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Review

The potential role of biochar in mitigating gaseous emissions from livestock waste – A mini-review

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ABSTRACT

The livestock industry plays a significant role in the economic well-being of many parts of the world with a host of environmental challenges. Key amongst them is the management of gaseous emissions emitted from livestock manure. Mitigation of gaseous emissions from livestock operations such as odor, odorous volatile organic compounds (VOCs), ammonia (NH_3), hydrogen sulfide (H_2S), and greenhouse gases (GHGs) have been of research interest for the last couple of decades. Biochar, a low-cost-value byproduct of biorenewable energy and thermochemical waste processing compared with syngas and bio-oil, has been actively researched as a potential surficial treatment of manure and emissions from stored or co-composted manure. Yet, the efficacy of biochar treatment differs, partly because biochar properties vary with feedstock and thermochemical processing conditions. To date, the results from laboratory-scale trials are encouraging, but a more focused effort is needed to bring this technology closer to farm-scale applications. Therefore, this review aims to summarize and highlight current research related to mitigating gaseous emissions from manure treated with biochar. Various types of biochar, and modes of biochar applications, e.g., manure additives and co-composting, dosage, and timing, are discussed in the context of targeted gas emissions mitigation. Gaps in knowledge remain, including demonstrated larger-scale mitigation performance and verifiable technoecomics. Standardization and certification of biochar properties suitable for specific environmental management applications are recommended. The potential synergy between mitigating emissions, improving manure quality, carbon, and nitrogen cycling in animal and crop production agriculture is found. Biochar can be a comprehensive solution to gaseous emissions while also upgrading manure as a high-quality additive that could improve the sustainability of animal and crop production systems.

1. Introduction

Thermochemical treatment can convert biomass into syngas and bio-oil via pyrolysis, which offers an alternative source of fuel (Zhang et al., 2007). Pyrolysis' by-product is biochar (BC), a carbon-rich material. To date, BC has mainly been proposed for use as a soil amendment on large scales, warranted by the projected biofuel generation capacity globally (Peters et al., 2015). Innovative synergies of thermal processing of biowaste and then using BC as fuel to (2) sustain thermal process and (2) generating new revenue streams are explored (O'Brien et al., 2020). Technoecomics of large-scale BC utilization are being developed. Thus alternative, value-added and feasible BC uses can aid in realizing its potential, especially on the nexus of agriculture and the environment (Bolan et al., 2022).

The '*biochar*' term describes materials with widely different physicochemical properties. Thus, the knowledge of basic BC properties is crucial, especially when aiming to use it for specific applications. Process temperature, process time, feedstock, oxygen level, pressure, and other variables, affect the BC physicochemical properties such as pH, surface area, porosity, surface functional groups, and impurities (Xu et al., 2017). Feedstocks such as crop and plant residues produce BC with a larger surface area and pores, which can be used for sorbing selected organic contaminants (Chen et al., 2008; Joseph and Taylor, 2014). Livestock manure-based BC has higher ash & nutrient contents and can be a source of fertilizer (El-Naggar et al., 2019; Hossain et al., 2020). It is

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Abbreviations:

AD	anaerobic digestion
BC	biochar
DIET	direct interspecies electron transfer
EBC	the European Biochar Certificate
GHGs	greenhouse gases
IBI	the International Biochar Initiative
NIOSH	The U.S. National Institute for Occupational Safety and Health
MC	moisture content
OM	organic matter
OSHA	The U.S. Occupational Safety and Health Administration
PELs	permissible exposure limits
PM	particular matter
STL	short term exposure limit
TWA	time-weighted average
VOCs	volatile organic compounds

opportune to consider value-added and feasible BC uses to address some long-standing challenges in animal and crop production systems (Kalus et al., 2019).

Livestock agriculture is generating economic opportunities for rural areas, but significant environmental impacts result from unbalanced development. Gaseous emissions cause air quality and environmental concerns on the local, regional, and national scales (Rotz et al., 2021). Main gaseous pollutants associated with animal agriculture include ammonia (NH_3), hydrogen sulfide (H_2S), greenhouse gases, and odorous volatile organic compounds (VOCs). Emissions of NH_3 represent a loss of manure nutrients that can be utilized by crops (Ni et al., 2009; Hoff et al., 2006). NH_3 gas also plays a significant part in forming secondary fine particulate matter (PM2.5) (Brandani et al., 2023), that eventually deposit, causing (e.g.) eutrophication of ecosystems. NH_3 can be toxic to plants (Esteban et al., 2016) and microorganisms (Koziel et al., 2017). Greenhouse gases (GHGs), including CO_2, CH_4, and N_2O, are linked with concerns about climate change (Yang et al., 2024). Agriculture accounted for ~24% of total U.S. GHG emissions in 2010 (EPA). Odorous VOCs such as phenols, volatile fatty acids, and sulfur-containing compounds are the primary source of the odor both in the gas-phase and fine PM that can impact farm neighbors (Cai et al., 2006).

The short- and long-term toxicity of gaseous emissions on farms are of concern, due to occupational exposure. The U.S. National Institute for Occupational Safety and Health (NIOSH) recommends the time-weighted average (TWA) 10-h concentration for NH_3 at 25 ppm and a short-term exposure limit (ST) of 15-min at 35 ppm (NIOSH, 1997). The H_2S emissions can cause serious safety and health concerns to on-site workers and livestock even when concentration is relatively lower compared with NH_3. The U.S. Occupational Safety and Health Administration (OSHA) recommends the permissible exposure limits (PELs) concentration for H_2S at 20 ppm and an acceptable maximum peak above the acceptable ceiling concentration at 50 ppm, with a maximum duration of 10 min (OSHA, 2017). In 2022, the agriculture sector was responsible for 593.4 million metric tons of CO_2 equivalent emissions, and manure applications and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions (EPA).

Serious and immediate health risks arise from inhalation of gases during routine manure management operations. 133 manure-related incidents were reported in the seven mid-western U.S. states (Nour et al., 2020) from 1976 to 2019. Among all the recorded incidents, most fatalities (57%) were caused by suffocation or asphyxiation from the toxic gases emitted from manure (Nour et al., 2020). Mitloehner and Calvo (2008) raised awareness that the number of incidents related to toxic emissions is most likely to be underestimated and not well documented (Mitloehner and Calvo, 2008). In addition, the health impact of the majority of constituents in a mixture of toxic gases emitted from manure is also poorly understood (Mitloehner and Calvo, 2008).

Technologies for mitigating gaseous emissions from livestock manure storage and livestock housing exist for on-farm adaptation, but very few are proven beyond lab- or pilot-scale trials (Maurer et al., 2016). The adoption of mitigation technologies and on-farm use are often not feasible due to socioeconomic limitations (Bird et al., 2022). Manure additive treatments based on proprietary bacterial mixtures are marketed in the U.S., but their effectiveness is not proven (Chen et al., 2020a, 2020b). The simplicity of using such 'pour into manure and forget' manure additives is attractive. Also, farmers appreciate manure treatments that are plant-based and perceived as 'safe' for land application. One example of a manure additive treatment is soybean peroxidase, an active ingredient in soybean hulls, a low-value fibrous biomass (Maurer et al., 2017a).

Use of BC for mitigation of gaseous emissions on a livestock farm-scale needs to be proven. Much progress has been made in lab- and pilot-scale trials and there is growing evidence from these trials that surficial application of BC onto manure can be effective in mitigating at least some target gases in the short- and long-term (Baral et al., 2023; Viaene et al., 2023; Scotto di Perta et al., 2024; Verdi et al., 2024). It is also evident, from these trials, that differences in BC properties, dose, and timing influence the mitigation efficacy.

This mini-review aims to organize the current state-of-the-art, identify the gaps, and recommend possible pathways that can bring the mitigating of gaseous emissions from manure using BC closer to farm-scale. The mitigation efficacy is summarized in the context of BC properties, manure properties, targeted gases, trial scales, doses, and duration. The benefits of the synergistic application of BC-manure mixture to crop fields, more sustainable nutrient cycling, and enhancement of biomethane production are also discussed.

