CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
2021, VOL. 51, NO. 2, 187–217
https://doi.org/10.1080/10643389.2020.1721980

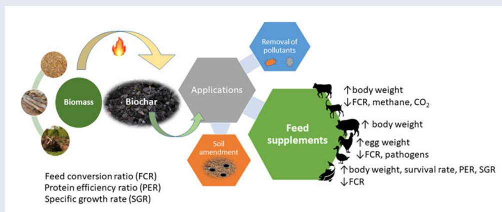
Taylor & Francis
Taylor & Francis Group

Use of biochar as feed supplements for animal farming

Ka Yan Man[a], Ka Lai Chow[b], Yu Bon Man[a], Wing Yin Mo[c], and Ming Hung Wong[a,d]

[a]Consortium on Health, Environment, Education and Research (CHEER), and Department of Science and Environmental Studies, The Education University of Hong Kong, Tai Po, Hong Kong; [b]Department of Geography, Hong Kong Baptist University, Kowloon Tong, Hong Kong; [c]Department of Science, School of Science and Technology, The Open University of Hong Kong, Hong Kong; [d]School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China

ABSTRACT



The production and application of biochar has become increasingly popular in the past 10 years. Biochar has similar characteristics to charcoal and activated charcoal: they are all pyrogenic carbonaceous matter derived from organic carbon-rich materials and produced by pyrolysis. Studies related to the incorporation of biochar in animal feed are limited. This review summarizes major studies related to the use of biochar as a feed additive for ruminants (cattle and goats), pigs, poultry (chickens and ducks) and fish. Documented positive responses to biochar supplementation include improved growth performance, blood profiles, egg yield, ability to resist pathogens including gut pathogenic bacteria and a reduction of methane production by ruminant animals. In addition, the high sorption capacity of biochar efficiently aids the removal of pollutants and toxins from animals' bodies as well as from farm environments. It is expected that there will be increasing use of biochar in animal farming. The potential use of biochar in the medical and human health sectors should also be explored.

KEYWORDS Animal husbandry; feed additives; fish culture

1. Introduction

Charcoal, activated charcoal and biochar are all types of pyrogenic carbonaceous matter. Table 1 shows the similarities and differences of the three products in terms of their raw materials, production processes, characteristics and applications. The three products are closely related and are differentiated mainly based on their applications. All three products share

CONTACT Ming Hung Wong minghwong@eduhk.hk Consortium on Health, Environment, Education and Research (CHEER), and Department of Science and Environmental Studies, The Education University of Hong Kong, Tai Po, Hong Kong.

Supplemental data for this article can be accessed on the publisher's website.

Table 1. Similarities and differences between charcoal, activated charcoal and biochar.

	Charcoal	Activated Charcoal	Biochar
Characteristics	All are carbonaceous pyrogenic materials and carbon-rich solids, with sorption ability due to their porous structure.		
Application	Fuel for heating and cooking.	Removing contaminants from water and air; remediation, filtration and purification; medical uses to treat poisonings and overdoses, and diarrhea, flatulence and indigestion.	Soil remediation and amendment (improving water properties and nutrient retention), and as a feed supplement.
Raw Materials			
Similarity	The starting materials are carbonaceous biomass or bio-based content such as wood, sawdust and cellulose residues.		
Difference	Typically from wood for fuel.	Specifications from the FAO indicate that the starting materials should be sawdust, peat, lignite, coal and petroleum coke.	Specifications from IBI and EBF indicate that the starting materials should be 100% bio-based materials such as natural and untreated trunk wood, and composition should not vary by more than 15%.
Production Conditions			
Similarity	They are all produced by pyrolysis, which is high temperature and low oxygen thermal decomposition process.		
Difference	Produced by pyrolysis only and does not undergo an activation process.	The feedstock undergoes pyrolysis at high temperature and then undergoes activation by chemical activating agents such as acids and inorganic salts, and activating gases such as steam or carbon dioxide.	The pyrolysis temperature ranges from 350 °C to 1000 °C, and the temperature does not vary by more than 20% during the process. Activation is used for biochar for soil remediation/ amendment but not for feed additives.
Example of production conditions	1. Pyrolysis *Temperature: 105 °C to 950 °C* *Heating rate: 10 °C/ min* *Residence time: 30 min*	1. Pyrolysis *Temperature: 110 °C to 600 °C* *Heating rate: 20 °C/ min* *Residence time: 10 min to 4 h* 2a. Chemical Activation (alkali or acid) *Temperature: 800 °C to 1000 °C* *Reagent: 200 cm^3 KOH per 20 g charcoal* *Activation time: 15-45 min* *Drying time: 2–24 h*	*For soil amendment* 1. Pyrolysis *Temperature: 350 °C to 1000 °C* *Heating rate: 7 °C/min to 40 °C/min* *Residence time: 10 min to 4 h* 2a. Chemical Activation (alkali or acid) *-In acid (30 % w/w phosphoric acid) overnight soaking and then heat at 450 °C for 4 h* *-In acid (0.1 M hydrochloric acid) 1 h soaking and dry at 80 °C overnight* *-In alkali (0.1 M potassium hydroxide) for 24 h, washing with*

(*continued*)

Table 1. Continued.

	Charcoal	Activated Charcoal	Biochar
			distilled water and drying at 65 °C for 24 h
		2b. Physical Activation (CO_2 or steam) *Temperature: 800 °C to 1100 °C* *Heating rate: 8 g steam/min* *CO_2 flow rate: 200 cm^3/min* *Pressure: 1.5 kg/cm^2* *Residence time: 1 h*	2b. Physical Activation (CO_2 or N_2 steam) *-Steam at 850 °C, 45 min* *-Carbon dioxide* *Temperature: 200 °C to 800 °C* *Heating rate: 10 °C/min* *CO_2 flow rate: 100 ml/min* *Pressure: 42.5 to 45.6 bar* *Residence time: 30 min to 1 h* *For feed additive* 1. Pyrolysis *Temperature: 350 °C to 1100 °C* *Heating rate: 7 °C /min to 40 °C/min* *Residence time: 3 min to 12 h*
References	Adrados et al. (2017); Bartocci, Zampilli, Bidini, & Fantozzi (2018); Wang, Skreiberg, Van Wesenbeeck, Grønli, & Antal (2016)	Abechi, Gimba, Uzairu, & Dallatu (2013); Aworn, Thiravetyan, & Nakbanpote (2008); Danish & Ahmad (2018); Yahya, Al-Qodah, & Ngah (2015)	European Biochar Foundation (EBF) (2012); International Biochar Initiative (IBI) (2015); Koltowski et al. (2017); Kwapinski et al. (2010); McFarlane et al. (2017); Pereira et al. (2014); Uchimiya, Lima, Klasson, & Wartelle (2010); Uchimiya, Wartelle, Klasson, Fortier, & Lima (2011)

