applied sciences

MDPI

Review

Can Biochar Improve the Sustainability of Animal Production?

Carly Graves [1], Praveen Kolar [1], Sanjay Shah [1], Jesse Grimes [2] and Mahmoud Sharara [1,*]

[1] Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695, USA; cgraves2@ncsu.edu (C.G.); pkolar@ncsu.edu (P.K.); sbshah3@ncsu.edu (S.S.)
[2] Prestage Department of Poultry Science, North Carolina State University, Raleigh, NC 27695, USA; jgrimes@ncsu.edu
* Correspondence: msharar@ncsu.edu; Tel.: +1-919-515-8242

Abstract: Animal production is a significant contributor of organic and inorganic contaminants in air, soil, and water systems. These pollutants are present beginning in animal houses and impacts continue through manure storage, treatment, and land application. As the industry is expected to expand, there is still a lack of affordable, sustainable solutions to many environmental concerns in animal production. Biochar is a low-cost, sustainable biomaterial with many environmental remediation applications. Its physicochemical properties have been proven to provide environmental benefits via the adsorption of organic and inorganic contaminants, promote plant growth, improve soil quality, and provide a form of carbon sequestration. For these reasons, biochar has been researched regarding biochar production, and application methods to biological systems have a significant influence on the moisture content, pH, microbial communities, and carbon and nitrogen retention. There remain unanswered questions about how we can manipulate biochar via physical and chemical activation methods to enhance the performance for specific applications. This review article addresses the positive and negative impacts of biochar addition at various stages in animal production from feed intake to manure land application.

Keywords: manure management; emission mitigation; odor; sustainable agriculture; composting; adsorption

check for updates

Citation: Graves, C.; Kolar, P.; Shah, S.; Grimes, J.; Sharara, M. Can Biochar Improve the Sustainability of Animal Production? *Appl. Sci.* **2022**, *12*, 5042. https://doi.org/10.3390/app12105042

Academic Editor: Manfred Lübken

Received: 26 March 2022
Accepted: 15 May 2022
Published: 17 May 2022

1. Introduction

As the world population is expected to reach 9.7 billion people by 2050, the global demand for animal protein is projected to increase correspondingly [1]. The United States Agriculture Department (USDA) projects meat chicken production to increase by 5% and milk production by 9% by 2030 [2]. At the same time, fewer resources, i.e., energy, arable land, and fresh water, are available to support food production [3], which challenges the sustainability of food animal production.

Animal production is challenged by significant inputs, with feed consuming the majority of water, land, and fuel inputs and associated with the largest greenhouse gas (GHG) emissions [4]. The low efficiency of converting dietary protein to animal protein (i.e., ~33% for broilers, 23% for swine, and 18% for milk) is a primary driver for the significant production inputs per unit of protein produced [5].

Animals generate significant amounts of nutrients in manure, bedding, wastewater, excess feed, and mortalities. A large share of these nutrients become emissions that negatively impact the air, water, and soil quality. Specifically, animal production is among the largest sources of global methane emissions (32%) [6] and produces significant amounts of other gaseous emissions as demonstrated in Table 1. In addition, excess nitrogen and phosphorus from manure management and utilization is translocated from the field via runoff to surface waters or by leaching through the soil to the groundwater.

Table 1. Primary airborne emissions of concern in animal production [7–12].

Gaseous Species	Sources	Negative Impacts
Methane (CH_4)	Enteric fermentation, manure management	Global warming, 25*x* CO_{2e} (GWP100) [1]
Carbon dioxide (CO_2)	Animal feed, on farm energy	Global warming, 1*x* CO_{2e}
Nitrous oxide (N_2O)	Applied and deposited manures, manure management Applied and deposited manures, manure management Applied and deposited manures, manure management	Global warming, 300*x* CO_{2e} [1]
Hydrogen sulfide (H_2S)	Manure storage (lagoons, pits, ponds)	Contributes to acid rain; odor; human health hazard at high concentration
Ammonia (NH_3)	Synthetic fertilizers, manure, manure land application	Contributes to $PM_{2.5}$ formation; soil nitrification and acidification; algal blooms; human respiratory health impacts
Volatile Organic Compounds (VOCs) (e.g., alcohols, ketones, esters)	Confined animal housing, manure	Potential health impacts (eye, nose, and throat irritation); at high concentrations may cause lung irritation, damage to the liver, kidney, or central nervous system
Fine particulate matter ($PM_{2.5}$)	Confined animal housing, manure or fertilizer land application, bedding	Microscopic solids or liquid droplets that cause human respiratory health impacts upon inhalation; contributes to haze and smog; contributes to acidic deposition in soil and water
Odor (e.g., sulfides, volatile fatty acids, phenol, etc.)	Manure, manure land application, wastewater	Quality of life impacts on downwind communities

[1] Global warming potential over 100 years, 1 ton of gas per 1 ton CO_2.

Considering the significant production inputs and emissions associated with animal production, there is a critical need to advance the environmental sustainability of animal production especially with projected sector growth. Among the promising materials and technologies that could advance the sustainability of animal production is biochar.

Biochar is a stable, carbon-rich product from the thermal treatment of biomass (waste or lignocellulosic) at high temperatures in the absence of oxygen. This treatment significantly alters the biomass physical and chemical properties, thereby, creating biochar with a porous structure, high surface area, and added functional groups on the surface. As a result of these changes, biochar possesses unique physical and chemical properties that can help capture pollutants (solid, liquid, or gaseous) that would otherwise be released into the environment by serving as an adsorbent [13]. Biochar can also be modified and engineered to adsorb specific contaminants through acid/base and steam treatments. For these reasons, biochar has been studied for a variety of environmental applications.

Utilizing biochar in animal production also has the potential to adsorb pollutants, improve the welfare and productivity of animal growth, increase soil carbon sequestration, and increase the value of manure-based fertilizer. Biochar in animal production would increase the circularity of the industry by reusing agricultural crop or manure waste in creating biochar and reintroducing it into the system to support production and sustainability. Figure 1 visualizes the results of our literature search using Web of Science (Clarivate Analytics) for studies related to biochar and animal agriculture between 2008 and 2022 using the following search terms "biochar AND (animal OR livestock OR poultry)".

The figure, developed using VOSviewer tool, highlights the key themes of investigation in this area, i.e., (1) producing and characterizing biochar properties and adsorptive performance, (2) incorporating biochar as an emission mitigation aid in composting-related studies, and (3) biochar soil incorporation for crop production. The figure highlights the potential for integrative research to bridge the gap across these areas to assess the life-cycle performance of biochar in animal agriculture systems.

Kalus et al. [13] reviewed the use of biochar in animal feed, manure treatment, and land application. However, there still remains research gaps in the areas of utilizing biochar modifications to target certain compounds/pollutants and biochar interactions with microbial communities. Figure 2 outlines the scope that this paper will address for biochar inclusion into animal production systems. The objective of this review is to describe research efforts to incorporate biochar into animal agriculture for the improvement of animal production parameters and the reduction of environmental impacts by answering the following questions:

1. In what ways can biochar support animal production systems?
2. How can biochar be engineered to increase its benefits for animal production systems?
3. What is the outlook/need for widespread implementation of biochar use in animal production systems?

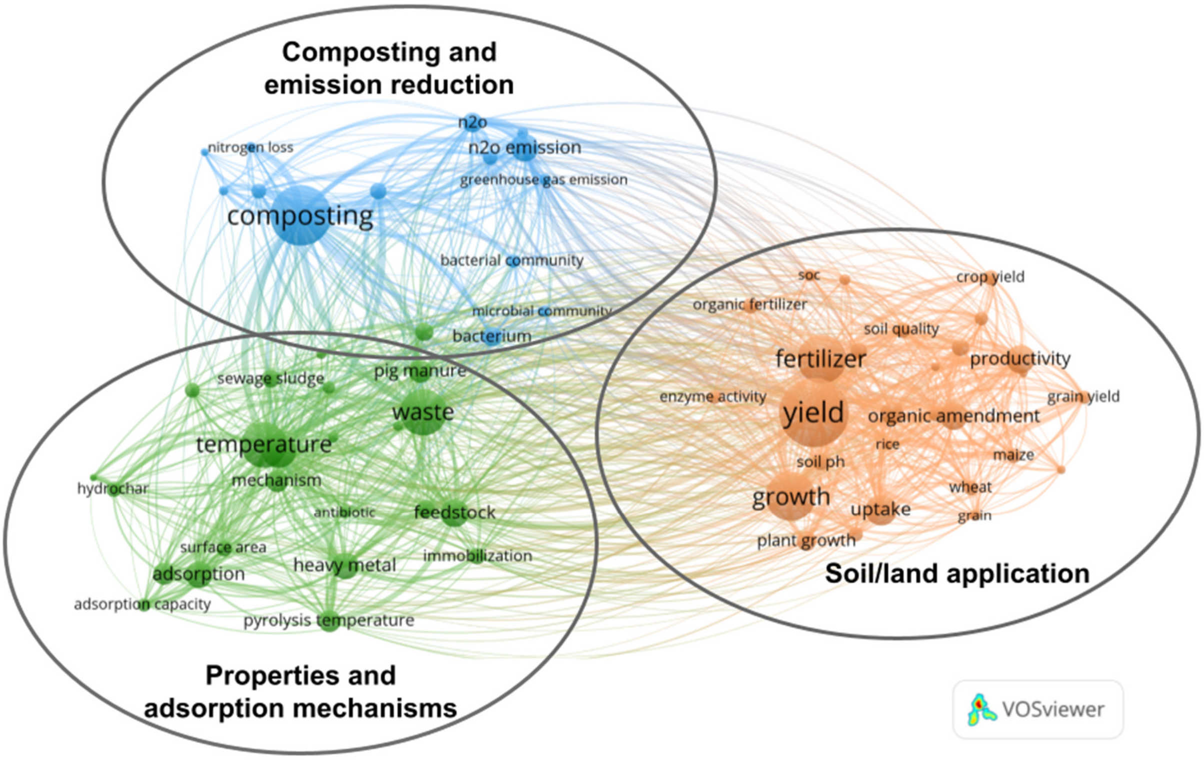


Figure 1. Word map of the key terms in abstracts and titles for 3557 publications (2008–2022) identified via a Web of Science literature search.

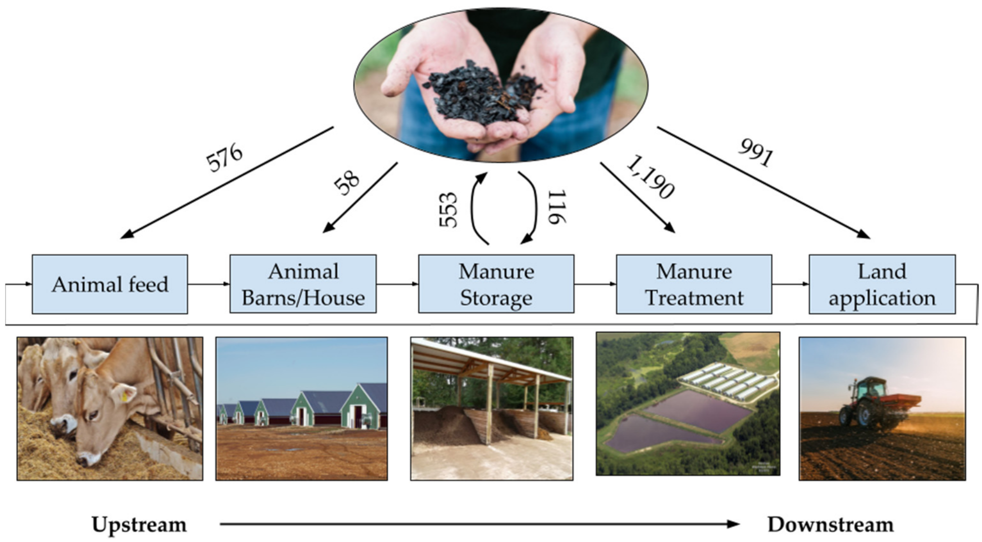


Figure 2. Biochar use-opportunities in animal production; the numbers of publication in each use-opportunity from Web of Science.

2. Summary of Biochar-Production Techniques

Depending on the feedstock, several thermal approaches are available to synthesize biochars. Some of the common techniques include pyrolysis, hydrothermal carbonization, and torrefaction. Biochar may also be produced via gasification, although the yield of biochar is usually small and therefore not included in this discussion. However, several articles on gasification-derived biochars are available in the literature.