2. Process for identifying the review scope

Wide-ranging research related to BC has been published in the last two decades. Many BC-themed reviews have summarized the selected aspects of BCs. Thus, the first step was to identify the knowledge gap and scope of this mini-review. Web of Science (2021) was used to search for relevant literature published until January 24, 2022. Initially, the 'topic' (biochar) yielded nearly 30,000 documents, of which nearly 1400 were 'reviews.' Interestingly, more than 50% of 'reviews' were published in 2020-21 alone. Additional refining of results by adding (TS= (biochar AND (manure OR animal waste)) yielded over 155 reviews. These reviews were mapped to show the bibliometric networks. The dataset used for VOSviewer was directly exported from Web of Science as a 'Plain Text File' with 'Full record' for the 'Record Content.' VOSviewer software used the 'Co-occurrence' analysis and set minimal occurrence at 12 to generate the keywords network, as shown in Fig. 1.

Screening of the results was then used to classify reviews into ten working categories depending on their scope. Fig. 2 illustrates the number of review papers in each of the categories. The following is the listing of the approximate number of reviews in each category, soil, and water (74), environmental applications (30), heavy metals and toxins removal (36), BC properties and characteristics (24), air quality-related (19), co-composting using BC (16), BC as feed additives (4), and mentioned BC but the focus is not closely related (33). Many reviews could be considered as belonging to more than one category, and the classification was rather arbitrary. Thus, a more thorough screening was made to identify the key reviews related to 'air quality, 'volatile organic compound', and 'greenhouse gases'.

The initial screening of review papers yielded over 250 reviews, all within the general nexus of agriculture and environment. The 'soil &

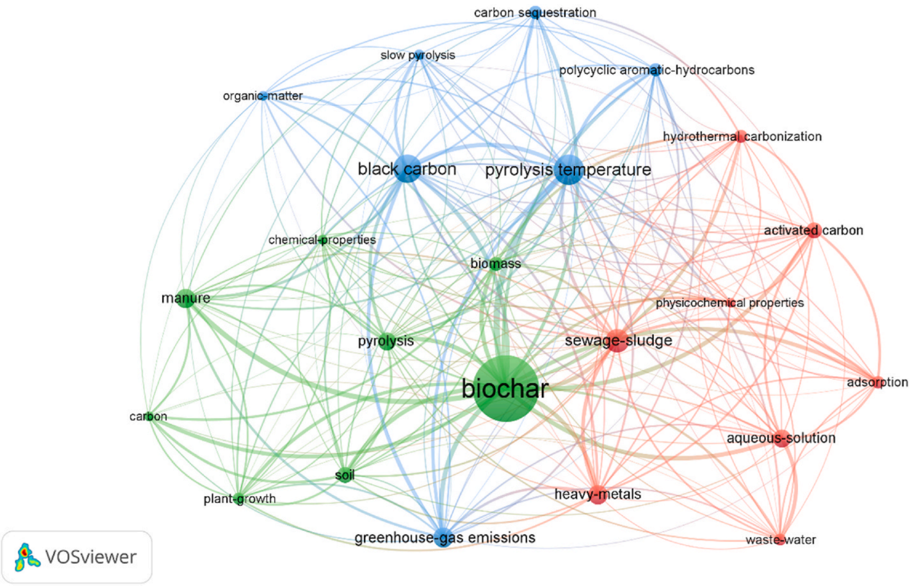

Fig. 1. Keywords network of reviews (published until the end of 2021) on biochar. The color shift from blue to yellow to red illustrates the progression of research focus over time. The bigger the node means higher number of appearances in the literature.

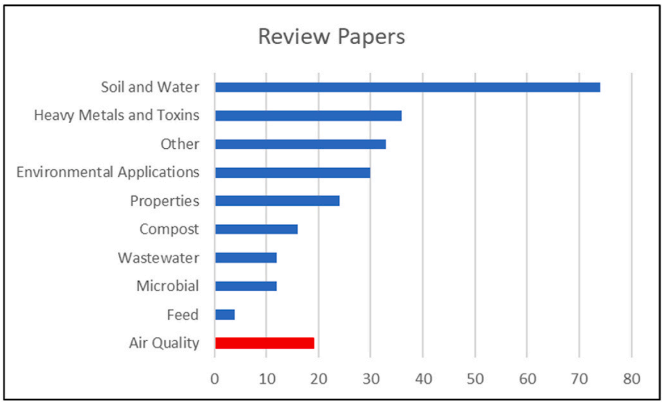

Fig. 2. Initial screening of reviews (published until the end of 2021) on biochar. This process narrowed the scope of this review topic.

water' theme was the largest and centered around the improvement of water and soil quality using BC for water retention, reduction of N leaching, pH management, stimulating microbial communities, and the removal of heavy metals and other toxins in soils and water. Examples include (Wu et al., 2017) which described BC's chemical recalcitrance, sorption capacity, and large surface area as beneficial for contaminated soil remediation. Feedstock and pyrolysis conditions can influence the positive or negative priming of microorganisms, and soil C mineralization, including soil C cycling (Vijayaraghavan, 2021). The 'heavy metal and toxins' themed reviews focused on how BC can be used to remediate contaminated water and soils. For example, Lahori et al. (2017) stated that BC can remove heavy metals in the soil; however, one type of BC cannot necessarily immobilize the multi-metals in contaminated soils. The third largest group is the general 'environmental applications' of BC focused on remediation for water and soil. Sun et al. (2018) showed that pyrolysis of P-rich biomass into BC and then applying the BC back to the soil could effectively recover the excessive P from the water. Using BC as an adsorbent for N and P can be valuable for turning the excessive nutrients bound to BC into valuable fertilizers (Shrestha et al., 2018). Properties of BC are summarized in numerous reviews. Tomczyk et al. (2020) detailed how BC characteristics are affected by multiple parameters (e.g., type of feedstock, pyrolysis temperature), and they affect the ability of BC to perform as a soil additive and a form of C sequestration. Oliveira et al. (2017) discuss how the physicochemical properties of BC, e.g., microporosity and pH, can impact the ability to remove pollutants. The role of BC in composting was also reviewed including specific foci reducing GHGs and N losses. Godlewska et al. (2017) reviewed the effect BC has on compost properties (e.g., nutrients availability, maturity indices). Wu et al. (2017) showed the BC's use as a composting amendment, especially its impact on organic matter's (OM) chemical characteristics and microbial structure. A review by Xiao et al. (2017) detailed the effect that BC addition on soil and composting can enhance microbial activity and improve the decomposition of OM through the stimulation of microbial structure. Gul et al. (2015) focused on the long-term impacts of BC addition and its properties on soil microbial communities. BC can also be beneficial in 'wastewater management' mostly centered around toxins removal. BC can act as a sorbent to functional groups and surface charges on the surface (Qambrani et al., 2017).

Interestingly, a handful of reviews revolve around BC used as a livestock feed additive. Specifically, focusing on BC's ability to provide either supplemental nutrient intake or remove toxins from animal feed or gut. BC could be useful in toxin adsorption, feed-use efficiency, and GHG reduction for several types of livestock (Sun et al., 2018). These effects may vary depending on the properties of BC and farm management.

3. Methods

A focused literature search yielded nearly 600 articles published before early February 2022. The search used keywords of 'biochar' combined with 'emission' and 'manure' or 'animal waste' (Web of Science, 2021). Nearly 60% of the articles were published after 2019, underlying the increased pace of scientific progress in this area (Fig. 1). This trend continues, as additional papers were identified using similar screening approach in the last stages of peer-review.