similar production conditions and properties. They are carbon-rich solids derived from carbon-rich biomass and produced by pyrolysis; that is, they are bio-based carbon materials. Charcoal made from wood-based materials has been used since ancient times as fuel for heating and cooking. Activated charcoal is derived from charcoal through activation by physical processes (using steam or carbon dioxide) or chemical processes (using an alkali or acid). Activation is an enhancement process to the charcoal, which promote its physico-chemical properties such as surface area. Biochar and activated charcoal are both derived from charcoal using similar or even the same production processes. Biochar is the precursor of activated charcoal (Azargohar & Dalai, 2006). It is used in water purification, syngas upgrading, biodiesel production, organic waste composting, and soil conditioning. It is also used for soil remediation because it improves water holding capacity, increases adsorption ability and improves microbial diversity. (Cha et al., 2016; Sanchez-Monedero et al., 2018).

The benefits of biochar as a soil additive for the remediation of contaminated sites are well documented. It has been used for removal of pollutants such as heavy metals/metalloids and pesticides (Hagemann et al., 2019), and used in the remediation of contaminated soils, such as mine tailings (Fellet, Marchiol, Delle Vedove, & Peressotti, 2011). Biochar can improve soil's water holding capacity by controlling runoff water (Beck, Johnson, & Spolek, 2011) and it improves soil structure and soil properties by altering the soil biota, subsequently improving nutrient mobility and provision (Lehmann & Joseph, 2015).

In the past 10 years, researchers have investigated the effects of incorporating biochar into animal feed for ruminants, pigs, poultry and fish (Lan, Preston, & Leng, 2016; Preston, 2014; Schmidt, Wilson, & Kammann, 2017; Toth & Dou, 2016). It has been reported that biochar can enhance the yield and quality of chicken eggs (Kutlu, Ünsal, & Görgülü, 2001; Prasai, Walsh, Midmore, & Bhattarai, 2018). The wood charcoal supplementation to the hens diet can help to reduce the incidence of cracked eggs through improved mineral intake from biochar, which contained high levels of ask, calcium, potassium and magnesium (Kutlu et al., 2001). It can also promote the growth and survival rate of fish (Khaki, Malcevschi, Voccia, & Marzano, 2017; Mabe et al., 2018) and promote immunity by increasing high-density lipoprotein (HDL) and decreasing low-density lipoprotein (LDL) in ducks (Islam et al., 2014). It also reduced pathogens such as *Campylobacter hepaticus* and *Gallibacterium anatis* in chickens due to its adsorption properties (Willson et al., 2019). Therefore, it is a possible alternative to antibiotics in the husbandry industry (Islam et al., 2014). The highly porous nature of biochar could also provide habitats for gut microbes such as methanogenic archaea, contributing to the relief of greenhouse gas (GHG) emissions by mitigating methane production from cattle and goats (Eger, Graz, Riede, & Breves, 2018). Greenhouse gas emissions are a crucial factor in global climate change. Biochar has been shown to improve microbial fermentation and lower methane production from ruminants (Leng, Inthapanya, & Preston, 2012a; Leng, Preston, & Inthapanya, 2012), which are an important source of agricultural GHGs. In addition, overall farm productivity can be improved as a result of reduced inputs of chemical fertilizers, as biochar can adsorb nutrients from the guts of cattle which are then excreted out as soil fertilizer (Joseph et al., 2015).

In summary, previous findings suggested that biochar is potentially an excellent feed additive that can improve animal growth, improve blood profiles, strengthen immunity, reduce pathogens, lower methane production by improving gut microbial fermentation, and result in an overall improvement in agricultural productivity.

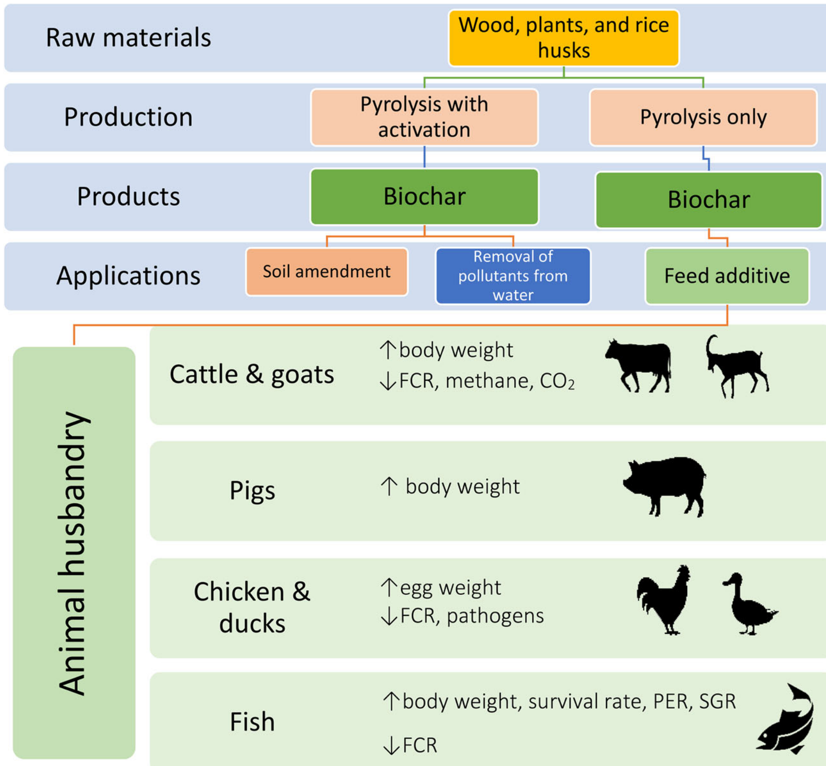


Figure 1. The production and end applications of biochar in animal husbandry.
Remarks: Symbols represents an improvement (↑) or decrease (↓). Abbreviations: FCR = feed conversion ratio, PEG = protein efficiency ratio, SGR = specific growth rate.