2.1. Production Processes

2.1.1. Pyrolysis

The name for this high-temperature process is derived from the Ancient Greek terms πῦρ (pûr, "fire") and λύσις (lúsis, "loosing"). The high temperature treatment removes volatile matter in the form of high-energy condensable (bio-oil) and non-condensable gases (CO_2, CO, H_2, and simple hydrocarbons). Pyrolysis involves the thermal treatment of a carbonaceous material in the absence of oxygen [14]. Typically, the raw material is heated at temperatures between 400 and 900 °C under a continuous flow of nitrogen or helium.

Depending on the heating rate, pyrolysis can be slow, fast, or flash, although slow pyrolysis is preferred for biochar production [15]. As the biomass is subjected to anoxic heating, it undergoes dehydration followed by the decomposition and volatilization of volatile compounds resulting in a porous carbon-rich solid mass called biochar [16,17]. Excellent reviews on the pyrolysis processes and the mechanisms are available in the literature [18,19].

Several types of biomass have been explored for pyrolysis to synthesize biochars for applications in water treatment, soil conditioning, and catalysis. A few of the biochars synthesized from animal wastes are discussed here. Tsai et al. [20] employed slow pyrolysis between 300 and 800 °C for the synthesis of biochar from swine manure. Subsequent analysis of the biochars indicated that the pH of the biochar increased with an increase in the carbonizing temperature.

In addition, a temperature of 700 °C was found to be the optimum for the development of mesoporous porosity in biochar. Swine manure was also used as a substrate for the synthesis of biochars for the removal of copper from wastewater. Meng et al. [21] pyrolyzed fresh and composted manure at 400 and 700 °C and investigated the adsorption of copper in a batch system. They observed that the adsorption was endothermic with adsorption capacities between 9.15 and 21.8 $mg_{Cu(II)}\ g^{-1}$ for fresh and composted biochars.

Yue et al. [22] employed the slow pyrolysis of cow manure at 300–700 °C (2 h) to prepare biochars. Surface analysis of the biochars suggested an increase in surface basicity with temperature that suggested their suitability in conditioning acidic soils. Biochars from cow manure were synthesized by Zhang et al. [23] using temperatures of 300, 500, and 700 °C. Based on their results, the porosity of biochars increased with an increase in temperatures. When tested for the adsorption of tetracycline from water, the biochars chemisorbed 15–26.7 mg g^{-1}. Pontiroli et al. [24] employed poultry litter as a precursor for the synthesis of high-surface-area (>3000 $m^2\ g^{-1}$) biochar equipped with hierarchical porosity that was used as a supercapacitor electrode.

2.1.2. Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is a highly suitable method to process carbonaceous materials with high moisture content, such as animal and municipal wastes [25,26]. Briefly, the materials are heated along with water at temperatures between 180 and 300 °C under autogenous pressure (2–10 MPa) [27,28]. At these temperatures, water, due to its increased ionization constant, serves as a reactant [29,30]. In addition, its dielectric constant decreases significantly allowing water to act as a non-polar solvent [31] and to initiate a series of reactions.

The biomass is first subjected to hydrolysis resulting in the cleaving of ether and ester bonds associated with biomass [32]. Subsequently, the water and oxides of carbon are released via dehydration and decarboxylation, respectively [33]. Finally, the remaining components are recombined into larger molecules via polymerization. Detailed mechanisms of these chemical reactions are summarized by Pauline and Joseph [34].

After the completion of all the reactions, the biomass is converted into a solid product called hydrochar, whose physical and chemical properties are somewhat similar to biochar [35]. However, the yield, surface chemistry, and energy content of the hydrochar will directly depend on the processing conditions, including the temperature, residence time, and the presence of catalysts. Numerous results of parametric studies on the optimization of the hydrochar properties are available in the literature [29].

Considering the advantages HTC offers, several materials have been converted into hydrochars. However, considering the theme of the article, only the HTC of animal wastes are summarized here. Cow manure was used as a feedstock for HTC at temperatures 180–260 °C for 5 and 30 min. Lang et al. [36] tested calcium oxide (CaO) as a catalyst during the HTC of swine manure. Their analyses suggested that CaO enhanced the porosity and hydrophilicity of biochar and was proposed as a suitable soil amendment capable of increased cation exchange capacity (CEC).

Lentz et al. [37] investigated HTC of nitrogen-doped hydrochars synthesized from swine manure slurry between 180–260 °C (24 h). Their results suggested that the HTC process yielded nitrogen-doped chars with points of zero charge between 6.7 and 7.8 making them highly suitable as adsorbents, and precursors for energy-storage devices. Bardhan et al. [38] suggested the co-processing of materials to enhance the yield and the properties of hydrochar. Swine manure and chicken manure were co-hydrothermally carbonized in various ratios by Qingyin et al. [39]. It appeared that combining swine manure with chicken manure caused a symbiotic interaction in terms of carbon and nitrogen functionalization in the resulting hydrochar and deoxygenation coupled with higher energy yield.

2.1.3. Torrefaction

Torrefaction is one of the mildest processes for the synthesis of biochar. The basic procedure includes heating biomass between 200 and 300 °C without oxygen at atmospheric pressure [40]. As the overall process shares similarities with pyrolysis, torrefaction is sometimes termed mild pyrolysis [41].

During torrefaction, water is removed from the biomass followed by the depolymerization of the hemicellulose, cellulose, and lignin [42]. As a result, the physical structure of the biomass is altered resulting in the formation of porous biochar with hydrophobic properties [43] Depending on the feedstock, torrefaction can be under dry conditions (inert), wet conditions (with water or steam), or oxidative conditions (oxygen or steam) [41]. Although wet torrefaction shares similarities with HTC, the purpose of wet torrefaction is predominantly to upgrade the biomass for subsequent processing [44,45].

Stepien et al. [46] tested the torrefaction of elephant manure to produce bio-coal. The manure was torrefied between 200 and 300 °C for 20–60 min and systematically analyzed for physical, chemical, and thermodynamic properties. Torrefaction at 200 °C for 20 min provided optimum benefits from an energy balance perspective. In a different study, the torrefaction of poultry litter and sludge was investigated between 250 and 280 °C for 15–60 min by Dhungana et al. [47].

Their analyses suggested that litter and sludge retained up to 73.6–99.5% of the energy of the original biomass and was consistent with the other lignocellulosic biomasses tested under similar conditions while the effects of temperature were more pronounced than processing times. The torrefaction of cattle manure was investigated by Akyurek [48] at 250 °C (60 min) to assess its feasibility as biomass pretreatment. They reported that torrefaction enhanced the energy content by 27% and the high heating value by 14%.

2.2. Activation of Biochar

The raw biochar obtained from any of the thermal processes described above is usually activated to further enhance its physical and chemical properties [49]. In general, two types of activation are employed: physical and chemical, which are summarized as under:

2.2.1. Physical Activation

Physical activation is performed to partially destroy the biochar structure to introduce additional porosity within the biochar matrix via oxidation [14]. The standard procedure is to subject the raw biochar to a stream of steam or CO_2 at a high temperature [50]. During activation, the gas molecules oxidize some of the carbon molecules and volatiles present in biochar into oxides of carbon, thereby, creating a porous network within the biochar [14,51]. In addition, the oxidizing gases can introduce certain oxygen functionalities on the biochar surface depending on the experimental conditions [52]. The detailed mechanisms of steam and carbon dioxide activation have been described by Cha et al. [14], Anto et al. [53], Sajjadi et al. [52], and others.

2.2.2. Chemical Activation

The goal of chemical activation is two-fold: to enhance the porosity and simultaneously enrich the surface with the desired functional groups that can impart the biochar with special properties [14]. Typically, the raw biochar is impregnated with a chemical agent for a predetermined time. Subsequently, the biochar is re-pyrolyzed to allow for the reaction between carbon and the chemical agent during which the pore structure is further expanded while the surface carbon is functionalized [54]. Several types of chemical agents have been used to activate the biochars.

Some of the common chemicals include acids (sulfuric acid, sulfonic acid, nitric acid, and phosphoric acid), bases (sodium hydroxide, potassium hydroxide, urea, and melamine), metal salts (zinc chloride, potassium carbonate), oxidants (hydrogen peroxide, permanganate, and ammonium persulfate), and gases (ozone and NH_3) [16,52,53,55–58]. Depending on the type of chemical activation, the activated biochars are usually equipped with sulfonic, carboxylic, phenolic, lactonic, pyridynic, pyrrolic, and quaternary nitrogen and phosphorus-carbon functionalities.

2.3. Properties of Biochar

Regardless of the mode of synthesis, the physical and chemical properties of biochars play a great role in the performance of biochar in various applications, including adsorption, catalysis, soil conditioning, bulking agent, and bedding material in animal agriculture. Some of the key properties are presented below.

2.3.1. Surface Area and Porosity

The specific surface area of biochar in conjunction with its porosity is perhaps the most important property that affects the performance of biochars. Biochars with high surface areas are naturally equipped with large numbers of active sites. However, the relation between the specific surface area and the efficacy of biochar is not always linear [59]. Biochar surface areas can range from 0 to 520 $m^2\ g^{-1}$ depending on the feedstock. Typically the surface area is highest for straw and wood biochars compared to manure-based biochars [60]. The total specific surface area of biochar is a result of the porosity that consists of a combination of the micro (<2 nm), meso (2–50 nm), and macro (>50 nm) pores.

When biochars are used as adsorbents, catalysts, soil conditioners, or energy storage devices, the efficacy of biochar is a function of the pore size and the chemical species being adsorbed [61]. When the size of the adsorbate species is larger than the pore size, the biochar may not perform at its optimum capacity. However, the process conditions during carbonization may be tuned to synthesize biochars equipped with an optimal proportion of micro, meso, and macropores to maximize the biochar's efficacy. This large surface area and distribution of pore size are likewise desirable for a variety of animal production applications.

2.3.2. Surface Chemistry

During thermal decomposition of the biomass and subsequent activation of biochar, several reactions occur between the biomass fragments resulting in the formation of chemical functionalities on the biochar surface [62]. Depending on the process and activation conditions, the surface is enriched with either oxygen-rich acidic groups or oxygen-deficient basic groups. The acidic groups, namely carboxylic, phenols, and lactones make the biochar surface hydrophilic and actively participate in the chemisorption of ammonia and ammonium from gaseous aqueous systems [63,64].

In addition, the acidic groups also participate in the cation exchange processes when applied to soils as conditioners [65]. Conversely, biochar surfaces enriched with nitrogen groups, such as pyridines and pyrroles, and certain basal planes within the biochar matrix impart basicity to the biochar surface and contribute to the adsorption of organic compounds and heavy metals in aqueous and gaseous systems [57].

2.3.3. Point of Zero Charge (PZC)

The efficacy of biochars when applied as adsorbents to some extent depends on their PZC [66]. The PZC is defined as the pH of the solution at which the biochar experiences a net neutral charge [67]. During the adsorption process, if the pH of the solution falls below the PZC of the biochar, the surface acquires a positive charge and facilitates the electrostatic adsorption of anionic species, such as nitrates, nitrites, and chlorides [68]. Conversely, when the pH of the solution increases beyond the PZC of the biochar, the surface turns negative and can actively adsorb cationic species, such as metal ions and ammonium [69].

3. Animal Feed

Animal nutrition has significant impacts on feed and growth efficiency as well as the properties of their excreted waste. Growers seek to maximize weight gain with the least amount of inputs and additives. The undigested macro and micronutrients pass into the manure and contribute to gaseous emission production. Approximately 60–85% of phosphorus, 70–80% of nitrogen, and 80–90% of potassium in animal feed are excreted as manure [70]. Biochar as a feed additive is not a new concept, and its chemical and physical properties have been hypothesized to reduce nitrogen content in excreta, decrease risk of pathogens, and strengthen the immune system of livestock and poultry among other benefits as shown in Figure 3 [71].