4. Summary of effectiveness of biochar on reducing emissions of odor, volatile organic compounds, NH_3, H_2S, and GHGs from livestock waste

The literature search yielded nearly 600 peer-reviewed papers and reviews. However, the initial review narrowed down the number of papers that are clearly within the scope of this review, i.e., the impact of direct BC application to manure on gaseous emissions. In addition, we observed that the majority of papers related to poultry manure were published in the context of co-composting. Thus, we restricted the review of papers on the poultry manure co-composting to the most recent papers (published after 2017) in this review.

In summary, the review of nearly 600 papers yielded 23 articles that adhered to the defined scope of this review. These 23 articles were then specifically evaluated to extract, summarize, and critically review the information pertaining to the manure and BC type and characteristics, including pH, process conditions and BC properties, mitigation efficacy towards targeted gases (odor, VOCs, NH_3, H_2S, GHGs), scale (lab-, pilot-, farm-), dose and time and mode of application, the research context, and main findings. The findings were organized by livestock and poultry species. The summary of this information is presented in Tables 1 and **2**. Table 1 summarizes the findings for swine, cattle, and dairy. Table 2 summarizes the findings for poultry, recognizing that the majority of research on BC and poultry manure was completed in the context of *composting*, and relatively few papers report on gaseous emissions.

5. Effects of biochar treatment of emissions of targeted gases from manure during storage and composting

Significant reductions in emissions were reported in the literature (Tables 1 and **2**) for subsets of targeted gases when manure was treated with BC. However, an increase in emissions (generation) of selected targeted gases such as GHGs was also observed. This reinforces the fact that a comprehensive assessment of mitigation efficiency needs to be considered, especially for impacts on GHGs. The degree of BC treatment effectiveness varies, and special care is needed when specific target gas mitigation is desired. Below is a short summary of BC treatment efficacy by main air pollutant and its drivers.

For odor mitigation, the 4–30% reported reduction depended on the biochar dose and, therefore, biochar layer thickness that was initially applied to the manure surface mattered. Dougherty et al. (2017) reported a statistically significant reduction of odor offensiveness from dairy manure treated with BC. Meiirkhanuly et al. (2020) observed that BC significantly reduced swine manure's odor concentrations in one trial out of three. Chen et al. (2021a) showed that the swine odor mitigation improved with the greater BC dose. More studies are needed to find the optimal dosage and determine the impact of BC properties on odor mitigation. No literature related to BC impact on odor from manure composting was found.

It is well-known that specific VOCs such as sulfur-containing VOCs, volatile fatty acids, and phenolics can contribute to manure odor. Based on the summarized literature, there was relatively little data and information on the effects of BC on VOC emissions mitigation. Five papers reported the mitigation effects of BC in reducing emissions of skatole (25–80%), indole (36–78%), phenol (28–89%), *p*-cresol (49–89%), and 4-ethyl phenol (53–87%). The apparent differences in the percent reduction were noted as stemming primarily from different doses, i.e., thickness of surficially-applied BC layer to manure.

For the BC impacts on NH_3 emissions, long-term trials (defined as two weeks or longer) resulted in 13–96% reduction, while short-term trials (one day or less) consistently resulted in 90–99% reduction. Notably, numerous papers report a 50–70% reduction when co-composting BC and poultry manure (Table 2). For liquid manures, controlling pH has been thought to be useful for NH_3 emissions. Thus, pH changes are important especially to shift the NH_3 & NH_4^+ equilibrium, possibly at near the air-manure interface, where surficially-applied BC temporarily resides (Meiirkhanuly et al., 2020). Holly and Larson (2017) observed as great a difference as 43% between trials based on feedstock alone. Hung et al. (2021) reported that wood-based BC did not impact the pH of livestock manure, but when mixed with urea ammonium nitrate (UAN) fertilizer solution, the BC reduced the pH of the solution and led to greater NH^{+} immobilization. It is expected that strongly alkaline soils increase NH_3 volatilization, but Mandal et al. (2016a) found that alkaline pH BC reduced NH_3 volatilization and enhanced wheat N uptake, suggesting that other sorption capacity driven by BC surface area and functional groups have a possible greater impact on NH_3 volatilization. Thus, the mitigating NH_3 emissions from manure might depend on the BC application method. From the practical standpoint, elimination of BC mixing with manure and favoring BC that floats and/or enhances partially submerged permeable cover should be explored.

Reports on the BC effectiveness in mitigating emissions of H_2S were found to be relatively few. Short-term effectiveness of one day or less was significant at 90–99% (similar to NH_3). This data stemmed from the same two papers that reported on the short-term mitigation of NH_3 by Chen et al. (2021a) and Kaikiti et al. (2021). Based on the similarities in percent reduction of both H_2S and NH_3 on a short-term basis, it is reasonable to conclude that the surficial BC application provides an effective permeable cover that effectively captures both gases released from manure. These findings are significant because short-term mitigation is crucial to reduce the hazardous short-term gas emissions during manure storage stirring and pump outs for field application. Three articles tested BC's ability to mitigate H_2S emissions for longer term trials (ranging from 1 month to 40 d). Two articles tested BC as an application to simulated deep pit manure storage, while the other tested its effectiveness for co-composting. The range of percent reduction was found to be relatively consistent across all trials, from 12 to 19% reduction of H_2S. Multiple feedstocks were used across the different trials, with Meiirkhanuly et al. (2020) using two separate feedstocks with different associated pH levels in their trials. Despite this, there was little variability in the percent reduction with Meiirkhanuly et al. (2020) only reporting a 3% reduction based on the particular BC types.

Reports on BC's effects on the emission of GHGs (CH_4, N_2O, and CO_2) were found to vary across the literature. The most diverging reports were associated with CH_4. There was an inconsistency in results as several articles identified significant percent reductions in CH_4 emissions, while other articles saw significant percentage increases in CH_4 emissions. Kaikiti et al. (2021) reported upwards of a 55% reduction of CH_4 during the short-term trial conducted with BC used as a cover for manure. In contrast to this, the longer-term trials conducted by Meiirkhanuly et al. (2020) reported an upward of 104–221% increase in CH_4 released from stored manure over the course of a month-long trial. This inconsistency is likely confounded by many factors, of which the trial elapsed time appears to be correlated with reports on short-term mitigative effects of BC, while the long-term trials increase the release of CH_4. This apparent lag time effect could be caused by microbial activity, which is well documented to be time-dependent in biogas production, but more research is needed to isolate specific drivers. The increase in the CH_4 emission could be related to several factors influencing the increase of biomethane production during anaerobic digestion (AD). Due to high loads of organics, the redox conditions in manure are strictly anaerobic. Application of BC to manure may increase the organics decomposition and the production of biomethane, similar to examples from anaerobic digestors where BC was applied. Practically for each physicochemical property of BC, hypotheses concerning the mechanism of influence on the fermentation process arose. The most important features and BC properties affecting the fermentation process include porosity, surface area, electrical conductivity, cation exchange capacity, pH, elemental composition, and so-called trace elements. The pores and surface area in the BC contribute to the creation of additional space for bacterial colonies, accelerating their development, and serving as an adsorbent of inhibitors (e.g. ammonia that inhibits the methanogenesis phase) (Alburquerque et al., 2013; Yargicoglu and Reddy, 2017). Electrical conductivity and ion exchange capacity are contributing to the direct transfer of electrons between the species of microorganisms occurring during CH_4 fermentation - DIET (direct interspecies electron transfer) (Valentin et al., 2023). Thanks to DIET, the microorganisms share the reducing equivalents to drive the methanogenic degradation of

Table 1

Summary of the effectiveness of BC on reducing emissions of odor, volatile organic compounds, NH_3, H_2S, and GHGs from *stored* in-situ manure. Bold font signifies statistical significance. A negative percent reduction value signifies the generation (increase) of emissions.