There is already a large amount of available information related to the production and usage of biochar for remediation (Oliveira et al., 2017). However, there is a severe lack of information about application of biochar derived from diversified feedstocks as feed supplements in animal farming. This review paper focuses on the effects of different biochar feedstocks as feed supplements for farming ruminants, pigs, poultry and fish, as well as identifying the knowledge gaps and research needs related to this. The effects on animal immunity, weight gain, specific growth rate, feed conversion ratio and protein efficiency ratio, as well as the effects of biochar on enteric methane mitigation are included. Figure 1 illustrates the uses and benefits of biochar in animal farming.

1.1. Raw materials used for production of biochar

Various organic materials of animal and plant origin, such as forestry residues (bark, sawdust, pitch pine and shavings), agricultural waste (wheat straw, crop residues, corn cobs, stover and wood waste), manure, non-food energy crops, construction scraps, yard trimmings, methane digester residues and grasses have been used to produce biochar for soil remediation and removing pollutants (Bruun, Ambus, Egsgaard, & Hauggaard-Nielsen, 2012; Kim, Kim, Cho, & Choi, 2012; Mullen et al., 2010).

Since 2010, biochar has increasingly been used as a feed additive in animal husbandry (O'Toole et al., 2016). As shown in Table 1, biochar used as a feed supplement is commonly made from biomass such as rice husks (Leng et al., 2012; Phongpanith, Inthapanya, & Preston, 2013), woody green waste (Prasai et al., 2016), pine wood chips (Saleem et al., 2018) and jarrah wood (Joseph et al., 2015).

1.2. Production of biochar as a feed supplement

All biomass used to produce biochar should go through pyrolysis, with or without activation (Mohan, Pittman, & Steele, 2006). Table 2 shows the specific functions of biochar made using different raw materials and with different production conditions. To produce biochar by pyrolysis, raw materials will be heated to a temperature ranging from 200 °C to over 1000 °C (Koltowski, Charmas, Skubiszewska-Zięba, & Oleszczuk, 2017) in a low oxygen environment, resulting in final products with different properties and with different functions (Břendová, Tlustoš, Száková, & Habart, 2012). Temperature, heating rate and residence time are the major variables that determine the functionality of biochar products for feed supplementation (Waheed, Nahil, & Williams, 2013). See Table 2 for details.

1.2.1. Feed additive

The organic matter used to make biochar feed additives undergoes thermochemical treatment at temperatures from 350 °C to 1100 °C, with a heating rate of 7 °C/min to 40 °C/min and a holding time from 3 min to 12 h (McFarlane et al., 2017; Pereira et al., 2014). The pyrolysis temperature should not vary by more than 20% during the process to fulfil the requirements of the EU regulation for making biochar as animal feed (European Biochar Foundation (EBF), 2012). Activation is not necessary for biochar products used as feed additives (see Tables 1 and 2).

1.3. Properties of biochar

The structural properties of biochar are greatly influenced by the composition of the raw materials, such as their cellulose, hemicellulose and lignin content, and by processing conditions such as activation and drying of the raw materials (Amin et al., 2017). In addition, the heating conditions, such as temperature, reaction time, and reactor type all contribute to the

Table 2. Raw materials and pyrolysis conditions for biochar with different functions.

Function	Specific function	Raw materials	Pyrolysis conditions	Reference
Soil amendment	Fertilizer and soil ameliorant	Willow (*Salix* spp.) Miscanthus (*Miscanthus giganteus*) Pine (*Pinus sylvestris*)	Temperature: 400-600 °C Heating rate: NA Residence time: 10-60 min	Kwapinski et al. (2010)
	Removal of heavy metals from soil	Cottonseed hulls (*Gossypium* spp.)	Temperature: 200-800 °C Heating rate: NA Residence time: 4 h	Uchimiya et al. (2011)
	Removal of heavy metals from soil	Broiler litter	Temperature: 350 °C/700 °C Heating rate: NA Residence time: 1 h	Uchimiya et al. (2010)
Removal of pollutants	Removal of trichloroethylene (TCE) from water	Soybean stover (*Glycine max*. L.)	Temperature: 300 °C /700 °C Heating rate: 7 °C/min Residence time: 3 h	Ahmad et al. (2014)
	Removal of antibiotics (tetracycline) from water	Rice husk (*Oryza sativa* L.)	Temperature: 723-773K Heating rate: NA (fast pyrolysis) Residence time: NA (fast pyrolysis)	Liu et al. (2012)
	Removal of lead and atrazine from water	Dairy manure	Temperature: 200 °C/350 °C Heating rate: NA Residence time: 4 h	Cao, Ma, Gao, & Harris (2009)
	Removal of naphthalene and 1-naphthol from water	Orange peel (*Citrus sinensis*)	Temperature: 150-700 °C Heating rate: NA Residence time: 6 h	Chen and Chen (2009)
	Removal of chromium from water	Oak wood (*Quercus* spp.) Oak bark (*Quercus* spp.)	Temperature: 400 °C/450 °C Heating rate: NA Residence time: 43-44s	Mohan, Rajput, Singh, Steele, & Pittman (2011)
Feed additive	Feed additives	Orchard grass (*Dactylis glomerata*) Chestnut oak (*Quercus prinus*) Yellow poplar (*Liriodendron tulipifera* L.) White pine (*Pinus strobus* L.)	Temperature: 1110 °C Heating rate: NA Residence time: >3 min	McFarlane et al. (2017)
	In vitro enteric fermentation experiment: methane reduction	Pine wood chips (*Pinus taeda*) Corn stover (*Zea mays* spp.)	Temperature: 350-550 °C Heating rate: 28 °C/min Residence time: NA	Pereira et al. (2014)

properties of the final products (Yu et al., 2019). Temperature is the most important factor among the three. In the heating process, thermal decomposition will leave behind a microporous carbon skeleton resembling the original structure. The activation of biochar is carried out to maximize its surface area and pore density, and therefore increase its ability to capture pollutants and other particulates. The extremely high surface area of biochar, which varies from 500 to 2000 m^2g^{-1}, together with its low density function as activated charcoal, has excellent adsorptive properties and is able to efficiently adsorb various substances, pollutants and gases (Lehmann & Joseph, 2015; Tan et al., 2016). The physical and chemical properties of biochar, especially porosity, surface area and nutrients composition, are crucial for determining its practical applications. The physio-chemical properties of biochar could mainly be determined by their sources of feedstocks and pyrolysis temperature (Jindo, Mizumoto, Sawada, Sanchez-Monedero, & Sonoki, 2014; Kim et al., 2012).