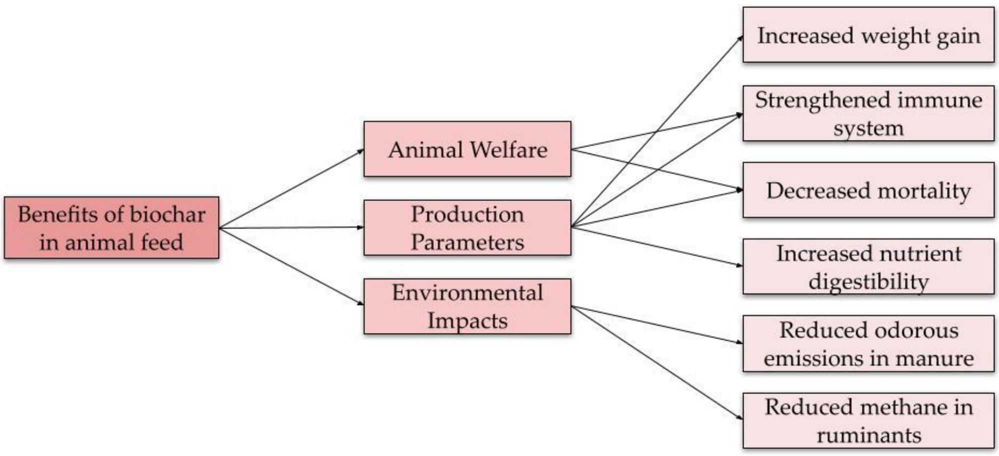


Figure 3. Summary of benefits of biochar as an animal feed additive.

Recent reviews, e.g., by Man et al. [72] and Schmidt et al. [73], focus on diet impacts of biochar on animal performance, such as weight gain, and less on the mechanisms of nutrient uptake or efficiency. A smaller subset of literature has focused on biochar as an animal feed additive for the purpose of reducing emissions in excreted manure.

While there are numerous publications on the use of biochar as a feed additive, few of them provide a useful characterization of the biochar, including the source and the manufacturing process [73]. This gap limits our ability to understand the mechanisms involved in biochar impacts on feed digestion and nutrient absorption.

3.1. Gut Health

The health of an animal's gastrointestinal tract is an important factor in overall health and performance (weight gain, milk/meat/egg quality and yield, etc.). Optimal stomach microbial activity improves the overall nutrition and feed digestibility, reduces pathogen inundation, and strengthens the immune system [74].

Goiri et al. [75] studied the effect of biochar feed addition on the gut pH, short chain fatty acid (SCFA) profile, and bacterial communities. This 42 day, live-bird trial used wood chip biochar added at 30 g kg^{-1} feed to a typical meat chicken diet. There was no change in the digestive organ pH throughout the trial compared to the control. SCFA profiles play an important role in overall animal physiology and metabolism, especially acetate.

While the overall microbial populations were similar between the control and biochar treatment, the biochar did shift communities resulting in increased production of acetic ($p = 0.01$) and caproic ($p = 0.003$) acid. Acetic acid in the gut is also an energy source for the muscles as well as toxic to some in vitro pathogenic bacteria [76]. Adsorption capacity of the biochar, while important, cannot answer all the phenomena observed when biochar is added to animal feed; therefore, biochar mechanisms in the gut remain an area for future research.

Prasari et al. [77] compared the use of wood/greenwaste biochar with bentonite and zeolite (commercial adsorbents) to suppress pathogen loads in laying chicken intestine while maintaining microbial richness. The additive supplementation rate for each treatment was 4%. All three treatments showed potential for the reduction of major poultry zoonotic pathogens without reducing microbiota diversity. Biochar reduced the reactive abundance of proteobacteria, gammaproteobacterial, and campylobacter classes of bacteria in the chicken cloaca by about half. These bacteria are associated with foodborne illness and can contaminate egg production. Supplementation with biochar could reduce the need for subtherapeutic antibiotic use in the poultry industry [78].

3.2. Production Parameters

Schubert et al. [79] evaluated the effect of two types of wood based biochar at a 2% inclusion rate in growing pig (3–13 weeks) diets. This study was looking particularly at nutrient digestibility and the following production parameters: average daily feed intake (ADFI), average daily weight gain (ADWG), and feed efficiency (G:F). Statistical analysis also utilized the parameter apparent total tract digestibility (ATTD), which compares the nutrient concentrations in the feed versus feces.

Neither biochar additive resulted in significant differences in ADWG, ADFI, or G:F. However, results from another finishing pig study by Chu et al. [80] using 0.3% and 0.6% bamboo biochar led to 4.5% and 8.2% improved ADWG and 14.9% and 11.7% improved G:F, respectively. It seems feedstock was the greatest contributor to these differences. The bamboo biochar had a smaller micropore structure compared with the wood-based biochar.

Several studies have also evaluated similar impacts on broiler diets, including Goiri et al. [75]. In addition to evaluating the biochar impacts on microbial communities, this study tested birds over their full growth period, broken up into two diets: starter (1–21 days) and grow-to-finish (21–42 days). The wood chip biochar was added at 30 g kg^{-1} feed to a typical meat chicken diet. Biochar in the starter diet led to a 2% decrease in ADWG and a 3.5% increase in FCR (both $p < 0.05$) vs. control.

The finisher diet with biochar addition, however, led to an 8% increase in ADWG and 6.7% decrease in FCR (both $p < 0.001$). These results are consistent with Evans et al. [81] who also observed a decrease in performance in young birds due to biochar addition to feed. There is a need to understand the optimal addition rates, and whether improvements in production parameters are based on the growth period diet or the age and biology of the animal. Additionally, testing these trends for swine and cattle would be valuable.

3.3. Emissions from Manure

Prasai et al. [82] evaluated the use of biochar in feed versus zeolite and bentonite, on nitrogen retention, carbon content, and moisture content in poultry litter. The biochar additive was included at 1%, 2%, and 4% w/w to the feed. Litter was sampled over a 46-day period, and monitored for an additional 35 days for decomposition. The 2% and 4% treatments reduced the total nitrogen content in the excreta by 17% and 27%, respectively, vs. the control.

However, for these same treatments, NH_3 emissions increased over the incubation and decomposition period by 47% and 43%, respectively. The carbon content for all treatments increased due to the addition of a stable form of carbon to the diet. This would lead to increased soil organic carbon when manure is land applied. The lowered nitrogen content was attributed to a higher nitrogen utilization by the birds, while the increased NH_3 volatilization was attributed to the higher manure pH, which shifted the NH_3/NH_4^+ equilibrium towards NH_3 [82].

In a similar study, Kalus et al. [83] tested the effect of biochar addition to feed at 2% and 4% w/w feed on 750 laying hens in terms of NH_3 and odor emissions from manure as well as production parameters, including animal weight gain and feed conversion ratio. Ammonia concentrations were reduced by 15% and 14% for the 2% and 4% biochar feed addition rates, respectively, compared to the control. Odor concentrations from the litter headspace were 32% lower for the 4% biochar feed litter than the control. The 2% addition rate was not tested due to experiment limitations.

Adsorption of NH_3 to the biochar surface, as well as altered gut microbial activity, resulted in lower nitrogen excreted in the manure and therefore lower NH_3 and odorous VOCs [83]. Differences in bird performance were not statistically significant. Average daily weight gain decreased by 5 and 2% in relation to the control for the 2 and 4% treatments, respectively. Feed conversion ratio increased by 2 and 4% for the two treatments, respectively, indicating a lower quality feed [83]. Evans et al. [81] also reported that biochar feed additives can have negative impacts on broiler production parameters.

Biochar additive treatments resulted in a 2% decrease in live weight gain, 11% increase in feed conversion ratio, and 8% increase in feed intake. The current literature in this area focuses on poultry, specifically broiler and layer litter. More information on emission effects from biochar supplemented feed needs to be explored for other animals, including swine and cattle. While biochar addition can have significant impacts on poultry production, the potential emission benefits must be balanced with improved animal performance as well. However, a better understanding and characterization of biochar manufacturing as a feed additive may be beneficial in producing a biochar product that both reduces emissions and improves animal performance.

3.4. Enteric Fermentation Methane Emissions

Ruminants, including beef and dairy cattle, sheep, goats, and bison utilize their unique digestive system and fermentation process to break down forage in the gut. This process is called enteric fermentation and produces large volumes of CH_4 emissions into the atmosphere [9]. This CH_4 loss takes away 2–12% of the rumen's energy intake, posing significant production concerns among climate and animal scientists [84]. Since enteric emissions contribute the largest source of CH_4 in the US, there are efforts to utilize feed additives to mitigate enteric fermentation emissions, and biochar has been explored for this purpose [84].

Biochar addition to biological systems increases access to carbon, leading to mixed results in terms of microbial activity and emissions. On the one hand, biochar inhibits methanogenesis (enteric fermentation pathway for CH_4 production) by increasing aeration and O_2 content. It has also been hypothesized that the high surface area, pore structure, and ion exchange capacity of biochar promotes the formation of biofilms, inhibiting ruminal CH_4 emissions [85]. However, some studies (e.g., Maurer et al. [86]) report increased CH_4 and CO_2 emissions since microorganisms have access to an additional liable carbon source.

Qomariyah et al. [87] incorporated cocoa-pod husk biochar at 0.1, 0.2, 0.3, and 0.4 mg ml^{-1} to a basal diet of grass and pollard (wheat milling byproduct) to dairy cows. In-vitro ruminal fermentation samples were incubated for 48 h. Compared to the control, biochar addition did not impact rumen pH, NH_3, or total gas production. There was a noticeable shift in volatile fatty acid (VFA) production, with a 21% increase in acetate production, and 7, 18, 29, 50, and 33% decrease in propionate, butyrate, isobutyrate, valerate, and isovalerate, respectively. While gas production was not affected, VFAs are the final product of ruminal fermentation and serve as the main source of energy and carbon for the formation of proteins.

A higher ratio of acetate:propionate has a positive impact on animal efficiency. Additionally, propionate competes with CH_4 in rumen fermentation, while acetate and butyrate can be used by methanogens in the rumen to reduce CO_2 and CH_4. Increased levels of biochar decreased protozoa counts by 6–7%, which then contributed to a decrease in total bacteria and in vitro ruminal dry matter and organic matter degradability. This is contradictory to Monsoni et al. [88], who suggested that decreases in the protozoa population are harmful to fiber digestion, which is crucial for the rumen diet. Mengistu et al. [89], Terry et al. [90], and Tamaya et al. [91] all reported similar findings, with no changes in the CH_4 production regardless of the biochar chemical/physical properties or inclusion rates. Schmidt et al. [72] suggested this is due to the indigestible, recalcitrant nature of biochar in the rumen.

Leng et al. [92] had more positive results in reducing CH_4 emissions via biochar feed addition. They evaluated rice-husk biochar at a 0.6% DM addition rate as a feed additive to young beef cattle basal diet. Over the 98 day experiment, there was a 22% reduction in CH_4 emissions and a 25% increase in live weight gain. The authors attributed the positive results to the porous characteristics of the biochar in helping facilitate redox reactions between bacteria and overall favored biofilm formation. Therefore, there may be a dependency on the stage of animal growth at which biochar is introduced in the feed.

4. In-House Applications

Air quality is a major concern for the welfare of the confined animals and the caretakers as well as the surrounding communities. There is a need to reduce emissions from livestock production by addressing odors directly in the animal houses.

Linhoss et al. [93] studied the impacts of pine shaving biochar addition, at 0.97 kg m^{-2}, to pine shaving poultry litter on bird health and performance and the water holding capacity (WHC) of the litter. It is essential to maintain a litter moisture content of 20–30% in poultry houses to minimize the microbial activity and NH_3 volatilization. The results for mortality and footpad lesions were inconclusive and produced statistically insignificant data. However, body weight and body weight gain were 3% higher for the biochar treatment ($p < 0.1$). Overall, there were no adverse effects of using biochar in bedding on the birds.

In the second phase of the study, Linhoss et al. [94] tested the impacts of biochar particle size and application rate on the water holding capacity (WHC) of the litter. Particle size was divided into three categories: fine (<0.25 mm), medium (0.25–0.85 mm), and coarse (>0.85 mm). Biochar was mixed with pine shavings at application rates of 0, 10, 20, 30, 40, 50, 75, and 100% w/w. The coarse particle size was 11% more effective at increasing the WHC of the litter than fine particle size.

While application rates of 75 and 100% had the highest WHC, these rates are not practical in normal production. However, each 1% increase between 10 and 20% equaled 1.9 and 1.2% increases in WHC for medium and coarse biochar, respectively. Greater than 20% resulted in incrementally small improvements in WHC, reducing the return on investment. These results are significant since the manure moisture content determines the decomposition method: aerobic versus anaerobic and therefore the types and concentrations of pollutants released.