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose * Time** Mode of (re-) application ***	Context	Main Findings
Scotto di Perta et al. (2024)	Buffalo digestate (Commer.) Mixed woodchips (~10)	30 min pyrolysis at 550 °C. Point zero charge = 8.38	N/A	N/A	**43%** one-time 2 cm thick surficial application	N/A	N/A	Lab-scale, 5 L containers	2 cm thick (7 kg/m^2) both surficial and mixed in, 1 cm-thick (3.5 kg/m^2)	Simulated long-term 84 d manure storage treatment	BC acted as an adsorbent for NH_3 and NH_{4+}. Mixed in BC dose was less effective compared with surficial treatment. 1 cm-thick treatment less effective than 2 cm-thick.
Verdi et al. (2024)	Slurry: organic pig breeding farm Digestate: mixture of conventional pig breeding farm manure and straw, olive cake and sorghum silage Manure: organic cattle breeding farm	Slow pyrolysis olive tree vines, apricot and apple trees pruning's in mobile kiln at 500 °C	N/A	N/A	N/A	N/A	Slurry: CO_2 26%; CH_4 21%. Digestate: CO_2 45%; CH_4 78%. Manure: CO_2 40%; CH_4 81%.	Lab-scale, 10 L containers	2:1 ratio of treated matrix to BC	Simulated open storage for 21 d	BC reduced the global warming potential for 55% (digestate), 22% (slurry) and 44% (manure)
Viaene et al. (2023)	Dairy manure (Commer) Woody fraction of green waste (8.42)	Woody fraction of green waste: 15 min at 450 °C	N/A	N/A	**12%**	N/A	CO_2: no effect CH_4: **16%**	Lab-scale, 10 L containers	One-time BC treatment mixed into manure at 10 g/L of manure) followed by 7 d storage	Simulated storage trials followed by application to soil	Research highlights importance of systems approach to manure management and utilization as a fertilizer
Baral et al. (2023)	Cattle manure Miscanthus (MBC) (10.4) Acid-activated (AMB) (4.8) Digestate (DBC) (11.0) Acid-activated (ADBC) (8.9)	Feedstock pyrolyzed at 675 °C with feed rate of 21 kg/h.	N/A	N/A	MBC: no effect AMBC: **51%** in the first month, **25%** over 4 months. DBC: no effect ADBC: **37%** in the first month, **28%** over 4 months.	N/A	N/A	Lab-scale, 20 L containers	One-time BC treatment, 7 mm thick layer, 4-month trial	Simulated storage of treated manure over 4-month trial.	Acid-activated BCs performed better in mitigating NH_3 emissions
Hung et al. (2021)	Liquid swine Dairy slurry Poultry Urea ammonium nitrate (UAN) (Commer.) Softwood (8.6), Hardwood (7.4)	Softwood pyrolyzed at 450 °C. Total pore space (2.5 m^2/g) and mineral N concentration (18 mg NH_4-N + NO_3-N/kg). Organic C (680 g/kg). Hardwood	N/A	N/A	No effect	N/A	N/A	Lab-scale (20 L of manure)	0, 2.5, 5, 10, and 25 % BC by volume mixed with manure One-time measurement after 21 d	Simulated covered manure storages where wood-based BC was mixed with manure for 21 d	Wood-based BCr did not impact the pH of livestock manure, but when mixed with UAN fertilizer solution, the wood-based BC reduced the pH of the solution

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Table 1 (*continued*)

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose * Time** Mode of (re-) application ***	Context	Main Findings
		pyrolyzed at 750 °C. total pore space (13.4 m^2/g), and mineral N (42 mg NH_4-N + NO_3-N/kg). Org. C (440 g/kg)									and led to greater NH^+ immobilization
Chen et al. (2021a) -reapplication	Swine & corn stover (9.2)	Pyrolyzed at 500 °C. 8.42 zero-point charge, C (61.37%), H (2.88%), N (1.21%), VS (16.27%) Fixed C (34.98%) Ash (46.82%)	4–22% One time BC application: 4–11% depending on the dose. Biweekly reapplication: 22%	−40-89% One time **25–48%** skatole 36–38% indole 28–49% phenol −40-49% p-cresol 53–66% 4-ethyl phenol One time **80%** skatole **78%** indole **89%** phenol **74%** *p*-cresol **87%** 4-ethyl phenol	**25–53%** One time BC application: **25–33%** Biweekly reapplication: **53%**	N/A	CH_4 (−16 to −46%) One time −16–15% Biweekly reapplication: −46%	Pilot-scale (75 L of manure)	2-month long testing, 2 BC doses (2 or 4 kg/m^2)	Simulated long-term treatment of stored manure	Bi-weekly BC reapplication improves the % reduction in gaseous emissions for several targeted pollutants
Chen et al. (2021b,c, 2020c)	Swine & corn stover (5.2)	Pyrolyzed at 500 °C. Corn stover was ground to 3 mm and treated with 8% (wt.) iron sulfate	N/A	N/A	**68–99%** Powder: **99%** Pellet: **68%**	**72–99%** Powder: **99%** Pellet: **72%**	N/A	Lab-scale (3 L of manure)	3 h long testing, (4 kg/m^2)	Short-term storage and simulating manure agitation	Although the % reductions of BC powder treatment were much higher than pellet treatment, % reduction of BC pellets still showed a significant reduction in both NH_3 and H_2S during manure agitation
Liu et al. (2021)	Swine walnut shell (10.34) coconut shell (7.54) coal-derived (7.61)	500 °C TOC (58.5–64.4%) ash (2.59–81.09%) 0.05–4 mm particle size	N/A	N/A	**123–400%** Walnut shell: **400%** Coconut shell: **387%** Coal: **123%**	N/A	**83–628%**	Pilot-scale (30 kg of manure)	68 d long testing with manure/BC ratio of 20:1 by wt.	Simulated long-term treatments of liquid manure	BC can also enhance NH_3 and GHG emissions
Meiirkhanuly et al. (2020)	Swine Red Oak (7.5) &	Red oak pyrolyzed at 500–550 °C. 6.75 zero-point charge,	Entire study: 59-30% Trial 1: 31-**17%**	Entire study: 13 - 97%	Entire study: 4–39% Trial 1: **18–19%**	Entire study: 2–23%	Entire study: CO_2 (-57 - 25%, CH_4 (−221 to	Lab-scale (1.7 L of manure)	1-month long testing, 2 BC	Simulated long-term manure	BC properties affected the gaseous reductions.

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Table 1 (*continued*)

