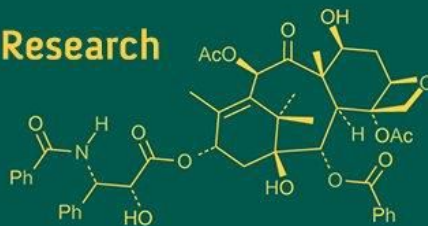


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A critical review on biochar applications in agriculture and animal husbandry

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Abstract

Biochar is a porous, carbon-rich material produced by the thermal decomposition of biomass under limited oxygen conditions. In recent years, it has gained substantial attention as a multifunctional and sustainable resource with broad applications in agriculture and animal husbandry. Although biochar was initially explored for soil remediation and carbon sequestration, its scope has expanded considerably to include uses in animal feed supplementation, manure management, composting, and overall environmental sustainability. This review compiles and synthesizes existing knowledge on biochar, with particular emphasis on its role in livestock production systems. Studies involving ruminants, poultry, swine, and aquaculture species indicate that biochar supplementation can enhance gut health, improve nutrient utilization efficiency, upgrade manure quality, and contribute to better environmental performance. Additionally, biochar has shown potential in reducing emissions of methane, ammonia, and nitrous oxide from agricultural operations. However, the effectiveness of biochar varies depending on factors such as feedstock type, pyrolysis conditions, and application rate. The review further discusses its broader environmental benefits, including greenhouse gas mitigation, nutrient recycling, and long-term carbon sequestration. It also addresses existing limitations and outlines future research priorities. Overall, when applied following scientifically validated guidelines, biochar represents a valuable component of climate-smart and sustainable agricultural systems.

Keywords: Biochar, animal husbandry, sustainable agriculture, livestock nutrition, soil health, greenhouse gas mitigation, carbon sequestration, manure management

1. Introduction

The continuous expansion of global agriculture and livestock production has placed immense strain on natural resources, resulting in soil degradation, nutrient depletion, and elevated greenhouse gas (GHG) emissions. Livestock systems are major contributors to emissions of methane (CH₄), ammonia (NH₃), and nitrous oxide (N₂O), which adversely affect climate regulation, air quality, soil health, and water ecosystems. Consequently, there is an urgent need for sustainable, affordable, and eco-friendly strategies that enhance productivity while minimizing environmental harm.

Biochar has emerged as a promising solution within sustainable agriculture and animal production systems. It is a stable, carbon-rich substance produced through the thermochemical conversion of organic biomass such as crop residues, forest by-products, and animal manure under oxygen-limited conditions (Lehmann and Joseph, 2015) [14]. Historically, its agronomic relevance is associated with the highly fertile Terra Preta soils of the Amazon Basin, characterized by elevated charcoal content, improved nutrient availability, and long-term soil productivity. In crop production, biochar has been widely investigated as a soil amendment due to its capacity to enhance soil structure, increase water-holding capacity, improve nutrient retention, and stimulate microbial activity, particularly in degraded or acidic soils (Lehmann *et al.*, 2015; Aegnehu *et al.*, 2017) [14, 1, 2]. These improvements frequently translate into better crop performance and reduced nutrient losses. More recently, attention has shifted toward its applications in animal husbandry, including livestock feeding, bedding systems, manure treatment, and composting practices.

The functional effectiveness of biochar stems from its distinctive physicochemical characteristics, such as high surface area, porous architecture, alkaline nature, and strong adsorption potential. These properties enable interactions with nutrients, gases, toxins, and microbial communities.

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In livestock systems, biochar is increasingly evaluated as a feed supplement because of its ability to bind toxins and pathogens within the gastrointestinal tract, stabilize gut conditions, enhance nutrient efficiency, and potentially reduce reliance on antibiotic growth promoters (Schmidt *et al.*, 2021; Nair *et al.*, 2023) ^[22, 19]. When incorporated into bedding or manure, biochar can improve housing conditions and manure quality by lowering moisture content, controlling odours, and conserving nutrients. It may also contribute to reducing environmental emissions associated with livestock production. Research suggests that biochar can influence rumen fermentation processes, suppress methanogenic archaea, and mitigate methane emissions in ruminants; however, outcomes vary depending on biochar characteristics and dietary composition (Leng *et al.*, 2012; Dittmann *et al.*, 2024) ^[16, 17, 5]. Furthermore, its addition to manure storage systems and composting operations has been reported to reduce ammonia volatilization, enhance nitrogen retention, improve fertilizer quality, and promote nutrient recycling within circular agricultural systems (Sanchez-Monedero *et al.*, 2019; Chung *et al.*, 2023) ^[21, 4].