1.3.1. Biochar derived from different feedstocks

Biochar derived from different sources would lead to various physical and chemical characterization, as well as chemical compositions (Jindo et al., 2014; Mukherjee & Zimmerman, 2013). For example, the yield of biochar is dependent on the types of feedstock. Feedstock with high lignin content, which is related to the formation of char, would usually generate higher biochar yield (Suliman et al., 2016). These deviations enable biochar to be added into the feeds as a supplement for feeding different animals. For instance, Jarrah wood biochar shared similar organic molecules as those found in wood vinegar, which was proven to be enhancing the growth of cow in the perspective weight gain and the taste of beef (Joseph et al., 2015; Kook & Kim, 2003). Moreover, the pH level of Jarrah wood biochar is close to the saliva of cows and thus may have the a buffering function (Joseph et al., 2015). The porosity of biochar can also be affected by the origins of feedstocks, such as the porosity of biochar derived from rice straw which was the highest, followed by apple tree branch, rice husk, and oak tree after the pyrolysis at 400 °C (Jindo et al., 2014). The microporosity of apple tree branch and oak tree increased more rapidly than rice straw and rich husk (non-wood feedstock) when the temperature raised from 400 to 800 °C. It is attributed to the relatively high ash content of rice plant materials and the access to micropores was hindered and led to a relatively lower surface area (Jindo et al., 2014). The high surface area and porosity could favor the livings of methanotrophic bacteria in rumen and facilitate the anaerobic methane oxidation (Leng et al., 2012).

1.3.2. Biochar produced by various pyrolysis temperature

After the high temperature pyrolysis, oxygen and hydrogen, including the oxygenated surface functioning groups (carbonyl, carboxyl and hydroxyl groups), left from the carbonized biomass as pyrolysis temperature increases and aromatic carbon structures of biochar started to form at 400 °C (Kim et al., 2012). The increased temperature also resulted in smaller biochar particles, and particle size is one of the major considerations in applying biochar as a feeding supplement in ruminant diets (Kim et al., 2012; McFarlane et al., 2017). Fine particle size led to higher forage digestibility and increased rumen fermentation kinetics compared with coarse biochar particles (McFarlane et al., 2017). In addition, higher pyrolytic temperature also altered the nutrient composition of biochar. Naeem, Khalid, Arshad, and Ahmad (2014) reported that the nutrients, including phosphorus, potassium, calcium, magnesium, zinc, iron and manganese increased with the heating temperature, except nitrogen, which declined as the pyrolytic temperature rose from 300 up to 500 °C (Naeem et al., 2014). These changes are pivotal in applying biochar as feed supplements due to the variations in nutrient needs of different animals. For example, nitrogen content in feeds is essential determinant factor to fish growth (Mo, Man, & Wong, 2018). Thu, Koshio, Ishikawa, & Yokoyama (2009) reported the utilization of nutrients by Tiger Puffer Fish (*Takifugu rubripes*) after the use of dietary bamboo charcoal in culturing. It is evident that the protein efficiency ratio of the fish group fed with 4% bamboo charcoal was significantly higher than those in the control group (Thu et al., 2009).

1.4. Regulations on biochar as feed supplements

1.4.1. Biochar as feed supplements

In Europe, the requirements for making biochar as a feed additive are stringent. The European Biochar Foundation (EBF) provides an outline, the European Biochar Certificate, for making feed-grade biochar that complies with the feeding purpose under the European Union Commission Regulations: (1) Commission Regulation (EC) 178/2002 and (2) Commission Regulation (EC) 834/2007 (European Biochar Foundation (EBF), 2012). These two regulations are related to the general principles and requirements of food law overseen by the European Food Safety Authority (EFSA), whose major concerns are food safety, regulations for organic livestock feeds, the sustainable development of organic production, labeling of organic products and repealing regulations (European Commission (EC), 2019). The European Biochar Certificate is a voluntary industry standard that differentiates between three different grades of biochar, each with its own ecological requirements and threshold values: basic, premium and feed. Basic and premium grades are intended for use in the growing of crops, whereas feed grade is intended for use as a feed additive. The ecological requirements relate to the biomass feedstocks for making biochar, and the threshold values refer to the physical and chemical properties of the biochar products (such as carbon and toxicant contents, respectively). The product criteria for feed grade biochar are more restrictive than those for basic and premium grades (European Biochar Foundation (EBF), 2012) (Table 3). The raw materials for biochar products used as feed additives should be made from 100% bio-based materials such as natural and untreated trunk wood, and the raw material composition should not vary by more than 15% (European Biochar Foundation (EBF), 2012). The criteria for gaining certification for the three different grades of biochar under this standard have been summarized below and in Table 3 (European Biochar Foundation (EBF), 2012):

1. Only the feedstocks on the “positive list” (e.g. leaves, roots, bark and wood) (Supplementary material, Table S3) are allowed to be used for producing biochar.
2. Feedstocks must be free of paint, solvents and other organic or non-organic contaminants such as plastic, electronic scrap, and rubber.
3. Biochar may only be produced from forest wood that was grown in Europe (appropriate standards, laws or certificates should be used to prove sustainable forest management).

The raw materials used for producing biochar are biomass and organic materials. They are similar to those for producing activated charcoal. Therefore, the regulations and specification for activated charcoal published by the Food and Agriculture Organization (FAO) and World Health Organization (WHO) are also applicable for biochar (Supplementary material, Table S2). The guidelines state that carbon for producing activated charcoal can be obtained from a wide variety of sources, such as sawdust, peat, cellulose residue, coconut shells, bamboo charcoal and lignite (FAO/WHO, 2010). If the materials undergo chemical activation by alkali or acid, the chemical activating agents should be removed with water before the biochar is used as a feed additive (FAO/WHO, 2010). Only the European Biochar Certificate program certifies biochar as an animal feed additive; only feed grade biochar is allowed to be added to animal feed in Europe. According to the guidelines (European Biochar Foundation (EBF), 2012), only biomass from untreated and natural wood is allowed as feedstock.