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose * Time** Mode of (re-) application ***	Context	Main Findings
	Corn Stover (9.2)	consisting of C (78.53%), H (2.54%), N (0.62%), and VS (26.38%). Fixed C & ash were 54.76% and 15.83% Corn stover pyrolyzed at 500 °C. 8.42 zero-point charge, C (61.37%), H (2.88%), N (1.21%), and VS (16.27%). Fixed C & ash were 34.98% and 46.82%	Trial 2: −12-21% Trial 3: −59-30%	Trial 1: 13-**97%** Trial 2: 8–**94%** Trial 3: 26–**99%**	Trial 2: **21%** Trial 3: 4–**39%**	Trial 1: 22–23% Trial 2: **19%** Trial 3: 2–**16%**	−26%), N_2O (-6 - 46%) Trial 1: CO_2 0–2% CH_4 **-55**- −26% N_2O -6 - 4% Trial 2: CO_2 (0–**17%** CH_4 **-104** - −41% N_2O 3–7% Trial 3: CO_2 0–**17%** CH_4 **-221** - −32% N_2O -1 -46%		doses (1.65 or 2 kg/m^2)	storage in three trials	Mitigation of one gas may lead to an increase in another. In this case, it mitigated VOCs, NH_3, and H_2S but generated GHGs
Pereira et al. (2020)	Swine (Commer.) Wood shavings (10.2)	bulk density: 0.1219 g/cm^3 humidity: 102.4 g/kg C: 806.0 g/kg N: 1.9 g/kg	N/A	N/A	**26%**	N/A	**50%** reduction in CO_2 when expressed as % of applied C **55%** reduction on CH_4 when expressed as % of applied C No effect on N_2O	Lab-scale (6 L of manure)	85 d testing, 2.5% by wt.	Simulated long-term liquid manure storage	BC treatments showed a significant reduction in the daily emissions of CO_2 and CH_4 for the first 13 & 17 d, respectively
Maurer et al. (2017b)	Swine Red Oak (7.28)	495–505 °C 1–25% Ash 60–75% C 175-μm particle dia	N/A	9–27% Indole for Trial 1: 12% after 9 d; 9% after 1-month Indole for Trial 3: 27% after 1-month No other effects on VOCs	13–23% Trial 1 saw no effect. Trial 2: After 6 d: **23%** After 9 d: **15%** After 1 month: **13%** Trial 3 saw no effect	12–30% Trial 3: After 9 days: **30%** After 1-month: 12%	CH_4 (−22 to −25%) Trial 2: After 10 d: 25% After 1 month: 22% 40% reduction on CH_4	Lab-scale (250 mL of manure Pilot-scale (75–120 L of manure)	1-month long testing, 3 BC doses (1.14 or 2.28 or 4.56 kg/m^2)	Simulated long-term manure storage in deep-pit to test effects of non-activated BC dose	Over a month-long trial, non-active BC provided a reduction in NH_3 and an increase in CH_4 emissions
Kaikiti et al. (2021)	Cattle Cattle Waste (10.43)	6–7 °C min^{-1} up to the desired temp. (550 °C) and held for 1.5 h, Density: 2.31 g/mL, Pore dia: 3.94 nm	N/A	Total VOCs: **~60%**	**~90%**	**~90%**	**40%** reduction in CH_4	Lab-scale (250 mL of manure	24 h, 10% by weight	Short-term mitigation of cattle manure	Waste-derived BC showed potential application toward gas removal
Dougherty et al. (2017)	Dairy Douglas-fir chips (9.32) & Douglas-fir bark and center wood (7.28)	Douglas-fir chips: 650 °C 86.9 mg/g ash 840.6 mg/g Fixed C 145.8 mg/g MC Douglas-fir bark &	Significant reduction in offensiveness 5–10 odor panelists testing	N/A	**72–80%** Douglas-fir bark and center wood did not reduce NH_3 emissions	N/A	N/A	Pilot-scale (17–70 L of manure)	2 – 3-month long testing (5 or 10 cm thick of BC)	Tested long-term effects of BC covers on the emissions from simulated manure pits	BC covers significantly reduced both NH_3 and odor released from manure while

(*continued on next page*)

Table 1 (*continued*)

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose * Time** Mode of (re-) application ***	Context	Main Findings
		center wood: 600 °C 6.8 mg/g ash 879.9 mg/g, Fixed C 81.9 mg/g MC	every 2 wk over 12 wk								sorbing nutrients from the manure
Brennan et al. (2015)	Dairy Wood Shavings (7.3)	650 °C for 4.5 h	N/A	N/A	**77%** 15 d post-application	N/A	N_2O **(63%)** 168 h post-application	Lab-scale (10 L)	168 h (3.96 m^3/ha)	Tested BC amended manure slurry in-field application	BC amended manure saw a significant reduction in NH_3 emissions, N_2O loss, and moderate GHG emission reduction
Holly and Larson (2017)	Dairy Wood (7.7) Corncob (9.88)	Wood chips pre-treated w/steam for 120 min 190 °C and 1207 kPa Both BC produced at 400 °C and held for 1 h	N/A	N/A	**53–96%** Wood BC cover: **96%** Wood BC incorporated: **84%** Cob BC cover: **59%** Cob BC incorporated: **53%**	N/A	N/A	Lab-scale (16 L)	7 weeks (5 cm)	Comparing the BC cover vs. incorporation of BC on their effectiveness of mitigation of NH_3 emissions	Floating covers and incorporation of BC can significantly reduce NH_3 emission, but wood BC cover showed a significantly higher %R

organic substrates (Viggi et al., 2017). The BC could serve as an electron transfer intermediate to accelerate the electron transfer from electron donor to electron acceptor by the cyclic transformation of oxidation and reduction states. Some recent studies proved that single-walled carbon nanotubes could establish the current between the electroactive syntrophic acetate-oxidizing bacteria and methanogens (Shen et al., 2020a). The BC alkalinity and buffer capacity is indicated as a stabilizing feature of the process by reducing the risk of acidification during AD with acid-phase products. In addition to the above hypotheses/mechanisms, carbon materials can regulate the chemical composition of the basic charge C/N ratio, trace elements such as Fe, Co, Ni, Zn, Mn, W, Cu, Se, all important during the methanogenesis step (Capson-Tojo et al., 2019). Additionally, the BC addition to an anaerobic digestor causes the formation of a protective layer around the microorganisms, favoring the production of microbial biofilm and the colonization of methanogens; it also binds inhibitors due to its hydrophobicity. In this way, it increases the access of bacteria to nutrients and removes (e.g.) ammonia and acetate (Indren et al., 2020). This was confirmed by studies under mesophilic conditions, during which the BC addition enriched the populations of microorganisms, among which archaea accounted for 44% (Lü et al., 2019). Another important role of BC in AD is to ensure process stability under stressful, suboptimal conditions, e.g., too high or too low pH. Due to its action as a buffer during the degradation of propionic acid, BC helped to stabilize the methanogen colonies (Lü et al., 2019; Ma et al., 2019). One of the investigated BC features playing a major role in the AD process, is the ability to limit the hydrolysis reaction, which reduces the lag phase and stimulates faster biomethane production (Jang et al., 2018). It is also related to the increase of its maximum yield, which is achieved in a shorter time. The reduction of the initial phase by 28.6% due to the BC use was observed by Wang et al., 2018a, and in studies by Indren et al. (2020) (by 33%), and 41% in the research of Liang et al. (2017). The positive BC influence on the fermentation process also consisted of improving the quality of biogas by adsorbing CO_2, H_2S, and other pollutants and increasing the CH_4 content. The addition of corn stover biochar in the study by Shen et al. (2015) increased the CH4 content to over 90% while reducing the H_2S to <5 ppb (Shen et al., 2015).

However, the mitigation of CH_4 was also reported by Agyarko-Mintah et al. (2017a, b) during the co-composting of two types of BC with poultry manure. Reported ranges varied slightly based on BC type but still between 78 and 85% reduction of CH_4 over the course of a 60-d trial, indicating that the BC could be mitigating gaseous emissions for at least some types of manure and treatment processes. In the literature, the negative impact of BC on CH_4 production during AD also have been reported (Kozłowski et al., 2023). These negative effects could be attributed to factors, like the release of heavy metals from certain types of BC, improper dose rates, CH_4 adsorption, and sudden application without the adaptation period. The observations, of the decrease of CH_4 emission from manure amended by BC, could be attributed to the adsorption phenomenon, and lack of microorganisms' adaptation to BC presence in the environment (Kozłowski et al., 2023). Valentin et al. (2023) studied the influence of the pre-incubation with BC of microorganisms on AD and revealed that the incubated system performed better than not incubated. Is shows that during short-term BC application to manure, the CH_4 emission may decrease because microbiological processes of AD are not developed.

Mitigation of N_2O with BC application was also reported at varying levels of effectiveness. Trials simulating long-term manure storage (longer than one month) with BC applied directly to the slurry were found to have either no effect or reported negligible changes and non-significant data. However, the effects of BC on N_2O emissions were confirmed mainly in the middle and later stages of the contact of nitrate/ammonia fertilizers with BC by promoting the nitrification of nitrifying bacteria and inhibiting denitrification of denitrifying bacteria, so as to reduce N_2O emission in soil (Tang et al., 2022.). Brennan et al. (2015) found a significant reduction in N_2O upwards of 63% for BC

Table 2
Summary of the effectiveness of BC on reducing emissions of odor, volatile organic compounds, NH_3, H_2S, and GHGs from *composted* manure. Bold font signifies statistical significance. A negative percent reduction value signifies the generation of emissions.