Despite these promising findings, inconsistencies across studies highlight considerable knowledge gaps. Variability in feedstock sources, pyrolysis parameters, application rates, and management strategies complicates data interpretation and comparison. Therefore, a comprehensive synthesis of current research is essential to better understand the mechanisms underlying biochar's effects, evaluate its benefits and limitations, and determine priorities for future investigation. This review aims to systematically examine biochar production techniques, properties, applications, and environmental implications in both agriculture and animal husbandry, with particular emphasis on livestock nutrition, manure management, greenhouse gas mitigation, and the advancement of climate-smart, circular agro-livestock systems.

2. Production and Properties of biochar

2.1 Feedstocks and production methods

Biochar can be produced from a wide range of biomass

Sources. Common feedstocks include agricultural residues such as rice husk, wheat straw, and maize stover; forestry by-products like wood chips; livestock manures and poultry litter; sewage sludge; and various agro-industrial wastes. The selection of feedstock plays a decisive role in determining the final characteristics of biochar, as it influences its chemical composition, nutrient concentration, ash content, and functional performance. Pyrolysis is the most widely used technique for biochar production. This process involves heating biomass at temperatures typically ranging from 300 to 700 °C under oxygen-limited conditions (Lehmann & Joseph, 2015) ^[14]. Depending on the heating rate and residence time, pyrolysis is categorized into slow, intermediate, or fast processes. Among these, slow pyrolysis commonly conducted at 350-600 °C over longer durations is generally favoured for agricultural and livestock applications because it produces greater biochar yields, enhances carbon retention, and improves material stability (Weber & Quicker, 2018) ^[31].

In addition to pyrolysis, other thermochemical conversion technologies are employed. Gasification operates at temperatures exceeding 700 °C and produces biochars characterized by high porosity and elevated mineral ash content; however, it typically results in lower yields and reduced carbon stability. Hydrothermal carbonization (HTC), on the other hand, is carried out in an aqueous environment at comparatively lower temperatures (180-250 °C). This process generates hydrochar with higher hydrogen-to-carbon ratios, although its long-term stability is generally lower than that of pyrolysis-derived biochar (Hagemann *et al.*, 2018; Nair *et al.*, 2023) ^[9, 19]. Overall, both the type of feedstock and the production parameters substantially influence key properties such as biochar yield, surface area, pore structure, pH, nutrient composition, and adsorption capacity. These characteristics ultimately determine its suitability and effectiveness in agricultural and animal husbandry applications.

Table 1: Feedstocks, production conditions, and key properties of biochar

Feedstock source	Production method/temperature	Key physicochemical properties	Major applications	Reference
Wood residues	Slow pyrolysis (400-600 °C)	High surface area, stable carbon, alkaline pH	Carbon sequestration, soil structure improvement	Lehmann & Joseph, 2015 ^[14]
Crop residues	Pyrolysis (350-550 °C)	Moderate surface area, nutrient retention	Soil fertility, crop productivity	Agegehu <i>et al.</i> , 2017 ^[1, 2]
Poultry litter	Pyrolysis (450-600 °C)	High ash, rich in P and Ca	Fertilizer replacement, poultry diets	Evans <i>et al.</i> , 2015 ^[6]
Cattle/swine manure	Pyrolysis (400-600 °C)	High nutrient content, high CEC	Manure management, soil amendment	Sanchez-Monedero <i>et al.</i> , 2019 ^[21]

2.2 Thermochemical conversion mechanisms

Biochar is primarily generated through the thermal decomposition of key biomass components namely cellulose, hemicellulose, and lignin under conditions of limited or no oxygen. During the pyrolysis process, a series of chemical reactions such as dehydration, depolymerization, decarboxylation, and aromatization progressively transform the original biomass into a stable, carbon-dense material (Lehmann & Joseph, 2015) ^[14].

