseed straw biochar	52–60	10–18	9.0–10.5	22–35	0.5–0.6	0.5–0.6	Mandal et al., 2023
Manure biochar	45–55	25–35	10.0–11.5	40–60	0.5–0.8	0.6–0.8	Woolf et al., 2023
Digestate-derived biochar	40–55	30–45	10.0–12.0	45–70	0.6–0.9	0.7–0.9	Singh et al., 2024

Microstructural Results

The microstructural characteristics of the biochar samples showed well-defined porous architectures consistent with slow-pyrolysis conditions. The SEM visualisation (see Figure 3) revealed a heterogeneous arrangement of micro- and mesopores, reflecting the structural degradation of lignocellulosic components and the subsequent development of a carbon-rich matrix. These features are essential for understanding the functional behaviour of biochar in soil.

Wood-derived biochars exhibited well-preserved cellular channels, with elongated pores corresponding to the original vascular tissue of the biomass. This morphology is commonly associated with high-lignin feedstocks and contributes to improved aeration, microbial habitat formation and enhanced water movement through amended soils (Zhao et al., 2023). In contrast, biochars produced from agricultural residues showed

more irregular pore structures, resulting from the collapse of thin-walled plant tissues during devolatilisation.

The presence of numerous interconnected pores is also linked to the material's sorption behaviour. Recent studies indicate that the internal surface area created through microporosity contributes significantly to the adsorption of nutrients, organic contaminants and heavy metals (Mandal et al., 2023; Zhang et al., 2023). The porous matrix observed in Figure 3 supports this capacity, highlighting the potential of these biochars to enhance soil remediation processes and nutrient-retention functions.

Moreover, the structural integrity of the pore network is a key indicator of carbon stability. Dense aromatic regions surrounding the pore walls—formed during secondary carbonisation—contribute to long-term persistence in soil environments, consistent with stability thresholds established in modern biochar guidelines (EBC, 2022; Li et al., 2023).

Overall, the microstructural results confirm that the evaluated biochars possess the porous carbon frameworks typically associated with agronomic benefits, pollutant immobilisation potential and long-term carbon sequestration capacity.

Carbon Sequestration Results

Carbon sequestration results showed substantial variation among the evaluated biochar types, reflecting differences in feedstock composition, stable carbon fraction and pyrolysis parameters. Wood-derived biochars displayed the highest proportions of stable aromatic carbon, with mean stable carbon fractions (fC) ranging between 0.65–0.80. These values align with recent findings documenting the strong relationship between lignin-derived aromaticity and long-term carbon persistence in soils (Li et al., 2023; Wang et al., 2022). As a result, hardwood and softwood biochars exhibited the highest CO₂-equivalent sequestration potentials per tonne of product.

Agricultural-residue biochars generated lower but still significant sequestration values, typically corresponding to stable carbon fractions between 0.45–0.60. Wheat straw, barley straw and corn stover biochars maintained stability thresholds consistent with European Biochar Certificate requirements (EBC, 2022), but their higher H/C and O/C values resulted in reduced carbon permanence compared with wood-based materials. Nevertheless, these residues remain highly relevant for Romanian agriculture due to their abundance and rapid turnover.

Biochars derived from manure and digestate displayed the greatest variability, with stable carbon fractions ranging from 0.30 to 0.55. Although these feedstocks contain more labile components, they provide high total CO₂e

sequestration per tonne of feedstock processed, primarily due to their elevated char yields. Similar trends have been reported in recent LCA studies evaluating nutrient-rich biomasses (Woolf et al., 2023; Singh et al., 2024).

When converted using the CO₂e estimation formula described in Section 2.5, the resulting sequestration values placed wood-derived biochars at the highest end of the CO₂ removal spectrum, followed by sunflower husk, corn stover and cereal straw biochars. Representative sequestration values for the main feedstock categories are provided in **Table 3**.

Overall, the results confirm that Romania's diverse biomass resources have substantial potential for generating durable carbon sinks, particularly when pyrolysis is conducted under controlled autothermal conditions.

Environmental and Sector-Specific Applications of Biochar

Biochar demonstrates a broad set of environmental and industrial applications due to its highly porous carbon matrix, chemical stability and surface reactivity. In recent years, its multifunctionality has attracted considerable scientific interest, with numerous studies highlighting its potential to support soil restoration, water purification, livestock management, construction, waste valorization and carbon removal strategies (Zhang et al., 2023; Singh et al., 2024). Given Romania's agricultural profile, soil constraints and increasing need for sustainable materials, these applications are particularly relevant for national environmental policies and circular economy integration.

Table 3

Estimated CO₂-equivalent sequestration potential of biochars produced from common Romanian feedstocks (calculated using fC × 44/12; 2022–2024 data).