1.5. Use as adsorbent in livestock farming

The high absorption and adsorption properties of biochar mean that applying it to grazing land can improve farm hygiene by binding toxic

Table 3. Summary of the criteria for gaining premium and feed grade biochar certification under European Biochar Certificate Standard (European Biochar Foundation (EBF), 2012).

Production criteria			
	Basic	Premium	Feed
Pyrolysis temperature	From 350 °C to 1000 °C and fluctuation < 20%		
Composition of the pyrolysis biomass	Only from natural and untreated trunk wood, and fluctuation < 15%		
Production period	<1 year		
Product criteria for the three grades of biochar			
	Basic	**Premium**	**Feed**
PAHs	<12 mg kg^{-1}	<4 mg kg^{-1} total (sum of 16 US EPA PAHs)	<4 mg kg^{-1} total (sum of 16 US EPA PAHs)
Carbon content	≥50%	≥50%	>80% of dry matter
Heavy metals, 88% of dry matter	Pb <150 mg kg^{-1} Cd <1.5 mg kg^{-1} Cu <100 mg kg^{-1} Ni <50 mg kg^{-1} Hg < mg kg^{-1} Zn <400 mg kg^{-1} Cr <90 mg kg^{-1}	Pb <120 mg kg^{-1} Cd <1 mg kg^{-1} Cu <100 mg kg^{-1} Ni <30 mg kg^{-1} Hg <1 mg kg^{-1} Zn <400 mg kg^{-1} Cr <80 mg kg^{-1}	Arsenic: <2 mg kg^{-1} Lead: <10 mg kg^{-1} Cadmium:<1 mg kg^{-1} Mercury: <0.1 mg kg^{-1}
Benzo-a-pyren	N/A	N/A	<25 µg/kg
Dioxin, furane, dioxin-like PCB (WHO-PCB) and non-dioxin-like PCB (DIN-PCB)	N/A	<20 ng/kg	PCDD/PCDF: a trigger value of 0.5 < 0.75 ng TE kg^{-1} dl-PCB: 0.35 ng TE kg^{-1}
PCB content	<0.2 mg/kg DM	<0.2 mg/kg DM	PCDD / PCDF + dl-PCB the threshold is 1.25 ng TE kg^{-1}
PCDD/Fs	<20 ng kg^{-1} I-TEQ	<20 ng kg^{-1} I-TEQ	sum 6 of DIN PCB, a limit value of 10 µg TE kg^{-1}
Fluor	N/A	N/A	<150 mg kg^{-1}
Dry matter, crude ash, ash insoluble in hydrochloric acid	N/A	N/A	Same as EU feed regulations
Crude protein, crude fiber, crude fat	N/A	N/A	No longer present in biochar under complete pyrolysis: 0 g kg^{-1}

*All the criteria measured on 88% dry matter basis.
Abbreviations: PAH = polyaromatic hydrocarbons, PCB = polychlorinated biphenyl, PCDD = polychlorinated dibenzodioxins, PCDF = polychlorinated dibenzofuranes DM = dry mass, TEQ = toxic equivalency factor.

substances and controlling pathogens, limiting the spread of diseases as well as removing odors and toxins from bacteria (Toth & Dou, 2016). The multiple benefits of using biochar with animals has raised the awareness of farmers about how to fully utilize biochar in animal husbandry. Maurer, Koziel, Kalus, Andersen, and Opalinski (2017) reported that floating biochar on top of pig manure for a month significantly mitigated the odor from the emission of ammonia from livestock excreta. Applying 5–10 v/v biochar to poultry farm litter can also reduce ammonia and improve the odor problems of chicken farms. The moisture level of farm litter can be controlled and regulated by the application of biochar. Furthermore, foot pad dermatitis in chicken and ducks can be alleviated (Gerlach & Schmidt, 2012b).

2. Historical perspectives on the use of activated charcoal in treating digestive disorders in humans and animals

2.1. Treatment of digestive disorders in humans

Charcoal was first reported as an antidote in 1811, when a chemist ingested charcoal after a lethal dose (5 g) of arsenic trioxide (Juurlink, 2016). In the last century, scientists achieved promising results treating acute poisoning with ingestion of activated charcoal, which prompted clinical trials. Due to its porous structure, activated charcoal can selectively remove the hydrogen or hydrogen-rich fractions from carbonaceous raw materials (Hagemann et al., 2019). The process of activation can be physical and/or chemical as described above. The toxic substances that can be effectively adsorbed by activated charcoal include alcohols, analgesics, antimicrobial agents, plant and animal toxins, and endogenous toxins, as well as gases such as methane and stomach gas. Furthermore, oral activated charcoal has been recognized as an aid for treating gastrointestinal disturbances such as dyspepsia, gas pain, and sour or acid stomach (Cooney, 2016).

2.2. Treatment of digestive disorders in animals

Charcoal has a long history of use in treating digestive disorders such as diarrhea, not only in humans but also in livestock (O'Toole et al., 2016). From the end of 19th to the early 20th century, feeding a regular dosage of charcoal was widely used to improve animal health and growth performance. Activated charcoal has been administered to relieve a range of different digestive problems in various animals including colic in horses (Edmunds et al., 2016), flatulence in dogs (Giffard, Collins, Stoodley, Butterwick, & Batt, 2001) and ingested toxins in horses (Kaye, Elliott, & Jalim, 2012). It is regarded as a universal poison antidote and has been used in time-restricted medications against bacterial toxins such as those produced by *Clostridium botulinum*, *Clostridium tetani* and *Campylobacter jejuni* in chickens (Prasai et al., 2016), as well as against viral animal diseases such as bovine rotavirus and bovine coronavirus *in vitro* (Toth & Dou, 2016).