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose[a] Time[b] Mode of (re-)application[c]	Context	Main Findings
Poultry											
Li et al. (2022)	Poultry Peanut straws	The feedstock was cut into 3–5 cm, 400 °C	N/A	18%	20%	16%	N/A	Lab-scale (60 L reactor)	40 d of testing, 10% of BC was added by wt.	Co-composting peanut straws BC (10%) with poultry manure impacts emissions of NH_3, H_2S, and total VOCs	Co-composting BC significantly increased the relative abundance of nitrifying and denitrifying bacteria and decreased the S-reducing bacteria
Chung et al. (2021)	Poultry Rice husk (8.7)	42.6% total organic carbon 30.8% moisture content	N/A	N/A	18–35%	N/A	Increased the CO_2 emission at the initial stage	Lab-scale (100 L Plastic Reactors)	50 d of testing, 3%, 5%, 10% of BC by weight	Co-composting rice husk BC & sawdust (25%) with chicken manure impacts emissions of NH_3 & GHGs	CO-composting rice husk BC and sawdust with poultry manure reduced NH_3 emissions but increased CO_2 emissions
Chen et al. (2020d)	Poultry Chicken manure (9.32)	550–600 °C 24-h residence time 1.04% MC 4.98 nm pore size	N/A	N/A	21.8–41.4%	N/A	N_2O: 9–44.5% Increased the CO_2 emission rate and cumulative emissions CH_4: 9.3–55.9%	Lab-scale (100 L PVC Reactors)	42 d of testing, 2–10% of BC by wt.	Co-composting chicken manure BC with chicken manure impacts emissions of NH_3 and GHGs	The addition of chicken manure BC can accelerate the degradation of chicken manure, reduce some unwanted gases. Higher dosages showed greater reductions
Awasthi et al. (2020)	Poultry (Commer.) Bamboo (Not reported)	Not Reported	N/A	N/A	**16–67%**	N/A	N_2O: **34–59%**	Lab-scale (100 L PVC reactors)	42 d (0–10% BC treatments)	Testing the effectiveness of BC dose on the mitigation of emissions from simulated manure pits	Bamboo-based BC is an effective treatment for improving C & N retention during composting of poultry manure
Zhang et al., 2020a	Hen manure Cornstalk (Not reported)	450–500 °C 73.52% total organic carbon 8.65% moisture content 0.42 cm^3/g pore volumes	N/A	N/A	**6–23%**	N/A	N/A	Lab-scale (19 L containers)	15 d, 10% of BC by wt.)	Co-composting cornstalk BC (with immobilized mixed bacteria) and sawdust (21%) with laying hen manure impacts emissions of NH_3	Cornstalk BC loaded with mixed bacteria can effectively reduce NH_3 emissions during composting
Rong et al. (2019)	Poultry Wheat Stalk (9.10) Rice Husk (8.91)	500–600 °C 6-h residence time	N/A	N/A	Wheat Stalk: **53.4–88.7%** Rice Husk: **62.5–89.3%**	N/A	N/A	Lab-scale (0.5 m × 0.5 m × 0.8 m) reactors	54 d (5–15% w/w BC treatments)	Co-composting the wheat stalk and rice husk BC with chicken manure to test dosage effect on the mitigation of NH_3 from stored manure	Both wheat stalk and rice husk biochar are capable of reducing NH_3 volatilization significantly during the composting of poultry manure
Agyarko-Mintah et al. (2017a)	Poultry Green	550 °C 5–10 °C	N/A	N/A	N/A	N/A	Poultry Litter: N_2O	Lab-scale (220 L	60 d (10% dry wt. BC	Testing BC amended	BC amendment is an effective

(*continued on next page*)

Table 2 (*continued*)

Reference	Manure & biochar type (pH)	Process Conditions and Biochar Properties	Odor	VOCs	NH_3	H_2S	GHGs	Scale	Dose[a] Time[b] Mode of (re-) application[c]	Context	Main Findings
	Waste (6.30) Poultry Litter (8.30)	min^{-1} heating rate 45 min residence time					by **64%** CH_4 by **78%** Green waste: N_2O by **70%** CH_4 by **85%**	composting bins)	added to composting mixture)	compost to determine changes in N retention and GHG emissions	means for reducing GHG emissions from composting poultry liter
Agyarko-Mintah et al. (2017b)	Poultry Green Waste (6.30) Poultry Litter (8.30)	550 °C 5–10 °C min^{-1} heating rate 45 min residence time	N/A	N/A	Poultry Litter: NH_3 by **55%** Green waste: NH_3 by **60%**	N/A	N/A	Lab-scale (220 L composting bins)	60 d (10% dry wt. BC added to composting mixture)	Testing BC amended compost to determine changes in N retention and GHG emissions	BC amendment to composting is an effective way to decrease nitrogen and NH_3 losses from the composting of poultry litter

[a] – numerical % reduction reported; however, it was not statistically significant.

[a] Dose expressed in the units of kg of BC per m^2 area of manure surface unless otherwise stated.

[b] time signified the duration of the experiments.

[c] Mode of the application refers to the topical (sometimes called ’floating’) or mixed with manure (sometimes referred to as ’incorporated’); one-time application (typically at the start of the experiment or on a reapplication schedule.

added to manure on the field. Additionally, trials conducted on BC co-composting with manure reported a significant reduction in N_2O emissions across all trials and papers (34–70% reduction) for long-term trials.

Only a few researchers reported on the effects of BC treatments on the CO_2 emission from manure. Chung et al. (2021) and Chen et al. (2020d) both recorded the effect of BC co-composting with manure, resulting in a general increase in emitted CO_2, particularly in the initial trial stages. In contrast, Meiirkhanuly et al. (2020) reported CO_2 reductions up to 17% for two out of three trials. Further evidence of BC capable of reducing CO_2 emissions from stored manure come from Pereira et al. (2020) who reported a reduction of up to 50%, expressed as a percent of applied carbon. The main process responsible for CO_2 emission mitigation is the adsorption of the highly porous BC (Guo et al., 2022).

6. Effects of time on biochar treatment effectiveness

Most of the BC trials ranged in length from a couple of days to a few months in duration. BC’s mitigation effects appeared to decrease over time, perhaps as a result of its gradual sinking into the liquid manure. The physical barrier that BC provided against gas emission breaks, and gases are released into the air. Increases in gas emissions were also seen at the end of some trials, specifically in CH_4 emissions, because they are time-dependent in the sense that bacteria and microbes need time to develop and generate CH_4. Thus, the BC reapplication interval is a critical concern as the manure needs to be stored for 10–12 months in a typical deep pit-type swine building. Chen et al. (2021a) showed that biweekly reapplication of BC effectively increased the mitigation effects on all targeted gases compared with the one-time dose over a two-month period. Still, the majority of experiments were conducted in a lab-scale setting.

7. Scaling up, technology readiness, and practical considerations

The majority of the studies were completed on the lab scale. A few studies have shown significant percent reductions for some targeted gases on pilot scales and therefore, might be ready for scale-up testing (Chen et al., 2021a; Liu et al., 2021; Dougherty et al., 2017). The farm-scale testing of BC is a challenge. Practical issues such as applying a uniform layer of BC powder on the swine manure and minimizing the losses by drift and uncontrolled deposition of soot-like substance, and therefore public-relations impact are essential to consider. (Chen et al., 2021c) studied the pelletization of BC powder and its effectiveness on the NH_3 and H_2S emissions during manure agitation. Pellets are easier to apply and make it possible to avoid excessive, uncontrolled BC loss during application. The BC pellets treatment showed significant effectiveness in reducing emissions, but the percent reductions were significantly lower than side-by-side BC powder applications. It is still unknown how effective BC treatment can be due to the continuous manure addition by the animals on the farm. Only Chen et al. (2021a) tried the biweekly addition of manure, but this might not represent the real scenarios with animals constantly adding manure.