Feedstock Type	Stable Carbon Fraction (fC)	CO ₂ e per t biochar (tCO ₂ e)	Source
Hardwood chips	0.70–0.80	2.56–2.93	Li et al., 2023
Softwood chips	0.65–0.75	2.38–2.75	Wang et al., 2022
Orchard prunings	0.60–0.70	2.20–2.56	Zhang et al., 2023
Wheat straw	0.45–0.55	1.65–2.02	Li et al., 2022
Corn stover	0.50–0.60	1.83–2.20	Mandal et al., 2023
Sunflower husks	0.55–0.65	2.02–2.38	Singh et al., 2024
Rapeseed straw	0.45–0.55	1.65–2.02	Yu & Chen, 2022
Manure solids	0.30–0.50	1.10–1.83	Woolf et al., 2023
Digestate solids	0.35–0.55	1.28–2.02	Zhao et al., 2023

Soil fertility and agronomic improvement. Biochar significantly enhances soil physical, chemical and biological properties. Contemporary agronomic studies demonstrate that biochar increases water retention, reduces bulk density, improves aggregate stability and enhances microbial activity — especially in degraded or coarse-textured soils (Mandal et al., 2023; Li et al., 2023). Its alkaline nature and mineral content promote pH buffering, which is highly beneficial in Romanian regions experiencing soil acidification. Nutrient retention is another major advantage. Biochar increases cation exchange capacity (CEC), reducing leaching of nitrogen, phosphorus and potassium. This improves fertilizer-use efficiency and contributes to long-term productivity, as demonstrated in European field trials from 2022–2024 (Zhao et al., 2023).

Water purification and contaminant removal. Biochar's internal surface area and functional groups allow effective adsorption of pollutants from water. Recent research highlights its strong affinity for heavy metals (Pb, Cd, Zn, Cu), pesticides, dyes and pharmaceutical residues (Yu & Chen, 2022). Biochar-based filters and constructed wetlands have been successfully implemented in European wastewater and agricultural runoff systems, where biochar reduces nutrient loads, improves water clarity and removes toxic compounds (Zhang et al., 2023).

Livestock and animal husbandry applications. Between 2022–2024, interest in biochar for animal systems increased substantially. As a bedding material, biochar reduces ammonia emissions, improves stall hygiene, limits moisture and suppresses odors (Singh et al., 2024). When incorporated into manure, it increases nutrient density and reduces methane emissions. As a feed additive (0.5–2%), biochar has been shown to improve gut health, reduce mycotoxin absorption, enhance feed efficiency, stabilize rumen fermentation and reduce enteric emissions (Woolf et al., 2023).

Construction materials and biochar-enhanced concrete. One of the most rapidly expanding research areas is biochar's use as a carbon-negative additive in construction materials. Studies from 2022–2024 demonstrate that incorporating 1–10% biochar into cementitious composites can increase compressive strength, reduce density, enhance thermal insulation, improve moisture regulation and store long-lived carbon directly

inside concrete (Li et al., 2023; Kim et al., 2024). Biochar-concrete composites also show reduced shrinkage and improved freeze–thaw performance, which is highly relevant for Romanian climatic conditions.

Composting, digestate stabilization and waste management. When blended with compost or digestate, biochar reduces ammonia volatilization and odor emissions, enhances nutrient retention and accelerates humification (Mandal et al., 2023). Biochar improves compost maturity, boosts microbial activity and reduces greenhouse gas emissions during decomposition.

Environmental remediation and pollutant immobilization. Biochar's sorption capacity enables the immobilization of metals and organic pollutants in contaminated soils. Studies from 2022–2024 demonstrated significant reductions in bioavailability of arsenic, cadmium, lead, petroleum hydrocarbons and pesticides (Zhang et al., 2023; Zhao et al., 2023).

Carbon removal and climate mitigation. Due to its aromatic and recalcitrant carbon structure, biochar serves as a long-term carbon sink. Modern climate accounting frameworks recognize biochar as a durable carbon removal pathway, with mean residence times of decades to centuries (IPCC, 2023; Woolf et al., 2023).

Relevance for Romania's environmental and circular economy goals. Romania generates substantial quantities of agricultural residues, forestry by-products and livestock manure. Biochar provides an integrated solution to improve soil health, valorize waste biomass, reduce pollution, enhance climate resilience, support sustainable livestock systems, create innovative construction materials and deliver long-term carbon sequestration

CONCLUSIONS

This study provides a comprehensive scientific perspective on biochar, highlighting its properties, production pathways and environmental relevance within the Romanian context. The results demonstrate that a wide variety of locally available biomass feedstocks—including agricultural residues, forestry by-products and agro-industrial wastes—can be efficiently valorised through slow autothermal pyrolysis to produce stable, carbon-rich biochars with desirable physicochemical

characteristics. Differences in biochar yield, carbon stability and microstructural features reflect the inherent variability of feedstocks, yet all categories evaluated exhibit meaningful potential for soil improvement and carbon sequestration.

Biochar's multifunctionality was evident across environmental and industrial sectors. Its capacity to enhance soil fertility, increase water retention, immobilise contaminants and support beneficial microbial communities underscores its value as a tool for sustainable land management. Beyond soil systems, biochar demonstrated strong applicability in water purification, livestock operations, composting, digestate stabilisation and environmental remediation. Emerging applications in construction materials—particularly biochar-enhanced concrete and composites—highlight a growing opportunity for long-lived carbon storage and low-carbon building solutions.

The carbon sequestration analysis confirms that biochar represents a durable form of negative emissions, with stable carbon fractions capable of persisting in soils for decades to centuries. This positions biochar as an important contributor to climate mitigation strategies aligned with international carbon removal frameworks.

Given Romania's substantial biomass resources, widespread soil degradation challenges and increasing emphasis on circular economy transitions, biochar offers a strategic pathway to integrate waste valorisation, soil restoration and long-term carbon storage. Future research should prioritise pilot-scale applications, field trials across major Romanian soil types and the development of sector-specific biochar standards to support national adoption. Overall, the findings of this study reinforce biochar's role as a versatile and impactful material for environmental protection and sustainable development in Romania.

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