3. Biochar as a feed supplement for growth promotion and immunity enhancement

Adding supplements, such as organic minerals, amino acids, fatty acids, antibiotics and vitamins to feed is commonly practised in livestock farming to improve the immunity, protein intake, growth performance and farming productivity of animals. In Europe, including Germany, Austria and Switzerland, 90% of the produced biochar is used in animal husbandry, mainly in cattle and poultry farming (Gerlach & Schmidt, 2012a), and used as a feed additive (Kammann et al., 2017). It is estimated that the application of biochar in the agriculture segment with the compound annual growth rate will meet about 12.5% in eight years start from 2018. Feed grade biochar is usually mixed with regular feed at approximately 0.1% to 4.0% of the daily feed intake (O'Toole et al., 2016). A number of studies have shown that adding biochar to feed can increase weight gain and feed intake (Evans, Boney, & Moritz, 2017; Phongphanith & Preston, 2016; Saroeun, Preston, & Leng, 2018); enhance animal health (Hien, Dung, Manh, & Le Minh, 2018); benefit nutrient intake; aid the detoxification of contaminants, pollutants and other toxins in feed; reduce antibiotics residues; and reduce enteric methane emissions (Leng, Inthapanya, & Preston, 2013; Winders et al., 2018; Khoa, Quang, Thang, Phung, & Kien, 2018). Table 4 summarizes the use of biochar in animal husbandry and the benefits observed in ruminants (cattle and goats), pigs, poultry (chicken and ducks) and fish, along with the corresponding raw materials and production conditions. In 2018, the total global consumption of meat from cattle, pigs, poultry and sheep was 33.8 million tonnes; with pigs being the most consumed (39%), followed by chicken (36%), cattle (21%) and sheep (4%) (United States Department of Agriculture (USDA), 2018). Fish farming is also an important sector of the food industry. These animals are discussed in detail below.

3.1. Ruminants: Cattle and goats

Ruminants are mammals in which the stomach has four compartments, namely the rumen, reticulum, omasum and abomasum. The abomasum is the "true" stomach, where the digestion process is the same as in monogastric animals. Ruminants can utilize non-protein nitrogenous materials; utilize complex forms of carbohydrates such as cellulose and hemicellulose, and convert forage and green grasses into valuable protein sources (Bath, 2018; Zervas & Tsiplakou, 2011).

3.1.1. Cattle

Castillo-González, Burrola-Barraza, Domínguez-Viveros, and Chávez-Martínez (2014) found that *in vitro* incubation of biochar with buffered rumen fluid had a positive effect on substrate digestibility. McFarlane et al. (2017) reported that 81 g/kg dry matter of plant-based biochar reduced the digestibility of forage and increased volatile fatty acid production. Saleem et al. (2018) found that pine-based biochar could improve *in vitro* ruminal fermentation, nutrient disappearance, and microbial protein synthesis, and reduce enteric methane production. Leng et al. (2012) reported that cattle

Table 4. Applications of biochar in animal husbandry.

Animals	Raw materials	Production	Quantity of biochar applied	Effects	References
Ruminants					
Cattle	Rice husks	Gasifier stove temperature of carbonization exceeds 400 °C	0.6% of daily diet DM	↑ weight gain ↓methane	Leng et al. (2012)
			1% of daily diet DM with 4% rice distillers' by-product	↑ weight gain ↓ FCR	Phongphanith & Preston (2016)
			biochar inclusion in urea-molasses blocks at levels of 0, 2, 4, 6 and 8%	↑weight gain ↓FCR	Saroeun et al. (2018)
	Plant material	At very high temperatures in the absence of oxygen	0.8 and 3 % DM	↓carbon dioxide production. ↓methane production	Winders et al. (2018)
Goats	Rice husks	Gasifier stove temperature of carbonization exceeds 400 °C	1% of daily diet DM	→feed intake, →apparent digestibility →N balance	Phongpanith et al. (2013)
	Fibrous biomass		1.1% of daily diet DM	↑weight gain ↓FCR ↑DM digestibility ↑N retention	Silivong & Preston (2015)
Pigs					
	Rice husks	Gasifier stove temperature of carbonization exceeds 400 °C	1% biochar of daily diet DM	↑weight gain by 20.1%	Sivilai et al. (2018)
	Commercial biochar		0% and 3% biochar of daily diet	→weight gain, →feed intake →FCR	Kupper et al. (2015)
Poultry					
Chicken	Woody green waste	Pyrolysis at 550 °C	1%, 2% and 4% biochar in daily diet	↑ egg weight ↓FCR	Prasai et al. (2018)
	Eucalyptus hardwood			↓ poultry pathogens (*Gallibacterium anatis*, *Campylobacter hepaticus*)	Willson et al. (2019)
	Rice husks	Gasifier stove temperature of carbonization exceeds 400 °C	1% biochar in daily diet	↓ plasma triglycerides ↓total coliforms in litter; ↓*E. coli* in feces	Hien et al. (2018)
	Woody green waste	Pyrolysis at 550 °C.	4% biochar in daily diet	↓gut pathogenic bacteria (*Campylobacter jejuni*) ↑egg weight	Prasai et al. (2016)

	Commercial broiler litter	Gasification	2% and 4% biochar	→ weight gain →FCR	Evans et al. (2017)
	Corn stover	Pyrolysis	2%, 4%, 6% biochar	↑body weight ↓FCR	Dim et al. (2018)
Fish					
Striped catfish (*Pangasius*	*hypophthalmus*)	Rice husks	Gasifier stove temperature of carbonization exceeds 400 °C	1% biochar in daily diet	↑ growth rate
Lan et al. (2016)					
Brown trout (*Salmo trutta*)	Not specified	Not specified	0.02 and 0.03% biochar in daily diet	↑growth performance and survival rate	Khaki et al. (2017)
Japanese flounder (*Paralichthys olivaceus*)	Bamboo		0.25, 0.5, 1, 2, and 4% bamboo charcoal in daily diet	↑weight gain ↑SGR ↓FCR ↑PER	Thu et al. (2010)
Tiger puffer fish (*Takifugu rubripes*)			0.004, 0.01, 0.1, 1 and 4% bamboo charcoal of daily diet	↑body weight gain ↑SGR	Moe et al. (2009)

Remarks: Symbols represent an improvement (↑), decrease (↓) or no adverse effect (→) of biochar on livestock. Abbreviations: FCR = feed conversion ratio, PEG = protein efficiency ratio, SGR = specific growth rate, DM = dry mass.