In slow pyrolysis, the process tends to preserve a greater proportion of oxygen-containing functional groups, resulting in biochars with moderate aromatic structures and comparatively higher cation exchange capacity. In contrast, fast pyrolysis and gasification promote greater aromatic

condensation, producing biochars with enhanced structural rigidity and stability but reduced surface functional groups (Weber & Quicker, 2018) ^[31]. Overall, these thermochemical conversion pathways significantly influence the physicochemical characteristics of biochar, including its reactivity, persistence, and interactions within soil environments and animal production systems.

2.3 Feedstock-specific nutrient profiles

The chemical and elemental composition of biochar largely mirrors the properties of the original biomass used for its production. Biochars derived from lignocellulosic materials such as wood and crop residues typically possess high carbon content but relatively low concentrations of mineral

nutrients. Owing to these characteristics, they are particularly effective for long-term carbon sequestration and enhancement of soil physical properties (Graves *et al.*, 2022) ^[8].

In contrast, biochars produced from animal manures and poultry litter are generally richer in essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium, and magnesium, due to the inherently mineral-dense nature of these feedstocks. For instance, Evans *et al.* (2015) ^[6] reported that poultry litter-derived biochar may contain approximately 2-3% phosphorus, highlighting its potential utility as a slow-release fertilizer and as an alternative phosphorus source in both crop cultivation and livestock production systems.

2.4 Physicochemical characteristics of biochar

The physicochemical attributes of biochar differ considerably depending on the feedstock source and production parameters. In general, biochar is characterized by an alkaline pH, high carbon stability, extensive surface area, well-developed pore structure, and substantial cation exchange capacity (CEC). Wood-derived biochars typically exhibit greater surface area and enhanced structural integrity, whereas manure-based biochars tend to contain higher ash content and elevated nutrient concentrations (Aegnehu *et al.*, 2017; Sanchez-Monedero *et al.*, 2019) ^[1, 2, 21].

Biochars produced at elevated temperatures usually possess a higher degree of aromaticity, increased surface area, and improved resistance to microbial degradation, making them

Suitable for long-term carbon sequestration. Conversely, biochars generated at lower temperatures retain more oxygen-containing functional groups and nutrients, thereby enhancing their chemical reactivity and nutrient-holding capacity (Ayaz *et al.*, 2021) ^[3].

Key physicochemical properties that determine biochar's suitability for agricultural and livestock applications include: Extensive surface area and well-defined porosity, Alkaline nature with soil buffering capability, High cation exchange capacity, Strong adsorption potential for nutrients, toxins, gases, and microorganisms, Chemical stability and resistance to microbial decomposition. Collectively, these characteristics underpin the multifunctional roles of biochar in soil improvement, animal digestive health, and manure management systems.

2.5 Pore Structure and adsorption capacity

Biochar possesses a well-developed porous architecture composed of macropores, mesopores, and micropores. Macropores primarily facilitate water retention and create favorable habitats for microbial colonization, whereas micropores contribute substantially to the overall surface area, enhancing the material's capacity to adsorb gases, nutrients, organic compounds, toxins, and heavy metals (Nair *et al.*, 2023) ^[19].

This strong adsorption capability enables biochar to immobilize contaminants such as lead (Pb) and cadmium (Cd), thereby reducing their bioavailability in soil systems and limiting their transfer into the food chain.