Overall, it can be summarized that many BCs can be effective in mitigating odor, selected odorous VOCs, NH_3, H_2S, and most reports are trending into apparent efficacy of treatments. However, there is still a need for more comprehensive research to address the sensitivity of results due to controlled BC properties, manures, modes of application, etc. With more evidence, it could be possible to recommend a BC type (or at least a BC with a range of properties) for application to particular farm-scale situations. The apparent diverging results, especially for GHGs, underscore this gap in knowledge. The BC standardization and use of certified material in research would be essential to further investigate the drivers behind mitigating or generating specific gases.

8. Biochar properties and standardization

Many research trials are based on a ‘black-box’ experimental design, which mainly focuses on whether there were reductions in gas emissions from manure. Without listing detailed BC properties, it is challenging to fairly compare the treatment effectiveness among the published reports since properties can impact the results. Thus, it is crucial to work towards certification and standardization of BC intended for specific uses (e.g., treating gaseous emissions from manure).

The European Biochar Certificate (EBC) (European Biochar Certificate) defines BC as a ’porous carbonaceous material produced via biomass pyrolysis’. Thus, this definition excludes other BC-like materials generated via the carbonization process and torrefaction. Aiming at specific applications, the BC must be certified under different classes. BC certified as *'EBC-BasicMaterial'* can be traded as building material; *'EBC-ConsumerMaterials'* can be used in products directly in contact with food-grade products; 'EBC-Feed' meets all the requirements of the EU feed regulations; 'EBC-Agro' and *'EBC-AgroOrganic'* meets all requirements of the EU fertilizer regulations; The 'EBC-Urban' provides a standard for BC use in tree planting, park maintenance, sidewalk embellishment, and rainwater drainage or filtration. The 'EBC-Urban' cannot be used as a soil amendment for food or feed production. The *'EBC-ConsumerMaterials'* and *'EBC-BasicMaterials'* cover all necessary environmental requirements for non-soil applications. Finally, the 'EBC Positive' lists biomass types permissible for the production of certified classes. For BC production, the pyrolysis temperature must be within 20% of the targeted setpoint. Similarly, if more than one type of biomass is used, its fraction cannot change >20%. The end product must report the organic C, N, P, K, Mg, Ca, Fe, pH, salt content, bulk density, and water content. Heavy metals must not exceed specified concentrations. The molar ratio between H and organic C must be lower than 0.7. The molar ratio between O and organic C must be lower than 0.4.

The International Biochar Initiative (IBI) (International Biochar Initiative) created a standardized and recognized system to certify BC under the IBI Biochar Standards in North America. The standard ensures that BC meets the minimal physical and chemical properties, especially for soil applications. BC producers must identify all the feedstock sources, including feedstock type, conversion rate, and harvest location. In addition, accredited laboratories test and provide the BC's basic utility properties and toxicant assessments. IBI approves and labels the biochar with the 'IBI Certified' BC seal for soil applications based on all the results (International Biochar Initiative).

Restrictions to BC properties (e.g., certified by EBC and/or IBI) for applications to soil should be useful to consider in the case of BC use as a manure additive, which will enter the food chain. Since BC used as manure additive will be applied on the fields as a manure-BC mixture, it would be rational to assume that BCs certified for soil amendment would be safe to use as a manure additive. The addition of relatively small quantities of BC to larger volumes of manure facilitates the dilution of potentially hazardous materials in BC, i.e., lowering the risk of immediate impact on the human or animal food chain. The long-term bioaccumulation of hazardous materials in the soil is still possible and should be evaluated. Indeed, BC used as manure additive also should be considered for their health and environmental impact on the livestock or farmers.

The emission of pollutants from manure mitigation by BC application depends on BC's numerous properties, which differ depending on the pyrolysis conditions, however, the temperature is the crucial one. For example, Zhao et al. (2021) showed that the electrical conductivity increased with the increment of temperature. BC produced under 400, 600, 800, and 1000 °C had the following electrical conductivity 0.001, 0.03, 0.8, and 6.3 S/m, respectively. Further increase in temperature above 800 °C caused the electrical conductivity increased significantly. The electrical conductivity of BC depends on the degree of carbonization, which may influence the DIET phenomenon (Valentin et al., 2023). The increase of pyrolysis temperatures increases a higher specific surface area (Howell et al., 2021) in the range of 450 and 650 °C. However, Ramola et al. (2020) revealed that the surface area of BC decreased when the temperature reached 700 °C.

The pH of most BC depends on the pyrolysis temperature, as it is a direct result of the carbonization degree, and ash content (Ahmad et al., 2012). Biochar pH generally increases with the increase of the pyrolysis temperature due to the rising content of more alkaline elements, ash contents, and exchangeable and soluble cations (Li and Chen, 2018, Świechowski et al., 2022).

The temperature influences the presence of the functional groups in BC. Sahoo et al. (2021) and Ahmad et al. (2014) showed that the increase of the pyrolysis temperature decreases in the polar functional groups. Hydrophobic chars containing only a few functional groups were produced under a temperature higher than 600 °C, which may influence the adsorption capacity for organic pollutants. The dehydration and deoxygenation reactions are responsible for that phenomenon. Yaashikaa et al. (2020) showed that the increase in the pyrolysis temperature significantly increases the pore structure of the BC, however, Maljaee et al. (2021) pointed out that exceeding 700 °C decreases the porosity.

9. Improved biogas production, improved digestibility and digestate quality

While BC generally is responsible for generating CH_4 emissions from manure, this outcome can be beneficial if harnessed properly. Studies have reported that BC addition improved CH_4 production in biological waste treatment processes. Specifically, it was shown that biomethane production could be enhanced in AD of organic fraction of municipal solid wastes, straw, manure, and sewage sludge. This finding is of interest to the livestock agriculture industry because biomethane production based on manure can be a significant source of income. For example, a review (O'Connor et al., 2022) of environmental benefits of food-waste anaerobic digestate recommended conducting studies to utilize digestates more efficiently by taking advantage of emerging technologies like BC. Various BC outsourced from forest waste, poultry waste, straw, sawdust, manure, algal biomass, brewer's spent grain, and wood were shown to improve biogas yields (Frias-Flores, 2020; Giwa et al., 2019). Studies of the influence of BC on AD were carried out both on a laboratory and industrial scale, during batch, semi-continuous and continuous experiments in earlier (Kumar et al., 1987) and recent studies (Meyer-Kohlstock et al., 2016).

The mechanisms of biomethane production as a function of BC addition were also explored in recent literature. Studies have shown that the BC addition in the AD process resulted in the formation of a protective layer around the microorganisms, favoring the production of microbial biofilm and the colonization of methanogens. BC can also bind inhibitors due to its hydrophobicity. Thus, BC can increase the access of bacteria to nutrients and removal of unwanted chemicals such as NH_3 and acetate (Indren et al., 2020). This was confirmed by studies under mesophilic conditions, where BC enriched the populations of microorganisms, among which *archaea* accounted for 44% (Lü et al., 2019). BC can also play an important role in stabilizing the AD process under stress conditions, e.g., pH outside of an optimal range. Buffering properties of BC can help to stabilize the methanogens during propionic acid degradation (Ma et al., 2019).

Possibly one of the most important discoveries was BC's ability to limit the hydrolysis reaction, which reduces the lag phase and stimulates faster biomethane production in the AD process (Jang et al., 2018). The range of the lag-phase reduction was from 29% to 64% (; (Wang et al., 2018b); Indren et al., 2020; Liang et al., 2017). (Wang et al., 2018b) reported the maximum biomethane production rate increased by 40.3%. This trend has been confirmed by Cimon et al. (2020), where during the first two weeks of CH_4 production there was an increase of 192–461%, compared to the control. Higher biogas yields reported were 8.6%–17.8% (Wei et al., 2020), 32% (Indren et al., 2020), 34.7% (Kumar et al., 1987), 54% (Zhang et al., 2020b) and 69% (Indren et al., 2020).