weight increased by 25% when 0.6% rice husk-based biochar was added to the diet, when compared to the control diet without biochar. Phongphanith and Preston (2016) found that 1% of rice husk-based biochar in addition to 4% rice distillers' by-product increased cattle weight by 60% and the feed conversion ratio (FCR) significantly improved from 11.5 to 7.86 ($p < .05$). Rice distillers' by-product is full of yeast (*Saccharomyces cerevisiae*) and is a good probiotic supplement that promotes growth and immunity in livestock by suppressing toxins and protecting anaerobic rumen bacteria from oxidation (Abdel-Tawwab, Abdel-Rahman, & Ismael, 2008). According to Saroeun et al. (2018), the inclusion of 2–8% rice husk-based biochar in urea–molasses blocks increased cattle body mass by 43%, and the FCR was significantly improved from 16.4 to 10.7 ($p < .05$). In addition, Winders et al. (2018) observed that inclusion of 0.8% and 3% plant-based biochar in the cattle diet significantly reduced carbon dioxide production. It seems clear that using biochar in cattle farming has some benefits, including adsorbing toxic substances in the gastrointestinal tract, detoxification by resorbing lipophilic toxins in plasma, and promoting the oxidation and deamination of biogenic amines in the intestines (Gerlach & Schmidt, 2012a).

3.1.2. Goats

Silivong and Preston (2015) showed that the percentage weight gain of goats whose diets were supplemented with 1.1% biochar (fibrous biomass) was 8.9% when compared to goats fed a no-biochar diet; the FCR improved from 15.5 to 11.4, and digestibility and nitrogen retention also improved. Another study found no adverse effect on goats in terms of feed intake, apparent digestibility and nitrogen balance when 1% rice husk-based biochar was added to the animals' diet (Phongpanith et al., 2013).

3.2. Pigs

A study by Sivilai, Preston, Leng, Hang, and Linh (2018) showed that diets incorporating rice husk-based biochar had a positive effect on native moo lath pigs, in which weight gain increased by 20.1% when 1% biochar was included in the diet, and by 22.9% when 1% biochar was combined with rice distillers' by-product. The FCR significantly improved from 3.96 to 4.43 respectively ($p < .05$). Kupper, Fischlin Häni, and Spring (2015) reported that no adverse effect was found on weight gain, feed intake or the FCR of weaned piglets fed with 3% biochar when compared to the control piglets (0% biochar). Chu, Kim, Kang, and Song (2013) found that bamboo biochar significantly improved the fatty acids composition of pig carcasses, with increased unsaturated fatty acids and decreased saturated fatty acids in the pig meat. Chu, Jung, et al. (2013) found that pigs fed with 0.3% bamboo biochar had a significantly improved fecal microflora composition, with increases in the focal anaerobic bacteria and lactic acid bacteria and decreases in the counts of pathogenic coliform bacteria and *Salmonella* spp. Chu, Kim, Kim et al. (2013) found that 0.6% of bamboo biochar added to pigs' daily diet resulted in significantly lower concentrations of lactate dehydrogenase, triglyceride and blood urea nitrogen in blood. They also found that the total serum antibody concentration, immunoglobulin G (IgG), and count of fecal *Lactobacillus* spp. were significantly higher in pigs fed with 0.3% and 0.6% bamboo biochar when compared to the control (0% biochar). In general, pigs' growth performance and immunity are promoted by adding 0.3% to 3% biochar to the daily diet.

3.3. Poultry: Chicken and ducks

Poultry provides eggs and meat for human consumption. Evans et al. (2017) revealed that 2% of broiler litter-based biochar supplemented in one-day-old broiler chicks' diet had no adverse effect on the chicks and resulted in similar weight gain and FCR compared with control feed. The results of an experiment in which poultry were fed biochar, bentonite or zeolite showed that biochar had the best granulation properties (1–4 mm) and moisture retention (85–90%). Dim et al. (2018) reported that broilers fed with 4% and 6% corn stover biochar were similar in final body weight but heavier ($p < .05$) than those fed 2% biochar kg^{-1} and those on the control diet (0% biochar kg^{-1}).The FCR improved from 3.02 (Control) to 1.89 (6%) ($p < .05$). Egg-laying poultry fed with wood-based biochar had better egg weights ($60.6\,g \pm 1.14\,g$) and FCR ($2.20\,g \pm 0.042\,g$) when compared to the control group (without biochar) (Prasai et al., 2018).

It has been suggested that the high surface area and pore size of charcoal particles are the crucial factors in binding between bacteria and the particles for pathogen control (Naka et al., 2001). Watarai and Tana (2005) found that pathogens were adsorbed to a greater extent than native intestinal microflora. The inclusion of 4% wood-based biochar in the daily diets of Bond Brown Layer (Rhode Island Red cockerel × Rhode Island White hen) pullets reduced pathogenic bacteria (*Campylobacter jejuni*) in the gut microbiota and the pullets' egg weight significantly increased by 5% (Prasai et al., 2016). Supplementing biochar in broilers' diets can deactivate toxins in the digestive system and help to activate the intestinal flora and boost its vitality (Gerlach & Schmidt, 2012b).

As noted previously, biochar acts as an antidote in the digestive system and can help remove harmful metabolites and deactivate toxins (Gerlach &

Schmidt, 2012b). Hien et al. (2018) evaluated the haematological parameters of chicken fed with 1% rice husk- based biochar and found that the biochar reduced blood plasma triglycerides. It has also been found that the omega-3 fatty acids in ducks increased when 1% wood biochar was supplemented in their feed. Islam et al. (2014) found that 1% biochar in daily feed could lower LDL concentration, increase HDL concentration ($p < .05$) and reduce the omega-6/omega-3 polyunsaturated fatty acids ratio. They also found that adding wood biochar (0.1%, 0.5%, or 1%) to ducks' diets had no adverse effect on their overall growth performance, which was similar to that of the group given antibiotics (0.01% chlortetracycline).