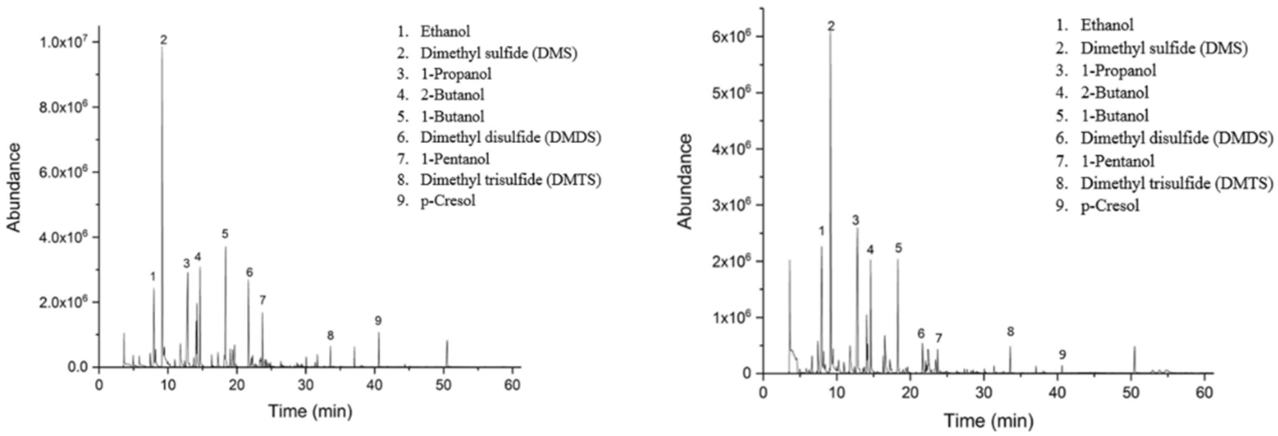
Ritz et al. [94] also tested biochar as a poultry litter amendment for NH_3 volatilization, as well as bird welfare parameters, such as the carcass quality, body weight, and feed consumption. They utilized peanut shell biochar as well as pine-chip- and coconut-husk-based biochar soaked in 53% H_2SO_4. The peanut shell biochar had a pH value of 9.2, whereas both acidified biochars had a pH of 2.0. The live bird trial applied treatments at comparable rates to commercial acidifying litter amendments: 0.24, 0.37, and 0.73 kg m^{-2}. No significant differences in bird performance were detected. The peanut shell biochar was not effective at adsorbing NH_3, due to its high pH and greater hydrophobicity compared to the acidified biochars. The acidified pine-bark and coconut-husk biochars reduced NH_3 emissions by 43 and 52%, respectively.

Manure properties have a great impact on the quality of fertilizer for land application. Flores et al. [95] also studied biochar as a poultry litter amendment, with a focus on NH_3 emissions, nutrients retained in the litter, and bird performance. Miscanthus grass and biochar were applied at 0, 5, 10, and 20% inclusion rates to once-used, traditional pine-shaving bedding litter. Measurements were taken 20 weeks after application. There was no significant difference in the NH3 concentrations from any of the treatments. However, the litter properties after the 20 week trial showed significant results.

The increase in biochar addition resulted in increased levels of phosphorus, sodium, potassium, calcium, magnesium, copper, pH, and total Kjeldjal nitrogen. The most notable results were a 3.4× increase in phosphorus at a 20% addition, as well as a 14.15× and 6.50× increase in ammonia-N and nitrate-N, respectively. Nitrates, as the primary source of plant N, translate to positive impacts in land application. The inclusion of 20% biochar resulted in a 3% increase in body weight as well as a 4% increase in feed intake at week 20. No statistically significant trends were observed for the feed conversion ratio.

Studies have also taken place using direct biochar application to swine manure. Hwang et al. [96] assessed the impact of a combination of plant material and animal waste biochar on the sorption capacity of 15 targeted VOCs when applied to fresh swine manure. Manure-based biochars proved to be poor sorbents showing zero adsorption for the primary VOCs of interest, dimethyl disulfide and dimethyl trisulfide. On the contrary, plant-based biochar had significant adsorption, specifically oak-based biochar produced at 500 °C. Overall, the volatile matter, fixed carbon, ash content, and pH did not affect the adsorption capacity.

Similar positive results were demonstrated by Kaikiti et al. [97] using manure-based biochar for the adsorption of VOCs in fresh cattle manure. Significant reductions in sulfur- and oxygen-containing compounds, including thiols, sulfides, alcohols, and ketones, were observed. Most notably were the 98.5% removal of 2,4-dithiapentane, 90% removal of p-Cresol, and 100% removal of phenol. Figure 4 shows the GC-MS abundance of the analyzed VOCs with an order of magnitude difference between the control and biochar-treated manure. The high adsorption capacity was attributed to the high porosity and surface area; however, it is unclear whether the biochar was modified with any alkali or acid treatments to enhance its performance.



(**a**) (**b**)

Figure 4. GC-MS results for as-received cattle manure (**a**) and manure with biochar treatment (**b**). Reprinted with permission from Kaikiti et al. [97]. 2021, Agapios Agapiou.

Several of these studies demonstrated applications of biochar on fresh manure sources simulating the act of incorporating biochar directly in animal houses. Linhoss et al. [94] were the first to test biochar in an active house with live animals. Further research is needed using live animal trials in house because even the short-term storage of litter or other waste samples can impact the odor properties of the material [98]. Additionally, studies evaluating biochar dosage, application form (powder vs. as-is), and application frequency or material regeneration require further investigation to become more accepted for on-farm use.

5. Manure Storage and Treatment

Manure storage and treatment are critical steps in animal production to ensure beneficial use of manure nutrients and organic matter, while reducing adverse impacts on the air, soil, and water quality. Bedded barns, as well as under-barn pits and ponds store the manure prior to land application, while anaerobic lagoons, anaerobic digesters (AD), and compost systems provide treatment. Biochar can be used either as a stationary-phase for nutrient/organic matter capture or as an additive [99]. In the following sections, we summarize the research investigating biochar use in manure-management systems.

5.1. Biochar and Manure Storage

Liquid manure can be a source of gaseous emissions, including ammonia, sulfides, VOCs, and greenhouse gasses (GHG), including methane and nitrous oxide. Dougherty et al. [100] studied the potential for different biochars to mitigate odor/gas emissions and improve nutrient uptake when applied as a surface cover for dairy manure.

Two biochars were tested: gasified wood chips at 650 °C (BC1) and wood bark via slow pyrolysis at 600 °C (BC2). The BC2 cover reduced headspace NH_3 emissions by 72–80%, whereas no significant difference was noticed for BC1. However, BC1 increased nutrient uptake from 0.21 to 4.88 mg N g^{-1} biochar and 0.64 to 2.70 mg P g^{-1} biochar compared to BC2. This was desirable as it could translate to the slow release of nutrients when land applied. These differing results were attributed to the high pH of BC1 (9.32) compared to BC2 (7.28).

Additionally, BC2 was more hydrophobic than BC1 allowing it to float better on the surface. They reported a trade-off between the biochar potential for NH_3 emission reduction and for nutrient absorption with increased hydrophobicity aiding biochar floatability and, consequently, the surface NH_3 reduction but reducing its nutrient absorption. In evaluating biochar from reed canary pellets (torrefied, 300 °C) as an NH_3-emission-control measure in manure digestate storage, Covali et al. [101] observed significant reductions in cumulative

NH_3 emissions after biochar addition, with acidified biochar outperforming untreated biochar, and surface application reducing emissions more than in mixed addition.

Chen et al. [102] hypothesized that biweekly biochar application as a surface cover would remedy the decline in the biochar mitigation impact over time. They conducted an eight-week study in deep-pit swine storage structures. Weekly tests revealed that the bi-weekly reapplication of biochar was more effective than a one-time application and that a higher application rate did not impact the emission and odor reduction. Ammonia decreased by 33%, 25%, and 53% for one-time 2 kg m^{-2} h^{-1}, one-time 4 kg m^{-2} h^{-1}, and bi-weekly 2 kg m^{-2} h^{-1}, respectively, all with p-values < 0.05. Additionally, the NH_3 levels dropped close to zero immediately after reapplication.

Odor reduction doubled from 11% to 22%, and CH_4 production tripled from 15% to 45% in bi-weekly applications versus both one-time applications. While increased CH_4 production is a trade-off between reduced odor (NH3 emission) and increased greenhouse gas (GHG) emissions, it can be valuable in an AD. Meiirkhaunuly et al. [103] conducted a study on emission reduction in deep-pit swine storage structures.

Red oak biochar was surface-applied at 0.64 cm (0.25 in) thickness to stored swine manure to reduce NH_3, H_2S, VOCs, and GHGs. The biochar significantly reduced *p*-cresol by 66–78% over the three week trial. The NH_3 and H_2S emissions were reduced by 19–39% and 16–23% over the duration of the experiment. Additionally, the odor intensity for the biochar-treated manure was reduced by 17–30% over the duration of the experiment. This experiment also proved that biochar could float on manure for days to weeks at a time.

Chen et al. [104] applied the positive results from Meiirkhaunuly et al. [103] to investigate reducing short-term release of H_2S emissions in deep-pit swine storage during agitation and pump-out. Two thicknesses of the same red oak biochar, 6 and 12 mm, were applied to the manure surface and then manually agitated while measuring the H_2S fluxes before and after (Figure 5). Both biochar treatments significantly reduced the H_2S cumulative emissions ($p < 0.0001$) after the three minute agitation; 84.7% and 39.3% reductions, respectively. This confirmed prior observations that higher application doses did not correlate to a greater reduction in H_2S emissions. Additionally, it is speculated that using a biochar with a higher pH than the red oak (7.5) would have a greater influence on the reduction of H_2S due to the transformation of S_2^- ions.

Figure 5. Swine manure surface: control (**left**), biochar evenly applied to surface (**center left**), 6 mm biochar layer after agitation (**center right**), and 12 mm biochar layer after agitation (**right**) with patches of open manure circled in red. Reprinted with permission from Chen et al. [104]. 2020, Jacek A. Koziel.

In evaluating the impact of high pH biochars on dairy manure emissions, Liu et al. [105] observed significant increases in NH_3, CH_4, and N_2O emissions compared to the control treatments. They attributed these increases to the combined impact of the biochar high pH, labile C fraction, and reduced bulk density.

5.2. Biochar and Manure Composting

Composting transforms manure into a stable and safe final product that offers a nutrient source to enhance plant growth [106]. The physicochemical properties of biochar make it a desirable compost additive to absorb gaseous emissions. Table 2 summarizes some research efforts that have demonstrated the effects of biochar as a compost additive for gaseous emission control. A more detailed review by Akdeniz [107] provides additional details.

Table 2. Implications of biochar for emission control during composting. Adapted from Chen et al. (2017).

Type of Biochar	Type of Waste *	Pyrolysis Temp.	Dosage	Emission Impact	Reference
Pine chips	PL	400 °C	20% [a]	64% reduction NH_3 71% reduction H_2S	Steiner et al. [108]
Rice husk	PL	-	3, 5, 10% [b]	18, 25, and 35% reduction NH_3 for 3, 5, and 10% dosages, respectively	Chung et al. [109]
Wood	DS	500–700 °C	17% [b]	33% reduction NH_3	Chowdhury et al. [110]
Wood pellets	AM	520 °C	5, 10, 15% [a]	40.4% and 56.8% reduction NH_3 for 10% and 15% dosages, respectively	Wang, et al. [111]
Wood	PL	500–700 °C	38% [b]	27–32% reduction total GHG emissions	Chowdhury et al. [112]
GW * and PL *	PL	550 °C	10% [b]	65–75% reduction N_2O and CH_4	Agyarko-Mintah et al. [113]
Rice husk	PL	500 °C	10, 20% [b]	148% CO_2 increase, 54.9% reduction CH_4	Jia et al. [114]
Bamboo	SM	600 °C	3% [a]	29.5% reduction total N_2O	Wang et al. [115]
Oak	PL	650 °C	3% [b]	No reduction CH_4 and H_2S	Sánchez-García et al. [116]
Woodchip	PL	-	5, 10% [a]	7.4% CO_2 increase	Czekala et al. [117]

* GW: green waste; PL: poultry litter; DS: manure-based anaerobic digestion solids; SM: swine manure; and AM: animal mortality. [a] Wet basis. [b] Dry basis.

Jia et al. [114] studied the effect of rice-husk biochar addition and dosage on the peak CH_4 and CO_2 emissions from chicken manure composting. The experiment was conducted for 43 days in 500 mL glass bottles at varying ratios of manure, biochar, and sawdust. Daily headspace gas spaces were collected and processed in a GC-MS. Although the experiment was not directly testing for NH_3 emissions, they noticed that the concentrations were very high at the beginning of the process while the compost was established. This was due to a sharp increase in pH from about 8.0 to 9.0 for all treatments over the first five days, though the biochar did increase the pH more than the control.