Table 2: Biochar production parameters and resulting physicochemical properties

Production method	Temperature (°C)	Residence time	Key characteristics	Reference
Slow pyrolysis	350-500	Hours to days	High biochar yield, preserved functional groups, moderate aromaticity	Lehmann & Joseph, 2015; Weber & Quicker, 2018 ^[14, 31]
Fast pyrolysis	450-600	Seconds	High aromaticity, high structural stability, lower char yield	Weber & Quicker, 2018 ^[31]
Gasification	>700	Minutes	High porosity, high ash content, low biochar yield	Nair <i>et al.</i> , 2023 ^[19]
Hydrothermal carbonization	180-250	Hours	Hydrochar with lower stability, high nutrient retention	Hagemann <i>et al.</i> , 2018 ^[9]

3. Biochar in soil and composting systems

3.1 Enhancement of soil physicochemical and biological health

Biochar is widely recognized as a durable soil amendment due to its high carbon stability and porous structure. Its application has been shown to lower soil bulk density, enhance soil aggregation, and improve water retention capacity, particularly in sandy, acidic, or degraded soils (Lehmann *et al.*, 2015; Aegnehu *et al.*, 2017) ^[14, 1, 2]. From a chemical perspective, biochar generally increases soil pH and enhances cation exchange capacity (CEC), thereby improving nutrient retention and reducing leaching losses of key elements such as nitrogen and phosphorus (Kammann *et al.*, 2017; Wei *et al.*, 2024) ^[11, 32].

Biologically, biochar provides a conducive habitat for soil microbial communities, leading to greater microbial biomass, elevated enzyme activities, and improved nutrient cycling processes. Long-term field investigations indicate that these combined physicochemical and biological enhancements contribute to sustained improvements in crop yields across cereals, legumes, vegetables, and forage species, with particularly pronounced benefits under

nutrient-deficient soil conditions (Shanmugaraj *et al.*, 2024; Shyam *et al.*, 2025) ^[23, 24].

3.2 Biochar as a catalyst in composting systems

Within composting systems, biochar functions as a bulking material, stabilizing agent, and process enhancer. Its highly porous structure improves airflow within compost piles, thereby maintaining aerobic conditions and minimizing the formation of undesirable anaerobic gases (Chung *et al.*, 2023) ^[4]. Additionally, biochar promotes faster compost stabilization by facilitating microbial decomposition of organic matter and providing protective microhabitats for beneficial microorganisms, including nitrifying bacteria (Khan *et al.*, 2014; Godlewska *et al.*, 2021) ^[13, 7].

3.3 Nitrogen conservation and emission reduction

Nitrogen losses through ammonia (NH₃) volatilization represent a major challenge in conventional composting systems. The incorporation of biochar has been shown to mitigate NH₃ emissions by physically adsorbing ammonia and chemically binding it to acidic functional groups on its surface (Wang & Zeng, 2018; Graves *et al.*, 2022) ^[8, 30]. As a

result, the final compost product retains higher levels of plant-available nutrients and functions as a more effective slow-release organic fertilizer when applied to soil (Lopez-Cano *et al.*, 2016) ^[18]. Moreover, several studies report that biochar addition can reduce methane (CH₄) and nitrous oxide (N₂O) emissions during composting, thereby lowering the overall greenhouse gas footprint of the process (Yuan *et al.*, 2017) ^[34].

Table 3: Effects of biochar addition during composting

Reference	Compost material	Biochar level	Major findings
Jindo <i>et al.</i> (2016) ^[10]	Manure + crop residues	5-10%	Reduced NH ₃ loss, improved compost maturity
Chung <i>et al.</i> (2023) ^[4]	Food waste + manure	5%	Improved nutrient retention, reduced CH ₄
Lopez-Cano <i>et al.</i> (2016) ^[18]	Manure compost	5%	Nutrient-enriched compost, slow-release fertilizer

Table 4: Nutrient and Mineral Profiles by Feedstock Type

Feedstock Source	Carbon Content	Primary Nutrients (N, P, K)	Best Use	Reference
Woody Biomass	High (>70%)	Low	Carbon sequestration & soil structure.	Graves <i>et al.</i> (2022) ^[8]
Poultry Litter	Low (30-40%)	High (esp. Phosphorus 2-3%)	Mineral supplement for broilers.	Evans <i>et al.</i> (2015) ^[6]
Crop Residues	Medium	Moderate	General soil fertility improvement.	Agegnehu <i>et al.</i> (2017) ^[1, 2]
Swine/Cattle Manure	Low	High Nitrogen & Zinc	Soil nutrient enrichment.	Graves <i>et al.</i> (2022) ^[8]