Another positive influence of BC was documented in improved biogas quality, since BC adsorbed impurities such as CO_2 and H_2S. The BC addition increased the CH_4 content to over 90% while reducing the H_2S to <5 ppb and removed 86% of CO_2 (Shen et al., 2015). Wei et al. (2020) reported an increase in biomethane content by 87%, while Yun et al. (2018) and Shen et al. (2016) reported up to 98% and 92%, respectively. Lü et al. (2019) reported 32.5% and 13.3% biomethane increase in mesophilic and thermophilic conditions, respectively. Shen et al. (2017) reported a 25% biomethane increase. Moreover, the addition of BC also resulted in a secondary biomethane yield peak (Shen et al., 2020b).

10. Intentional modification of biochar properties

Modification of BC properties can enhance the effectiveness of its targeted applications and can be engineered for maximizing its GHG mitigation potential (Mandal et al., 2016b)". This is still an unexplored field when it comes to the mitigation of gaseous emissions from manure. On-farm AD and biomethane generation can largely reduce fugitive emissions from stored manure. There is plentiful evidence in the literature that intentional modification of BC properties could be feasible, especially if economic outcomes are expected. Changes in thermal process parameters can lead to changes in BC properties. A wide range of treatments were described in the literature, including the effect of steam, CO_2, ozone, temperature above 700 °C, KOH, NaOH, NH_3, K_2CO_3, $ZnCl_2$, H_3PO_4, H_2SO_4, ethanol, and HCl (Cha et al., 2016). Such modifications were aiming to increase the pore fraction, specific surface area, and/or the formation of functional groups, that can be useful in removing pollutants from water and soil (Rajapaksha et al., 2016; Benis et al., 2020). Optimizing the BC activity via modification can, however, impact other properties, such as electrical conductivity, zeta potential, buffering capacity, and relative abundance of oxygen-containing functional groups, which in turn affect various aspects of processes used in environmental applications, including biomethane generation. Thus, there is an opportunity to explore BC activity routes aiming to increase the potential of BC to the sorption of various pollutants or compounds (Vijayaraghavan, 2019).

To date, only handful of studies report using modified BC in the AD process. In a study (Li et al., 2019), manganese oxide-modified BC improved the processes of production and degradation of intermediate acids and stabilized the fermentation process by pH buffering. The cumulative biomethane recovery was 122% when compared to the control. A similar positive effect was reported by (Zhang and Wang, 2020) who used $MnFe_2O_4$-modified BC during AD of sludge. The cumulative biomethane yield was 56% higher and BC treatment was credited with improving process efficiency by stimulating the *Methanosarcina* bacteria activity. The biodegradation of sludge's OM was also improved significantly, marked by the 35% increase of volatile fatty acids degradation rate. The modified BC addition led to the immobilization of heavy metals in the sludge. However, the excessive $MnFe_2O_4$-modified BC addition can have an inhibitory effect on AD. The research conducted by Wuri et al. (2019) on the effectiveness of BC outsourced from poultry manure and digestate to capture CO_2 from biogas was analyzed. However, when CO_2 sorption using BC immersed in ammonia solution was tested, it had no effect on removing CO_2 from biogas.

BC properties affecting the biowaste fermentation process include porosity, surface area, electrical conductivity, cation exchange capacity, pH, and elemental composition, including trace elements. Pore space and surface area generates additional space for bacterial colonies, and sorbing inhibitors (e.g., ammonia) (Alburquerque et al., 2013; Yargicoglu and Reddy, 2017). Electrical conductivity and ion exchange capacity contribute to the direct transfer of electrons between microorganisms, termed DIET (direct interspecies electron transfer). In DIET, the microorganisms share the reducing equivalents to drive the methanogenic degradation of substrates (Cruz Viggi et al., 2017). The BC could serve as electron transfer intermediate to accelerate the electron donor-acceptor transfer and enhance the cyclic transformation of oxidation and reduction states. The recent study by Shen et al. (2020a) proved that single walled carbon nanotubes could establish the current between the electroactive syntrophic acetate-oxidizing bacteria and methanogens. The DIET has been thought to be the main reason for the enhancement of biomethane production by different types of BC, however, the details of how DIET works, the involved microbes by different types of BC, the mechanism of BC on the ATP yields, and biomass changes or biomethane yields are still unknown. The alkalinity of BC and buffer capacity is indicated as a stabilizing feature of the process by reducing the risk of acidification of the reactor with acid phase products. In addition, BC can be used to regulate the chemical composition of the basic charge C/N ratio, as well as the number of trace elements such as Fe, Co, Ni, Zn, Mn, W, Cu, Se, both of which are important components during the methanogenesis step Capson-Tojo et al. (2019). Thus, many properties of BC may influence the biomethane production from biowaste; there is a need for the determination of the real nature of the microbial mechanism of the BC influence on biomethane production, and the contribution of each of the properties in this mechanism, under specific conditions of the fermentation.

There is a potential to exploit the modified BC use to optimize the AD process for manure treatment. While the upfront cost for thermophilic (enclosed) AD is high, the AD process can mitigate many of the fugitive gaseous emissions by eliminating or at least minimizing the need for open manure storage. Also, the production of BCs from biowaste such as manure and using it for the biomethane yield lends itself to the concept of a circular economy, leading to the perception of the organic waste fraction as secondary raw material. This application would result not only in the development of sustainable waste management but could also bring economic and environmental benefits. Thus, the selection of methods used to modify BCs and the understanding of the mechanisms of its impact on the fermentation are necessary for AD improvement.

11. Biochar-treated manure is better fertilizer

There is a potential synergy between mitigating emissions and improving manure quality for land application that should be explored further, especially in the context of scaling-up BC treatment to field trials. There is emerging evidence that BC can be a comprehensive solution to (1) mitigating gaseous emissions from manure storage while also (2) upgrading manure as a high-quality fertilizer that could then (3) improve the sustainability of animal and crop production systems. Banik et al. (2021a) showed that manure-BC incubation enabled BC to stabilize the carbon and several nutrients from swine manure. The subsequent manure-BC mixture application to soil improved soil quality and plant nutrient availability compared to conventional manure application. Banik et al. (2021b) reported that soil OM significantly increased in manure-BC treatments and suggested that the presence of BC can influence the soil N and P, especially because nutrients are not lost at the early stages of corn and soybean growth. The results also show that manure-BC has the potential to be a better soil amendment than conventional manure applications. One of the major issues with livestock manure is the presence of heavy metals such as arsenic in chicken manure. Application of BC can reduce the bioavailability of these heavy metal contaminants thereby improving the fertilizer value of manure (Bolan et al., 2004). Bonds et al. (2022) reported a comprehensive dataset documenting the interactions of BC with manure, soil, and plants. This dataset also included BCs mixed with manure alongside both manure and soil controls for improvement in soil quality, reduction in nutrient movement, and increase in plant nutrient availability.

12. Conclusions

This study summarized how biochar (BC) affects manure and BC properties, as well as BC's impact on targeted gas emissions including odor, VOCs, NH_3, H_2S, GHGs. Most studies showed BC can reduce certain gas emissions, but a few noted increases. There are different methods to apply BC, such as adding it directly onto the surface of manure or co-composting with manure. More research is needed to scaling up from lab experiments to farms. Biochar shows promise as a comprehensive solution for reducing gaseous emissions while enhancing manure as a high-quality fertilizer, thereby improving the sustainability of animal and crop production systems. Standardizing and certifying BC properties for specific environmental management purposes is recommended.

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CRediT authorship contribution statement

Baitong Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Jacek A. Koziel:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Andrzej Bialowiec:** Writing – review & editing, Supervision, Conceptualization. **Samuel C. O'Brien:** Writing – review & editing, Visualization, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No new data was generated for this review paper. Bibliographic summaries were generated using search engines in Web of Science.

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