The 20% biochar treatment resulted in a 54.9% reduction in peak CH_4 emissions. This reduction was attributed to three possible causes: (1) the high porosity of biochar and its potential to increase aeration in the compost mixture, (2) high porosity and surface area resulting in the greater adsorption and retention of CH_4, and (3) the higher pH in biochar-amended compost. For some of the same reasons that biochar might have decreased CH_4 emissions, it also contributed to a 148% increase in CO_2 emissions. The increased aeration due to the porosity of the biochar supports aerobic decomposition, resulting in increased CO_2 respiration from these microorganisms.

Czekala et al. [117] produced similar results with increased CO_2 emissions from biochar as a compost additive. This study tested the cumulative gas flux instead of peak gas flux as Jia et al. did [114]. Wood-based biochar was added to poultry manure at 5% and 10% addition rates in 165 L reactors for 42 days. Cumulative CO_2 emissions increased by 6.9 and 7.4% for the 5 and 10% addition rates, respectively, compared to the control. Czekala et al. [118] attributed this increase to the high porosity of the biochar, which created better aeration conditions for the compost. This resulted in possibly abiotic oxidation of the biochar but, more likely, an additional carbon source for microorganisms thereby increasing the CO_2 respiration.

While there are numerous studies on the effects of biochar as a compost additive, it is important to understand the mechanisms of adsorption for this application to achieve the desired effects. An area that still needs to be explored further is the ability of biochar to increase certain emissions while decreasing others. Additionally, further research is needed on composting with higher-moisture-content manure, possibly in the form of a slurry or pumpable liquid, as well as the effect of biochar post modifications for a more uniform reduction of gaseous emissions.

5.3. Biochar and Manure Anaerobic Digestion

Anaerobic digestion has been an important waste management and bioenergy treatment for liquid swine waste and poultry litter. Here lies another opportunity during these storage and treatment steps to reduce odors and emissions by incorporating biochar.

Anaerobic digestion produces ~45–75% CH_4 and the remaining as CO_2; however, small amounts of NH_3 are also produced and cause stress on the system since NH_3 inhibits methanogenesis. Cheng et al. [118] investigated the use of HCl acidified, rice-straw biochar to reduce this stress during pig-waste anaerobic digestion. Treatments included 2, 5, 10, and 15 g biochar added to 800 mL pig wastewater and brewery sludge (a 7:3 ratio).

Biochar addition improved the digestion process as demonstrated through a decrease in the VFA production and an increase in the total biogas production. The higher biochar concentrations resulted in a greater decrease in ammonia-N due to the high surface area and large adsorption capacity. The overall biogas production increased from 1705 mL for the control to 2306 mL for the 15 g treatment. The methane content in the biogas remained constant for all treatments at ~58–59%. The increased biochar addition also reduced the lag time, or time from the start of reaction to the production of biogas, indicating that biochar increased the rate of degradation.

Pan et al. [119] studied the effect of biochar pyrolysis temperature, porosity, and surface area on enhancement of anaerobic digestion of cow manure. Cow manure and mushroom bran biochar were both produced at 400–600 °C. Anaerobic digestion inoculum was mixed with 1.524 g of biochar and 265 mL of water. Unlike Cheng et al. [118], the biochar enhancement did not reduce the lag time; however, both treatments did increase the cumulative biogas production. The optimal methane production was achieved in the 400 °C manure biochar and 550 °C mushroom biochar treatments.

The 400 °C manure biochar increased methane production by 81.3% compared to the control by increasing the overall gas production. The 550 °C mushroom biochar increased methane production by 77.6% due to a shortened fermentation period. The biochar surface area and porosity was linked to the pyrolysis temperature but not to the gas production. It is hypothesized that the biochar enhanced the interactions between methanogenic and acetogenic bacteria, which resulted in a decrease in the relative abundance of other bacteria.

All of these studies are reinforced by Xiao et al.'s [120] meta-analysis of 27 studies to examine the most important biochar parameters for influence on the methanogenic performance. Statistical analysis of these studies indicated that the biochar feedstock, pyrolysis temperature, and concentration in the digester were the most influential over the pH, size, surface area, and methanogen species.

6. Land Application

Soil organic matter is essential to soil fertility and crop performance. Land application of manures is a great practice to enhance soil fertility; however, this also poses environmental concerns related to increased N_2O emissions and the leaching of excess nutrients into surface and groundwater. In addition to providing a natural fertilizer source, the land application of manure is also an incredibly efficient way to repurpose large accumulations of manure, litter, lagoon effluent, etc. This application can take place in a variety of ways: spread after composting, sprayed as a liquid directly from a treatment lagoon, or even hauled with an excavator from dry-stack storage [121].

While there are many places in the manure life-cycle for biochar application, land application has great potential as this is the end destination of the manure. This also means that biochar incorporated into feed, bedding, and manure storage/treatment will all end up being land applied as well. Biochar has also been proven to increase soil organic matter and carbon, facilitate carbon sequestration, and reduce soil GHG emissions [122]. This section will focus on the variety of ways that biochar can be incorporated into land application of manure to reduce gaseous emissions and the leaching of excess nutrients while increasing crop yields and plant nutrient-uptake efficiency.

6.1. Land Application of Biochar and Manure Separately

Watanabe et al. [123] conducted a five-crop season field test to evaluate the impacts of land application of biochar addition to cattle manure on the soil CO_2, CH_4, and N_2O flux. Seasonal CO_2 variation was consistent between the control and biochar treatments. Overall, the differences in N_2O and CH_4 emissions were negligible between the treatments and control. Although biochar treatments increased the crop yields in certain plots, as well as increased carbon storage, this was not a major point of interest in the study.

Biochar did not have negative effects on the gaseous emissions; however, it did not show significant results regarding emission reduction. The comparison of these two studies raises questions about the validity of lab-scale experiments when translated into full-scale operation. While biochar has proven impacts on soil microbial communities, water-holding capacity, and aeration, actual environmental considerations, such as weather patterns and types of crops add a variety of factors to study.

Niraula et al. [124] conducted a study to compare dairy effluent saturated biochar (SBC) and unsaturated wood-derived biochar (UBC) on bermuda grass growth and soil fertility. Both treatments were applied at 1%, 2%, 4,% and 8% loading rates, and the performance was evaluated for 10 weeks in a greenhouse pot study. The SBC significantly outperformed UBC in N and P retention in the soil at 2%, 4%, and 8% loading rates. Specifically, SBC and UBC increased the total N by 36% and 20%, 74% and 34%, and 74% and 56%, at 2%, 4%, and 8% loading, respectively.

Likewise, SBC and UBC increased the total P by 28% and 10%, 34% and 21%, and 75% and 39%, at 2%, 4%, and 8% loading, respectively. In terms of plant growth, SBC outperformed UBC in stem dry weight, root dry weight, number of leaves, and total biomass by more than double for each parameter and loading rate. Both biochar treatments showed increased populations of N-fixing bacteria due to better aeration of the biochar-amended soils. Overall, the saturation with nutrient-rich dairy effluent was absorbed by the biochar and contributed to the retention and slow release of valuable, bioavailable nutrients for plant and soil health.

6.2. Land Application of Biochar Enhanced Compost

Current reviews by Agegnehu et al. [125] and Guo et al. [60] provide in-depth details on biochar-amended compost for land application to improve soil quality. Yuan et al. [126] investigated the impact of biochar-enhanced poultry manure compost on soil CO_2 and N_2O emissions. Rice hull biochar was incorporated into the compost at 1 and 5% addition rates for 120 days in lab-scale modules with loamy soils. Compared to regular manure compost, the biochar manure compost reduced the cumulative soil N_2O emissions by 27%.

Although possible mechanisms for this include biochar toxicity, increased aeration, and NO_3^- immobilization (suppressing bacterial denitrification), the authors identified the challenge to generalize biochar mitigation mechanisms due to the large variation in biochar characteristics. Biochar enhanced manure compost also reduced the cumulative CO_2 emissions by 35% compared to regular manure compost. This relationship was attributed to higher fungi-to-bacteria ratio, which has previously been associated with lower CO_2 respiration and greater soil carbon storage.

Agegnehu et al. [127] compared the use of wood biochar alone (10 t ha^{-1}) as well as incorporated into chicken-manure compost compared to commercial fertilizer on soil quality, crop yield, and GHG emissions from tropical agricultural soils. Compared to fertilizer alone, the biochar amendments increased the maize yield and total biomass by 29% for biochar alone and 12% for co-composted biochar. Additionally, biochar and biochar amendment compost improved the soil organic C, total N, available P, and CEC by 43–73%, 14–29%, 59–117%, and 20–41%, respectively. Interestingly, CO_2 and N_2O emissions were higher with biochar amendments than with traditional fertilizer application. The author does not give a reason for this trend but does allude that soil type could play a factor in the emission results.

6.3. Biochar Bioretention Systems to Treat Agricultural Run-Off

Nitrates from manure and fertilizer land application are a primary pollutant of concern from agricultural fields. Nitrates move through the soil in soluble form and can pose health concerns when present in drinking water and in foraging biomass. Nitrates in waterways cause rampant growth of algae depleting available oxygen for aquatic life [128]. Biochar has been explored as a water biofilter extensively in stormwater applications. However, less research has been done to utilize the power of biochar to reduce contaminants from manure land application on agricultural fields. The following examples demonstrate the limited attempt to use biochar biofilters to treat agricultural run-off pollutants.

Rahman et al. [129] used wood-chip biochar pyrolyzed at 900 °C in an existing bioretention cell (run-off treatment) to evaluate nitrogen removal of dairy wastewater mixed with stormwater. Bioretention cells were constructed to compare pure sand (S) versus a biochar sand combination (B). Each treatment was also tested with an established Muhly grass version (SP and BP) to see if the plants contributed to increased treatment giving a total of four treatments. The highest TAN removal was observed from both biochar systems at about 91% removal compared to the sand systems at 68%.

This was attributed to the high CEC of the biochar (10.57 kmol kg^{-1}) allowing more time for nitrification compared to the pure sand biofilters. The biochar amended filters also resulted in lower NOx concentrations (0.72–1.18 mg L^{-1} vs. 2.09–3.15 g L^{-1}) likely due to the total organic carbon (TOC) retained due to the high adsorption of the biochar. This was used as an electron donor for denitrification. The biochar's high surface area (537 m^2 g^{-1}) and porosity enhanced the microbial communities in the filter resulting in greater adsorption and ammonification. The overall high moisture and nutrient retention also contributed to better plant growth.

Sanford et al. [129] used biochar-amended vegetated filter strips for the treatment of nitrates in silage bunker (feed storage) runoff. Information was not given about the biochar feedstock or addition rate to the system. Biochar addition increased the subsurface effluent nitrogen from 49 to 64% compared to influent. Specifically, subsurface effluent nitrate was reduced by 40% compared to the control. Overall, the biochar addition reduced nitrogen soil leaching by 15%, increased soil nitrogen retention by 25% and reduced nitrogen lost through gaseous emissions by 10%. The authors suggested that increasing oxygen functional groups on the biochar would increase nitrogen retention.

It is unclear why more studies have not been conducted in this area given the positive results reported by Rahman et al. [129] and Sanford et al. [129]. Going forward, reviewing the performance of stormwater biochar biofilters will be the best starting point to design and optimize off-site water filtration systems for agricultural run-off and pollutants.

7. Conclusions/Future Work

There is a great amount of research dedicated to biochar applications in agriculture in general, with growing interest in connecting biochar uses to animal agriculture. The current review examined some of the most recent literature on the use of biochar at various stages of animal production to support sustainability goals. Biochar was demonstrated to be effective in capturing a variety of organic and inorganic compounds in manure. These attributes showed a uniformly positive impact on manure storage and treatment with a less positive impact for inclusion in feed or during land application.

Future work should address the potential for biochar modifications, such as steam activation or acid/base modification, to enhance affinity for a wider range of emissions or to optimize the adsorption of a particular contaminant. There continue to be gaps in knowledge regarding the biochar net impact on various aspects of animal agriculture. For instance, biochar incorporation in feed was shown to have a mixed effect on feed efficiency, emissions, and nutrient absorption. There is a need for the complete reporting of the biochar parent material, production conditions, and modifications to better assist in understanding the modes of action in the gut.

Furthermore, there appears to be an age-related impact of biochar as a feed ingredient that needs to be closely examined. None of the studies investigating biochar use in feed assessed its impacts on manure characteristics during storage or after land application. Similarly, biochar use in emission mitigation during composting showed mixed results. The variability in the biochar characteristics, composting feedstock, and composting process arrangement all contributed to the inconsistent performance observed with biochar addition.