4. Applications of Biochar in Animal Husbandry

4.1 Biochar as a Feed Additive

Biochar has traditionally been utilized in veterinary practice as a detoxifying substance. Contemporary research indicates that its inclusion at low dietary levels typically ranging from 0.5 to 2% of dry matter can enhance gastrointestinal health by adsorbing toxins, mycotoxins, and pathogenic

microorganisms. These effects contribute to improved feed conversion efficiency and overall animal performance (Schmidt *et al.*, 2021; Nair *et al.*, 2023) ^[22, 19]. Furthermore, biochar is increasingly being explored as a sustainable alternative to antibiotic growth promoters, aligning with efforts to reduce antimicrobial use in livestock production systems (Kazemi, 2025) ^[12].

Table 5: Impact of Biochar as a Dietary Feed Additive

Animal Species	Inclusion Level	Observed effects	Reference
Dairy cattle	1-3% DM	Stable milk yield; inconsistent enteric methane reduction.	Terler <i>et al.</i> (2023); Dittmann <i>et al.</i> (2024) ^[27, 5]
Beef cattle/sheep	0.5-2% DM	Improved feed efficiency, reduced CH ₄	Leng <i>et al.</i> , 2012 ^[16, 17]
Swine (Piglets)	0.5-1%	Adsorption of toxins/pathogens; reduced diarrhea.	Schmidt <i>et al.</i> (2021) ^[22]
Broiler Chickens	6-7%	Successfully replaced rock phosphorus; no negative effect on tibia ash.	Evans <i>et al.</i> (2015) ^[6]
Layer Chickens	Supplemented	Improved eggshell thickness and quality.	Prasai <i>et al.</i> (2018) ^[20]
Steers (Finishing)	0.8%-3.0% DM	Minimal effect on methane; altered rumen microbiota.	Winders <i>et al.</i> (2019); Terry <i>et al.</i> (2019b) ^[33, 28]
Fish	Variable	Improved water quality	Wang <i>et al.</i> , 2023 ^[29]

4.2 Rumen fermentation and enteric methane mitigation

In ruminant production systems, biochar supplementation has the potential to alter rumen microbial populations and influence fermentation dynamics. It has been proposed that biochar facilitates direct interspecies electron transfer, thereby diverting hydrogen away from methanogenesis and contributing to reduce enteric methane emissions (Leng *et al.*, 2012; Tamayao *et al.*, 2021) ^[16, 17, 26]. Although *in vitro* experiments frequently demonstrate significant decreases in methane production, *in vivo* findings are more variable. The extent of methane mitigation appears to depend largely on factors such as the physicochemical characteristics of the biochar and the composition of the animal's diet (Dittmann *et al.*, 2024) ^[5].

4.3 Poultry, swine, and aquaculture applications

In poultry production, biochar supplementation has been associated with enhanced mineral utilization, improved eggshell strength, better growth performance, and improved litter quality. Evans *et al.* (2015) ^[6] reported that poultry litter-derived biochar could completely substitute rock phosphate in broiler diets without adversely affecting

performance. In swine production systems, biochar inclusion has been shown to reduce the occurrence of diarrhea and support intestinal health, primarily through its ability to adsorb pathogenic microorganisms and toxins (Schmidt *et al.*, 2021) ^[22]. Similarly, in aquaculture, biochar application contributes to improved water quality and more efficient feed utilization, ultimately promoting higher growth rates and survival of aquatic species.

4.4 Bedding, housing, and manure management

When incorporated as a bedding amendment, biochar effectively absorbs moisture and ammonia, thereby minimizing odors, enhancing barn sanitation, and improving overall animal welfare conditions (Graves *et al.*, 2022) ^[8]. Additionally, the integration of biochar into manure management systems has been shown to improve nutrient conservation, reduce greenhouse gas emissions during storage and composting, and enhance the agronomic value of manure as an organic fertilizer (Sanchez-Monedero *et al.*, 2019) ^[21].