For acceptance in animal production, there also needs to be more work done on determining the optimal dosages, form (powder vs. non-powder), and feedstock type for different applications (in-house, lagoon storage, feed, etc.). There are numerous variables at play in biochar production that would benefit from more consistent and complete reporting of biochar properties (the surface-area, particle-size, and pore-size distribution; surface functional groups; etc.). At this point, the net impacts of biochar addition in animal production are less clear due to the gaps in systematic evaluations of the roles of biochar across the production cycle. In a multi-stage system with complex mechanisms, it is important to understand the net effects of biochar addition on the productivity and net impacts of animal production.

Author Contributions: Conceptualization, C.G. and M.S.; Literature investigation, C.G., M.S., P.K., J.G. and S.S.; writing—original draft preparation, C.G.; writing—review and editing, C.G., M.S., P.K., J.G. and S.S.; supervision, C.G. and M.S.; project administration, C.G. and M.S.; funding acquisition, M.S., P.K., J.G. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This review was supported through funding from NC Department of Agriculture and Consumer Services, Bioenergy Research Initiative (NCDA&CS BRI), grant no. 21-61-4003, "Miscanthus Biochar Potential as Broiler Litter Amendment".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Henchion, M.; Moloney, A.P.; Hyland, J.; Zimmermann, J.; McCarthy, S. Review: Trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. *Anim. Int. J. Anim. Biosci.* **2021**, *15*, 100287. [CrossRef] [PubMed]
2. Dohlman, E.; Hansen, J.; Boussios, D. *USDA Agricultural Projections to 2030*; OCE-2021-1; USDA: Washington, DC, USA, 2021.
3. Reynolds, L.P.; Wulster-Radcliffe, M.C.; Aaron, D.K.; Davis, T.A. Importance of Animals in Agricultural Sustainability and Food Security. *J. Nutr.* **2015**, *145*, 1377–1379. [CrossRef]
4. Matlock, M.; Thoma, G.; Matlock, M.; Boles, E.; Leh, M.; Sandefur, H.; Bauista, R.; Ulrich, R. *A Life Cycle Analysis of Land Use in US Pork Production*; National Pork Board: Des Moines, IN, USA, 2015. Available online: https://porkcheckoff.org/wp-content/uploads/2021/02/11-133-MATLOCK-UofArk.pdf (accessed on 1 March 2022).
5. Wu, G.; Bazer, F.W.; Cross, H.R. Land-based production of animal protein: Impacts, efficiency, and sustainability. *Ann. N. Y. Acad. Sci.* **2014**, *1328*, 18–28. [CrossRef] [PubMed]
6. World Meteorological Organization. Global Methane Assessment Released. 2021. Available online: https://public.wmo.int/en/media/news/global-methane-assessment-released (accessed on 1 March 2022).
7. Aneja, V.P.; Schlesinger, W.H.; Erisman, J.W. Effects of Agriculture upon the Air Quality and Climate: Research, Policy, and Regulations. *Environ. Sci. Technol.* **2009**, *43*, 4234–4240. [CrossRef] [PubMed]
8. Environmental Protection Agency. Health and Environmental Effects of Particulate Matter (PM). 2022. Available online: https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm (accessed on 1 March 2022).
9. Environmental Protection Agency. Overview of Greenhouse Gases. 2022. Available online: https://www.epa.gov/ghgemissions/overview-greenhouse-gases (accessed on 1 March 2022).
10. Environmental Protection Agency. Volatile Organic Compounds' Impact on Indoor Air Quality. 2022. Available online: https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality (accessed on 1 March 2022).
11. Abdalla, C.W.; Lawton, J.L. Environmental Issues in Animal Agriculture. *Choices* **2006**, *21*, 177–181. [CrossRef]
12. Pfost, D.L.; Fulhage, C.D.; Hoehne, J.A. Odors from Livestock Operations: Causes and Possible Cures. University of Missouri Extension, 2018. Available online: https://extension.missouri.edu/publications/g1884 (accessed on 1 March 2022).
13. Kalus, K.; Koziel, J.A.; Opaliński, S. A Review of Biochar Properties and Their Utilization in Crop Agriculture and Livestock Production. *NATO Adv. Sci. Inst. Ser. E Appl. Sci.* **2019**, *9*, 3494. [CrossRef]
14. Cha, J.S.; Park, S.H.; Jung SRyu, C.; Jeon, J.; Shin, M.; Park, Y. Production and utilization of biochar: A review. *J. Ind. Eng. Chem.* **2016**, *40*, 1–15. [CrossRef]

15. Wang, D.; Jiang, P.; Zhang, H.; Yuan, W. Biochar production and applications in agro and forestry systems: A review. *Sci. Total Environ.* **2020**, *723*, 137775. [CrossRef]
16. Patra, B.R.; Mukherjee, A.; Nanda, S.; Dalai, A.K. Biochar production, activation and adsorptive applications: A review. *Environ. Chem. Lett.* **2021**, *19*, 2237–2259. [CrossRef]
17. Seow, Y.X.; Tan, Y.H.; Mubarak, N.M.; Kansedo, J.; Khalid, M.; Ibrahim, M.L.; Ghasemi, M. A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications. *J. Environ. Chem. Eng.* **2022**, *10*, 107017. [CrossRef]
18. Tripathi, M.; Sahu, J.N.; Ganesan, P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 467–481. [CrossRef]
19. Wang, J.; Wang, S. Preparation, modification and environmental application of biochar: A review. *J. Clean. Prod.* **2019**, *227*, 1002–1022. [CrossRef]
20. Tsai, W.T.; Liu, S.C.; Chen, H.R.; Chang, Y.M.; Tsai, Y.L. Textural and chemical properties of swine-manure-derived biochar pertinent to its potential use as a soil amendment. *Chemosphere* **2012**, *89*, 198–203. [CrossRef] [PubMed]
21. Meng, J.; Feng, X.; Dai, Z.; Liu, X.; Wu, J.; Xu, J. Adsorption characteristics of Cu (II) from aqueous solution onto biochar derived from swine manure. *Environ. Sci. Pollut. Res. Int.* **2014**, *21*, 7035–7046. [CrossRef] [PubMed]
22. Yue, Y.; Lin, Q.; Xu, Y.; Li, G.; Zhao, X. Slow pyrolysis as a measure for rapidly treating cow manure and the biochar characteristics. *J. Anal. Appl. Pyrolysis* **2017**, *124*, 355–361. [CrossRef]
23. Zhang, P.; Li, Y.; Cao, Y.; Han, L. Characteristics of tetracycline adsorption by cow manure biochar prepared at different pyrolysis temperatures. *Bioresour. Technol.* **2019**, *285*, 121348. [CrossRef] [PubMed]
24. Pontiroli, D.; Scaravonati, S.; Magnani, G.; Fornasini, L.; Bersani, D.; Bertoni, G.; Milanese, C.; Girella, A.; Ridi, F.; Verucchi, R. Super-activated biochar from poultry litter for high-performance supercapacitors. *Microporous Mesoporous Mater.* **2019**, *285*, 161–169. [CrossRef]
25. Wang, T.; Zhai, Y.; Zhu, Y.; Li, C.; Zeng, G. A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. *Renew. Sustain. Energy Rev.* **2018**, *90*, 223–247. [CrossRef]
26. Sarrion, A.; Diaz, E.; Angeles a la Rubia, M.; Mohedano, A.F. Fate of nutrients during hydrothermal treatment of food waste. *Bioresour. Technol.* **2021**, *342*, 125954. [CrossRef] [PubMed]
27. Fang, J.; Zhan, L.; Ok, Y.S.; Gao, B. Minireview of potential applications of hydrochar derived from hydrothermal carbonization of biomass. *J. Ind. Eng. Chem.* **2018**, *57*, 15–21. [CrossRef]
28. Xiao, L.P.; Shi, Z.J.; Xu, F.; Sun, R.C. Hydrothermal carbonization of lignocellulosic biomass. *Bioresour. Technol.* **2012**, *118*, 619–623. [CrossRef]
29. Mäkelä, M.; Benavente, V.; Fullana, A. Hydrothermal carbonization of lignocellulosic biomass: Effect of process conditions on hydrochar properties. *Appl. Energy* **2015**, *155*, 576–584. [CrossRef]
30. Khan, T.A.; Saud, A.S.; Jamari, S.S.; Ab Rahim MH Park, J.; Kim, H. Hydrothermal carbonization of lignocellulosic biomass for carbon rich material preparation: A review. *Biomass Bioenergy* **2019**, *130*, 105384. [CrossRef]
31. Krylova, A.; Zaichenko, V. Hydrothermal Carbonization of Biomass: A Review. *Solid Fuel Chem.* **2018**, *52*, 91–103. [CrossRef]
32. Shen, Y. A review on hydrothermal carbonization of biomass and plastic wastes to energy products. *Biomass Bioenergy* **2020**, *134*, 105479. [CrossRef]
33. Reza, M.T.; Yang, X.; Coronella, C.J.; Lin, H.; Hathwaik, U.; Shintani, D.; Neupane, B.P.; Miller, G.C. Hydrothermal Carbonization (HTC) and Pelletization of Two Arid Land Plants Bagasse for Energy Densification. *ACS Sustain. Chem. Eng.* **2016**, *4*, 1106–1114. [CrossRef]
34. Pauline, A.L.; Joseph, K. Hydrothermal carbonization of organic wastes to carbonaceous solid fuel–A review of mechanisms and process parameters. *Fuel* **2020**, *279*, 118472. [CrossRef]
35. Heidari, M.; Dutta, A.; Acharya, B.; Mahmud, S. A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion. *J. Energy Inst.* **2020**, *92*, 1779–1799. [CrossRef]
36. Land, Q.; Chen, M.; Guo, Y.; Liu, Z.; Gai, C. Effect of hydrothermal carbonization on heavy metals in swine manure: Speciation, bioavailability, and environmental risk. *J. Environ. Manag.* **2019**, *234*, 97–103. [CrossRef]
37. Lentz, Z.; Kolar, P.; Classen, J.J. Valorization of swine manure into hydrochars. *Processes* **2019**, *7*, 560. [CrossRef]
38. Bardhan, M.; Novera, T.M.; Tabassum, M.; Islam, M.A.; Islam, M.A.; Hameed, B.H. Co-hydrothermal carbonization of different feedstocks to hydrochar as potential energy for the future world: A review. *J. Clean. Prod.* **2021**, *298*, 126734. [CrossRef]
39. Li, Q.; Zhang, S.; Gholizadeh, M.; Hu, X.; Yuan, X.; Sarkar, B.; Vithanage, M.; Mašek, O.; Ok, Y.S. Co-hydrothermal carbonization of swine and chicken manure: Influence of cross-interaction on hydrochar and liquid characteristics. *Sci. Total Environ.* **2021**, *786*, 147381. [CrossRef] [PubMed]
40. Tumuluru, J.S.; Sokhansanj, S.; Hess, J.R.; Wright, C.T.; Boardman, R.D. A review on biomass torrefaction process and product properties for energy applications. *Ind. Biotechnol.* **2011**, *7*, 384–401. [CrossRef]
41. Yaashikaa, P.R.; Kumar, P.S.; Varjani, S.; Saravanan, A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnol. Rep.* **2020**, *28*, e00570. [CrossRef]
42. Yek PN, Y.; Cheng, Y.W.; Liew, R.K.; Mahari WA, W.; Ong, H.C.; Chen, W.; Peng, W.; Park, Y.; Sonne, C.; Kong, S.H. Progress in the torrefaction technology for upgrading oil palm wastes to energy-dense biochar: A review. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111645. [CrossRef]

43. Kwoczynski, Z.; Čmelík, J. Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process. *J. Clean. Prod.* **2021**, *280*, 124302. [CrossRef]
44. He, C.; Tang, C.; Li, C.; Yuan, J.; Tran, K.; Bach, Q.; Qiu, R.; Yang, Y. Wet torrefaction of biomass for high quality solid fuel production: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 259–271. [CrossRef]
45. Barskov, S.; Zappi, M.; Buchireddy, P.; Dufreche, S.; Guillory, J.; Gang, D.; Hernandez, R.; Bajpai, R.; Baudier, J.; Cooper, R. Torrefaction of biomass: A review of production methods for biocoal from cultured and waste lignocellulosic feedstocks. *Renew. Energy* **2019**, *142*, 624–642. [CrossRef]
46. Stępień, P.; Świechowski, K.; Hnat, M.; Kugler, S.; Stegenta-Dąbrowska, S.; Koziel, J.A.; Manczarski, P.; Białowiec, A. Waste to Carbon: Biocoal from Elephant Dung as New Cooking Fuel. *Energies* **2019**, *12*, 4344. [CrossRef]
47. Dhungana, A.; Dutta, A.; Basu, P. Torrefaction of non-lignocellulose biomass waste. *Can. J. Chem. Eng.* **2012**, *90*, 186–195. [CrossRef]
48. Akyürek, Z. Torrefaction for Energy Valorization of Cattle Manure: Combustion Performance, Kinetics, Thermodynamics. *Solid Fuel Chem.* **2022**, *55*, S1–S10. [CrossRef]
49. Sizmur, T.; Fresno, T.; Akgül, G.; Frost, H.; Moreno-Jiménez, E. Biochar modification to enhance sorption of inorganics from water. *Bioresour. Technol.* **2017**, *246*, 34–47. [CrossRef] [PubMed]
50. Azargohar, R.; Dalai, A.K. Steam and KOH activation of biochar: Experimental and modeling studies. *Microporous Mesoporous Mater.* **2008**, *110*, 413–421. [CrossRef]
51. Panwar, N.L.; Pawar, A.; Salvi, B.L. Comprehensive review on production and utilization of biochar. *SN Appl. Sci.* **2019**, *1*, 168. [CrossRef]
52. Sajjadi, B.; Zubatiuk, T.; Leszczynska, D.; Leszczynski, J.; Chen, W.Y. Chemical activation of biochar for energy and environmental applications: A comprehensive review. *Rev. Chem. Eng.* **2018**, *35*, 777–815. [CrossRef]
53. Anto, S.; Sudhakar, M.P.; Ahamed, T.S.; Samuel, M.S.; Mathimani, T.; Brindhadevi, K.; Pugazhendhi, A. Activation strategies for biochar to use as an efficient catalyst in various applications. *Fuel* **2021**, *285*, 119205. [CrossRef]
54. Panahi HK, S.; Dehhaghi, M.; Ok, Y.S.; Nizami, A.; Khoshnevisan, B.; Mussatto, S.I.; Aghbashlo, M.; Tabatabaei, M.; Lam, S.S. A comprehensive review of engineered biochar: Production, characteristics, and environmental applications. *J. Clean. Prod.* **2020**, *270*, 122462. [CrossRef]
55. Das, L.; Kolar, P.; Classen, J.J.; Osborne, J.A. Adsorbents from pine wood via K2CO3-assisted low temperature carbonization for adsorption of p-cresol. *Ind. Crops Prod.* **2013**, *45*, 215–222. [CrossRef]
56. Ansanay, Y.; Kolar, P.; Sharma-Shivappa, R.; Cheng, J.; Arellano, C. Pretreatment of switchgrass for production of glucose via sulfonic acid-impregnated activated carbon. *Processes* **2021**, *9*, 504. [CrossRef]
57. Kasera, N.; Kolar, P.; Hall, S.G. Nitrogen-doped biochars as adsorbents for mitigation of heavy metals and organics from water: A review. *Biochar* **2022**, *4*, 17. [CrossRef]
58. Akhil, D.; Lakshmi, D.; Kartik, A.; Vo, D.N.; Arun, J.; Gopinath, K.P. Production, characterization, activation and environmental applications of engineered biochar: A review. *Environ. Chem. Lett.* **2021**, *19*, 2261–2297. [CrossRef]
59. Al-Degs, Y.S.; El-Barghouthi, M.I.; Khraisheh, M.A.; Ahmad, M.N.; Allen, S.J. Effect of surface area, micropores, secondary micropores, and mesopores volumes of activated carbons on reactive dyes adsorption from solution. *Sep. Sci. Technol.* **2005**, *39*, 97–111. [CrossRef]
60. Guo, X.X.; Liu, H.T.; Zhang, J. The role of biochar in organic waste composting and soil improvement: A review. *Waste Manag.* **2020**, *102*, 884–899. [CrossRef]
61. Song, B.; Cao, X.; Gao, W.; Aziz, S.; Gao, S.; Lam, C.H.; Lin, R. Preparation of nano-biochar from conventional biorefineries for high-value applications. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112057. [CrossRef]
62. Enaime, G.; Baçaoui, A.; Yaacoubi, A.; Lübken, M. Biochar for wastewater treatment—conversion technologies and applications. *Appl. Sci.* **2020**, *10*, 3492. [CrossRef]
63. Ro, K.S.; Lima, I.M.; Reddy, G.B.; Jackson, M.A.; Gao, B. Removing gaseous NH_3 using biochar as an adsorbent. *Agriculture* **2015**, *5*, 991–1002. [CrossRef]
64. Vu, T.M.; Trinh, V.T.; Doan, D.P.; Van, H.T.; Nguyen, T.V.; Vigneswaran, S.; Ngo, H.H. Removing ammonium from water using modified corn cob-biochar. *Sci. Total Environ.* **2017**, *579*, 612–619. [CrossRef]
65. Huff, M.D.; Lee, J.W. Biochar-surface oxygenation with hydrogen peroxide. *J. Environ. Manag.* **2016**, *165*, 17–21. [CrossRef]
66. Manfrin, J.; Gonçalves, A.C., Jr.; Schwantes, D.; Conradi, E., Jr.; Zimmermann, J.; Ziemer, G.L. Development of biochar and activated carbon from cigarettes wastes and their applications in Pb2 adsorption. *J. Environ. Chem. Eng.* **2021**, *9*, 104980. [CrossRef]
67. Suliman, W.; Harsh, J.B.; Abu-Lail, N.I.; Fortuna, A.; Dallmeyer, I.; Garcia-Perez, M. Modification of biochar surface by air oxidation: Role of pyrolysis temperature. *Biomass Bioenergy* **2016**, *85*, 1–11. [CrossRef]
68. Nath, H.; Saikia, A.; Goutam, P.J.; Saikia, B.K.; Saikia, N. Removal of methylene blue from water using okra (*Abelmoschus esculentus* L.) mucilage modified biochar. *Bioresour. Technol. Rep.* **2021**, *14*, 100689. [CrossRef]
69. Kołodyńska, D.; Krukowska, J.A.; Thomas, P. Comparison of sorption and desorption studies of heavy metal ions from biochar and commercial active carbon. *Chem. Eng. J.* **2017**, *307*, 353–363. [CrossRef]
70. UMass Extension Crops, Dairy, Livestock and Equine Program. Manure as a Nutrient Resource. Center for Agriculture, Food, and the Environment, 2020. Available online: https://ag.umass.edu/crops-dairy-livestock-equine/fact-sheets/manure-nutrient-resource.k (accessed on 1 March 2022).

71. Kalus, K.; Konkol, D.; Korczyński, M.; Koziel, J.A.; Opaliński, S. Laying Hens Biochar Diet Supplementation—Effect on Performance, Excreta N Content, NH_3 and VOCs Emissions, Egg Traits and Egg Consumers Acceptance. *Collect. FAO Agric.* **2020**, *10*, 237. [CrossRef]
72. Man, K.Y.; Chow, K.L.; Man, Y.B.; Mo, W.Y.; Wong, M.H. Use of Biochar as Feed Supplements for Animal Farming. *Crit. Rev. Environ. Sci. Technol.* **2021**, *51*, 187–217. [CrossRef]
73. Schmidt, H.P.; Hagemann, N.; Draper, K.; Kammann, C. The use of biochar in animal feeding. *PeerJ* **2019**, *7*, e7373. [CrossRef]
74. Celi, P.; Cowieson, A.J.; Fru-Nji, F.; Steinert, R.E.; Kluenter, A.M.; Verlhac, V. Gastrointestinal Functionality in Animal Nutrition and Health: New Opportunities for Sustainable Animal Production. *Anim. Feed. Sci. Technol.* **2017**, *234*, 88–100. [CrossRef]
75. Goiri, I.; Ruiz, R.; Atxaerandio, R.; Lavin, J.L.; Díaz de Otálora, X.; García-Rodríguez, A. Assessing the Potential Use of a Feed Additive Based on Biochar on Broilers Feeding upon Productive Performance, pH of Digestive Organs, Cecum Fermentation and Bacterial Community. *Anim. Feed. Sci. Technol.* **2021**, *279*, 115039. [CrossRef]
76. van Der Wielen, P.W.; Biesterveld, S.; Notermans, S.; Hofstra, H.; Urlings, B.A.; van Knapen, F. Role of Volatile Fatty Acids in Development of the Cecal Microflora in Broiler Chickens during Growth. *Appl. Environ. Microbiol.* **2000**, *66*, 2536–2540. [CrossRef]
77. Prasai, T.P.; Walsh, K.B.; Bhattarai, S.P.; Midmore, D.J.; Van, T.T.; Moore, R.J.; Stanley, D. Biochar, Bentonite and Zeolite Supplemented Feeding of Layer Chickens Alters Intestinal Microbiota and Reduces Campylobacter Load. *PLoS ONE* **2016**, *11*, e0154061. [CrossRef]
78. Willson, N.L.; Van, T.T.; Bhattarai, S.P.; Courtice, J.M.; McIntyre, J.R.; Prasai, T.P.; Moore, R.J.; Walsh, K.; Stanley, D. Feed supplementation with biochar may reduce poultry pathogens, including *Campylobacter hepaticus*, the causative agent of Spotty Liver Disease. *PLoS ONE* **2019**, *14*, e0214471. [CrossRef]
79. Schubert, D.C.; Chuppava, B.; Witte, F.; Terjung, N.; Visscher, C. Effect of Two Different Biochars as a Component of Compound Feed on Nutrient Digestibility and Performance Parameters in Growing Pigs. *Front. Anim. Sci.* **2021**, *2*, 633958. [CrossRef]
80. Chu, G.M.; Kim, J.H.; Kim, H.Y.; Ha, J.H.; Jung, M.S.; Song, Y.; Cho, J.H. Effects of Bamboo Charcoal on the Growth Performance, Blood Characteristics and Noxious Gas Emission in Fattening Pigs. *J. Appl. Anim. Res.* **2013**, *41*, 48–55. [CrossRef]
81. Evans, A.M.; Loop, S.A.; Moritz, J.S. Effect of poultry litter biochar diet inclusion on feed manufacture and 4- to 21-d broiler performance. *J. Appl. Poult. Res.* **2015**, *24*, 380–386. [CrossRef]
82. Prasai, T.P.; Walsh, K.B.; Midmore, D.J.; Jones BE, H.; Bhattarai, S.P. Manure from biochar, bentonite and zeolite feed supplemented poultry: Moisture retention and granulation properties. *J. Environ. Manag.* **2018**, *216*, 82–88. [CrossRef] [PubMed]
83. Kalus, K.; Konkol, D.; Korczyński, M.; Koziel, J.A.; Opaliński, S. Effect of Biochar Diet Supplementation on Chicken Broilers Performance, NH_3 and Odor Emissions and Meat Consumer Acceptance. *Animals* **2020**, *10*, 1539. [CrossRef]
84. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. Tackling climate change through livestock—A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO). U.S. Energy Information Administration. U.S. Energy Information Administration—EIA—Independent Statistics and Analysis. 2013. Available online: https://www.eia.gov/environment/emissions/ghg_report/ghg_methane.php#:~{}:text=The%20major%20sources%20of%20U.S (accessed on 1 March 2022).
85. Leng, R.A. Interactions between Microbial Consortia in Biofilms: A Paradigm Shift in Rumen Microbial Ecology and Enteric Methane Mitigation. *Anim. Prod. Sci.* **2014**, *54*, 519–543. [CrossRef]
86. Maurer, D.L.; Koziel, J.A.; Kalus, K.; Andersen, D.S.; Opalinski, S. Pilot-Scale Testing of Non-Activated Biochar for Swine Manure Treatment and Mitigation of Ammonia, Hydrogen Sulfide, Odorous Volatile Organic Compounds (VOCs), and Greenhouse Gas Emissions. *Sustain. Sci. Pract. Policy* **2017**, *9*, 929. [CrossRef]
87. Qomariyah, N.; Retnani, Y.; Jayanegara, A.; Wina, E.; Permana, I.G. Influence of Biochar and Liquid Smoke Additives from Cacao-Pod Husks on in Vitro Ruminal Fermentation Characteristics. *Adv. Anim. Vet. Sci.* **2020**, *9*, 533–543. [CrossRef]
88. Mosoni, P.; Martin, C.; Forano, E.; Morgavi, D.P. Long-term defaunation increases the abundance of cellulolytic ruminococci and methanogens but does not affect the bacterial and methanogen diversity in the rumen of sheep. *J. Anim. Sci.* **2011**, *89*, 783–791. [CrossRef]
89. Mengistu, G.F.; McAllister, T.A.; Tamayao, P.J.; Ominski, K.H.; Ribeiro, G.O.; Okine, E.K.; McGeough, E.J. Evaluation of Biochar Products at Two Inclusion Levels on Ruminal In Vitro Methane Production and Fermentation Parameters in a Timothy Hay-Based Diet. *Can. J. Anim. Sci.* **2022**, *1*, 1–5. [CrossRef]
90. Terry, S.A.; Ribeiro, G.O.; Gruninger, R.J.; Chaves, A.V.; Beauchemin, K.A.; Okine, E.; McAllister, T.A. A Pine Enhanced Biochar Does Not Decrease Enteric CH4 Emissions, but Alters the Rumen Microbiota. *Front. Vet. Sci.* **2019**, *6*, 308. [CrossRef] [PubMed]
91. Tamayao, P.J.; Ribeiro, G.O.; McAllister, T.A.; Yang, H.E.; Saleem, A.M.; Ominski, K.H.; Okine, E.K.; McGeough, E.J. Effects of Post-Pyrolysis Treated Biochars on Methane Production, Ruminal Fermentation, and Rumen Microbiota of a Silage-Based Diet in an Artificial Rumen System (RUSITEC). *Anim. Feed. Sci. Technol.* **2021**, *273*, 114802. [CrossRef]
92. Leng, R.; Preston, T.; Inthapanya, S. Biochar reduces enteric methane and improves growth and feed conversion in local "Yellow" cattle fed cassava root chips and fresh cassava foliage. *Livest. Res. Rural. Dev.* **2017**, *24*, 199.
93. Linhoss, J.E.; Purswell, J.L.; Street, J.T.; Rowland, M.R. Evaluation of Biochar as a Litter Amendment for Commercial Broiler Production. *J. Appl. Poult. Res.* **2019**, *28*, 1089–1098. [CrossRef]
94. Ritz, C.W.; Tasistro, A.S.; Kissel, D.E.; Fairchild, B.D. Evaluation of Surface-Applied Char on the Reduction of Ammonia Volatilization from Broiler Litter. *J. Appl. Poult. Res.* **2011**, *20*, 240–245. [CrossRef]