Table 6: Role of Biochar in Manure Management and Composting

Composting Parameter	Impact of Biochar	Primary Mechanism	Reference
Ammonia Loss	Reduced by up to 50%	Physical adsorption & microbial nitrification support.	Wang & Zeng (2018); Graves <i>et al.</i> (2022) ^[30, 8]
Compost Maturity	Accelerated	Improved aeration & microbial habitat within pores.	Chung <i>et al.</i> (2023); Khan <i>et al.</i> (2014) ^[4, 13]
Nutrient Value	Increased N & P	Capture of nitrate in co-composted pores.	Lopez-Cano <i>et al.</i> (2016); Kammann <i>et al.</i> (2017) ^[18, 11]
Greenhouse Gases	Reduced N ₂ O	Mitigation of denitrification through improved oxygen flow.	Yuvan <i>et al.</i> (2017)

5. Environmental implications of biochar use

5.1 Carbon sequestration and climate change mitigation

Biochar is characterized by its long-term stability in soil environments, with its carbon content persisting for decades to even centuries. This durability makes it an effective strategy for long-term carbon storage and emission reduction (Lehmann & Joseph, 2015; Wei *et al.*, 2024) ^[14, 32].

Biochar contributes to climate change mitigation through both direct and indirect mechanisms. Directly, it sequesters carbon in stable forms within the soil. Indirectly, it can reduce emissions of methane (CH₄) and nitrous oxide (N₂O) from agricultural soils and livestock production systems,

thereby lowering the overall greenhouse gas footprint (Kammann *et al.*, 2017; Singh *et al.*, 2025) ^[11, 25].

5.2 Water quality and pollution control

Biochar plays a significant role in safeguarding water resources by minimizing nutrient runoff and leaching losses from agricultural systems. Its strong adsorption capacity enables it to immobilize heavy metals and organic contaminants, thereby preventing their movement into surface and groundwater bodies. Through these mechanisms, biochar contributes to improved water quality and enhanced environmental protection (Lehmann *et al.*, 2015; Nair *et al.*, 2023) ^[14, 19].

Table 7: Environmental and sustainability benefits of biochar

Environmental metric	Effect of biochar	Time scale	Reference
Carbon sequestration	Long-term storage	Decades-centuries	Lehmann & Joseph, 2015 ^[14]
GHG mitigation	Reduced CH ₄ and N ₂ O	Short-long term	Kammann <i>et al.</i> , 2017 ^[11]
Nutrient recycling	Improved fertilizer efficiency	Seasonal-multi-year	Agegnehu <i>et al.</i> , 2017 ^[1, 2]
Water quality	Reduced nutrient leaching	Long term	Wei <i>et al.</i> , 2024 ^[32]

Although biochar has demonstrated considerable potential, its large-scale adoption remains constrained by several challenges. Variability in feedstock characteristics, lack of standardized production protocols, inconsistent animal responses, and limited long-term field and feeding studies hinder broader implementation. Moreover, the complex interactions between biochar and gut microbiota, soil ecosystems, and nutrient cycling processes are not yet fully elucidated (Schmidt *et al.*, 2021; Kazemi *et al.*, 2025) ^[22, 12].

Future investigations should prioritize the development of standardized production and application methodologies, determination of optimal inclusion rates, long-term safety assessments, and evaluation of economic feasibility. Additionally, research efforts should focus on species-specific optimization, formulation of region-specific guidelines, integration of biochar within circular agro-livestock frameworks, and assessment of its combined use with other climate-smart agricultural strategies (Shyam *et al.*, 2025) ^[24].

6. Conclusion

Biochar represents a promising strategy for strengthening integrated crop-livestock production systems. Its application enhances soil fertility, improves nutrient efficiency, upgrades manure quality, and contributes to better environmental outcomes. Utilization of biochar in feed supplementation, bedding materials, manure management, and soil amendment supports nutrient recycling while promoting long-term carbon sequestration. Nevertheless, variability in outcomes arising from differences in feedstock types, pyrolysis conditions, and application rates highlights the necessity for standardized

quality parameters and context-specific recommendations. Future research should emphasize long-term, multi-species, and regionally adapted studies to validate safety, consistency, and overall effectiveness. When implemented alongside sound agronomic and livestock management practices, biochar has substantial potential to advance sustainable, resilient, and resource-efficient agri-food systems.

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