95. Flores, K.R.; Fahrenholz, A.; Grimes, J.L. Effect of Pellet Quality and Biochar Litter Amendment on Male Turkey Performance. *Poult. Sci.* **2021**, *100*, 101002. [CrossRef] [PubMed]
96. Hwang, O.; Lee, S.-R.; Cho, S.; Ro, K.S.; Spiehs, M.; Woodbury, B.; Silva, P.J.; Han, D.-W.; Choi, H.; Kim, K.-Y.; et al. Efficacy of Different Biochars in Removing Odorous Volatile Organic Compounds (VOCs) Emitted from Swine Manure. *ACS Sustain. Chem. Eng.* **2018**, *6*, 14239–14247. [CrossRef]
97. Kaikiti, K.; Stylianou, M.; Agapiou, A. Use of biochar for the sorption of volatile organic compounds (VOCs) emitted from cattle manure. *Environ. Sci. Pollut. Res. Int.* **2021**, *28*, 59141–59149. [CrossRef]
98. Dunlop, M.W.; Blackall, P.J.; Stuetz, R.M. Odour emissions from poultry litter—A review litter properties, odour formation and odorant emissions from porous materials. *J. Environ. Manag.* **2016**, *177*, 306–319. [CrossRef]
99. Huggins, T.M.; Haeger, A.; Biffinger, J.C.; Ren, Z.J. Granular biochar compared with activated carbon for wastewater treatment and resource recovery. *Water Res.* **2016**, *94*, 225–232. [CrossRef]
100. Dougherty, B.; Gray, M.; Johnson, M.G.; Kleber, M. Can Biochar Covers Reduce Emissions from Manure Lagoons While Capturing Nutrients? *J. Environ. Qual.* **2017**, *46*, 659–666. [CrossRef]
101. Covali, P.; Raave, H.; Escuer-Gatius, J.; Kaasik, A.; Tõnutare, T.; Astover, A. The Effect of Untreated and Acidified Biochar on NH-N Emissions from Slurry Digestate. *Sustainability* **2021**, *13*, 873. [CrossRef]
102. Chen, B.; Koziel, J.A.; Banik, C.; Ma, H.; Lee, M.; O'Brien, S.C.; Li, P.; Andersen, D.S.; Białowiec, A.; Brown, R.C. Mitigation of Gaseous Emissions from Stored Swine Manure with Biochar: Effect of Dose and Reapplication on a Pilot-Scale. *Atmosphere* **2021**, *12*, 96. [CrossRef]
103. Meiirkhanuly, Z.; Koziel, J.A.; Chen, B.; Białowiec, A.; Lee, M.; Wi, J.; Banik, C.; Brown, R.C.; Bakshi, S. Mitigation of Gaseous Emissions from Swine Manure with the Surficial Application of Biochars. *Atmosphere* **2020**, *11*, 1179. [CrossRef]
104. Chen, B.; Koziel, J.A.; Białowiec, A.; Lee, M.; Ma, H.; Li, P.; Meiirkhanuly, Z.; Brown, R.C. The Impact of Surficial Biochar Treatment on Acute H2S Emissions during Swine Manure Agitation before Pump-Out: Proof-of-the-Concept. *Catalysts* **2020**, *10*, 940. [CrossRef]
105. Liu, M.; Liu, C.; Liao, W.; Xie, J.; Zhang, X.; Gao, Z. Impact of biochar application on gas emissions from liquid pig manure storage. *Sci. Total Environ.* **2021**, *771*, 145454. [CrossRef]
106. Bernal, M.P.; Alburquerque, J.A.; Moral, R. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* **2009**, *100*, 5444–5453. [CrossRef]
107. Akdeniz, N. A systematic review of biochar use in animal waste composting. *Waste Manag.* **2019**, *88*, 291–300. [CrossRef]
108. Steiner, C.; Das, K.C.; Melear, N.; Lakly, D. Reducing nitrogen loss during poultry litter composting using biochar. *J. Environ. Qual.* **2010**, *39*, 1236–1242. [CrossRef]
109. Chung, W.J.; Chang, S.W.; Chaudhary, D.K.; Shin, J.; Kim, H.; Karmegam, N.; Govarthanan, M.; Chandrasekaran, M.; Ravindran, B. Effect of biochar amendment on compost quality, gaseous emissions and pathogen reduction during in-vessel composting of chicken manure. *Chemosphere* **2021**, *283*, 131129. [CrossRef]
110. Chowdhury, M.A.; de Neergaard, A.; Jensen, L.S. Composting of solids separated from anaerobically digested animal manure: Effect of different bulking agents and mixing ratios on emissions of greenhouse gases and ammonia. *Biosyst. Eng.* **2014**, *124*, 63–77. [CrossRef]
111. Wang, Y.; Akdeniz, N.; Yi, S. Biochar-amended poultry mortality composting to increase compost temperatures, reduce ammonia emissions, and decrease leachate's chemical oxygen demand. *Agric. Ecosyst. Environ.* **2021**, *315*, 107451. [CrossRef]
112. Chowdhury, M.A.; de Neergaard, A.; Jensen, L.S. Potential of aeration flow rate and bio-char addition to reduce greenhouse gas and ammonia emissions during manure composting. *Chemosphere* **2014**, *97*, 16–25. [CrossRef] [PubMed]
113. Agyarko-Mintah, E.; Cowie, A.; Van Zwieten, L.; Singh, B.P.; Smillie, R.; Harden, S.; Fornasier, F. Biochar lowers ammonia emission and improves nitrogen retention in poultry litter composting. *Waste Manag.* **2017**, *61*, 129–137. [CrossRef] [PubMed]
114. Jia, X.; Wang, M.; Yuan, W.; Ju, X.; Yang, B. The Influence of Biochar Addition on Chicken Manure Composting and Associated Methane and Carbon Dioxide Emissions. *BioResources* **2016**, *11*, 5255–5264. [CrossRef]
115. Wang, C.; Lu, H.; Dong, D.; Deng, H.; Strong, P.J.; Wang, H.; Wu, W. Insight into the Effects of Biochar on Manure Composting: Evidence Supporting the Relationship between N_2O Emission and Denitrifying Community. *Environ. Sci. Technol.* **2013**, *47*, 7341–7349. [CrossRef] [PubMed]
116. Sánchez-García, M.; Alburquerque, J.A.; Sánchez-Monedero, M.A.; Roig, A.; Cayuela, M.L. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. *Bioresour. Technol.* **2015**, *192*, 272–279. [CrossRef]
117. Czekała, W.; Malińska, K.; Cáceres, R.; Janczak, D.; Dach, J.; Lewicki, A. Co-composting of poultry manure mixtures amended with biochar—The effect of biochar on temperature and C-CO_2 emission. *Bioresour. Technol.* **2016**, *200*, 921–927. [CrossRef]
118. Cheng, Q.; Xu, C.; Huang, W.; Jiang, M.; Yan, J.; Fan, G.; Zhang, J.; Chen, K.; Xiao, B.; Song, G. Improving Anaerobic Digestion of Piggery Wastewater by Alleviating Stress of Ammonia Using Biochar Derived from Rice Straw. *Environ. Technol. Innov.* **2020**, *19*, 100948. [CrossRef]
119. Pan, J.; Sun, J.; Ao, N.; Xie, Y.; Zhang, A.; Chen, Z.; Cai, L. Factors Influencing Biochar-Strengthened Anaerobic Digestion of Cow Manure. *Bioenergy Res.* **2022**. [CrossRef]
120. Xiao, L.; Lichtfouse, E.; Senthil Kumar, P.; Wang, Q.; Liu, F. Biochar Promotes Methane Production during Anaerobic Digestion of Organic Waste. *Environ. Chem. Lett.* **2021**, *19*, 3557–3564. [CrossRef]

121. Risse, L.M.; Cabrera, M.L.; Franzluebbers, A.J.; Gaskin, J.W.; Gilley, J.E.; Killorn, R.; Radcliffe, D.E.; Tollner, W.E.; Zhang, H. Land Application of Manure for Beneficial Reuse. In *Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*; Rice, J.M., Caldwell, D.F., Humenik, F.J., Eds.; ASABE: St. Joseph, MI, USA, 2006. [CrossRef]
122. Sohi, S.P.; Krull, E.; Lopez-Capel, E.; Bol, R. Chapter 2—A Review of Biochar and Its Use and Function in Soil. *Adv. Agron.* **2010**, *105*, 47–82.
123. Watanabe, A.; Ikeya, K.; Kanazaki, N.; Makabe, S.; Sugiura, Y.; Shibata, A. Five crop seasons' records of greenhouse gas fluxes from upland fields with repetitive applications of biochar and cattle manure. *J. Environ. Manag.* **2014**, *144*, 168–175. [CrossRef]
124. Niraula, S.; Choi, Y.K.; Payne, K.; Muir, J.P.; Kan, E.; Chang, W.S. Dairy Effluent-Saturated Biochar Alters Microbial Communities and Enhances Bermudagrass Growth and Soil Fertility. *Agronomy* **2021**, *11*, 1794. [CrossRef]
125. Agegnehu, G.; Srivastava, A.K.; Bird, M.I. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Appl. Soil Ecol. A Sect. Agric. Ecosyst. Environ.* **2017**, *119*, 156–170. [CrossRef]
126. Yuan, Y.; Chen, H.; Yuan, W.; Williams, D.; Walker, J.T.; Shi, W. Is biochar-manure co-compost a better solution for soil health improvement and N_2O emissions mitigation? *Soil Biol. Biochem.* **2017**, *113*, 14–25. [CrossRef] [PubMed]
127. Agegnehu, G.; Bass, A.M.; Nelson, P.N.; Bird, M.I. Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci. Total Environ.* **2016**, *543 Pt A*, 295–306. [CrossRef]
128. Rahman MY, A.; Truong, N.; Ergas, S.J.; MH Nachabe, M.H. Biochar-Amended Modified Bioretention Systems for Livestock Runoff Nutrient Management. *Fla. Water Resour. J.* **2020**. Available online: https://fwrj.com/techarticles/0920%20t3.pdf (accessed on 1 March 2022).
129. Sanford, J.R.; Larson, R.A. Treatment of Horizontal Silage Bunker Runoff Using Biochar Amended Vegetative Filter Strips. *J. Environ. Manag.* **2020**, *253*, 109746. [CrossRef]