3.4. Fish

Relatively few studies have investigated the use of biochar in fish culture. It was found that juvenile Japanese flounder (*Paralichthys olivaceus*) fed with 0.5% bamboo charcoal had significantly increased weight gain ($p < .05$), specific growth rate (SGR), FCR, and protein efficiency ratio (PER) (Thu, Koshio, Ishikawa, & Yokoyama, 2010). Six levels of bamboo charcoal (biochar) (0, 0.004, 0.01, 0.1, 1 and 4%) were added to the fish diet (initial fish body weight, 53 ± 2 g), and the results showed that the body weight gain and specific growth rate (SGR) were significantly higher ($p < .05$) in the fish fed the diet supplemented with 4% biochar (Moe, Ishikawa, Koshio, & Yokoyama, 2009). Khaki et al. (2017) showed that brown trout (*Salmo trutta*) with the highest final body weight received diets supplemented with biochar (0.2 and 0.3 per kg diet), exhibiting significantly increased weight gain, SGR and FCR ($p < .05$). Lan et al. (2016) found that growth rates revealed that using 1% rice husk-based biochar to feed striped catfish (*Pangasius hypophthalmus*) were increased by 36% ($p < .05$). Quaiyum, Jahan, Jahan, Akhter, and Sadiqul (2014) observed that 2% of bamboo biochar added to the daily diet of striped catfish significantly increased their body weight, survival rate, FCR and SGR. .

4. Specific functions of biochar as a feed supplement

In addition to the animal growth responses, biochar has two specific functions as a feed supplement: (1) gut methane mitigation and (2) removal of pollutants and toxins from the environment and from animals.

4.1. Gut methane mitigation

Greenhouse gas emissions are a global issue that influences climate change. The key GHGs emitted are carbon dioxide, methane, nitrous oxides and fluorinated gases. It has been estimated that methane accounted for 10% of global GHG emissions in 2016 (equivalent to 657 million tonnes of CO_2) (US Environmental Protection Agency (USEPA), 2016). There is an urgent need to mitigate GHGs such as methane.

Methane from enteric fermentation in domestic livestock was estimated to be equivalent to 171 million tonnes of CO_2 in 2016. About 36% of methane emissions came from agricultural manure management (10%) and enteric fermentation in livestock such as cattle, buffalo, sheep and goats (26%) (US Environmental Protection Agency (USEPA), 2016). These ruminants gain energy from fibrous feed, relying on symbiotic relationships with bacteria, fungi and protozoa in their rumen (Castillo-González et al., 2014). Microbial populations play an important role in releasing energy by digesting the fiber and producing fermentation acids. A by-product of this process is metabolic hydrogen, which should be kept at a very low levels to digest the fiber efficiently. Methanogenic archaea facilitate this digestion process within the complicated microbial ecosystem in the rumen; energy is gained for growth and multiplication after combining carbon dioxide and hydrogen to produce methane (Eger et al., 2018).

Methane from the rumen is mainly disposed of by eructation via the gut, and a small proportion is absorbed into the blood and expired through the lungs (Danielsson et al., 2017; Deusch et al., 2017). Most enteric methane is absorbed or excreted via the lungs, but some is emitted through the anus (Hook, Wright, & McBride, 2010). Enteric methane originating in the rumen and hindgut fermentation can account for 6–14% of daily methane production (Moss, Jouany, & Newbold, 2000; Martin, Morgavi, & Doreau, 2010).

4.1.1. Mechanisms of biochar action in mitigating enteric methane

In the rumen condition, a new microbial habitat created inside. It allows methanogenic- methanotrophic interaction, which could increase anaerobic methane oxidation (Leng et al., 2012a) and improve overall microbial-growth efficiency (Leng et al., 2012a; Leng, Preston, & Inthapanya, 2012b; Liu et al., 2012). Methanotrophic proteobacteria and methanogenic archaea are the key bacteria responsible for enteric methane production. Feng, Xu, Yu, Xie, and Lin (2012) found that biochar amendment reduced methane emissions as well as potentially stimulating methanogenic archaea. This mean that methane production outpaced methane utilization by methanotrophs. It has been shown that adding biochar to soil improves aeration, thereby making the soil conditions more favorable for methanotrophs and increasing methane oxidation (Van Zwieten et al., 2009). Similar conditions are present in the rumen (Leng et al., 2012a, 2012b), biochar addition provides habitat and stimulates growth for methanotrophs. As a result, the oxidation of methane by methanotrophs is greatly enhanced inside the digestive system of ruminants. The mechanism by which biochar lowers methane production relates to its insoluble components (Leng et al., 2012). The major reason biochar reduces methane is its ability to absorb and adsorb gasses (Danielsson et al., 2017). Therefore, the daily inclusion of biochar in animal feed could be a promising method for mitigating methane production (Leng, 2018). The mechanism behind this mitigating process may be stimulation of the growth of microbes, and then the substrate the microbes use would serve as hydrogen sink. Alternatively, biochar may stimulate an increase in microbial groups that oxidize methane. Therefore, inclusion of biochar will reduce methane production (Elghandour et al., 2018). There have been many investigations related to the use of biochar as a supplementary feed for ruminants for this purpose.

When biochar was incubated with rumen fluid, the release of methane was reduced by 15% (Leng et al., 2012a). An *in vitro* experiment conducted by Hansen, Storm, and Sell (2012) also showed that methane was reduced by between 11% and 17% when 9% w/w of biochar was added to feed in a sealed filter bag. Phanthavong, Viengsakoun, Sangkhom, and Preston (2015) showed in an *in vitro* rumen incubation experiment that biochar could reduce methane production by between 0.5% and 1.7% when compared to a control without biochar after 24 h incubation. Biochar can improve *in vitro* ruminal fermentation, nutrient disappearance and microbial protein synthesis, and reduce enteric methane production (Saleem et al., 2018).

In vivo studies found that the emission of methane decreased by 11% to 13% when 1% w/w biochar was added into cattle diets (Leng et al., 2012). Biochar added to the daily diets of cattle also decreased their methane emissions and increased the efficiency of live weight gain (Leng et al., 2012). Leng et al. (2012a) showed that a combination of biochar and nitrate reduced methane by 41% and biochar in digestate fermenting diets reduced production of methane by 22%. Biochar was found to reduce methane emissions when it was added to cattle and goat diets (Leng et al., 2012a; Silivong & Preston, 2015). Khoa et al. (2018) found that cattle fed with biochar (0.5% and 1% w/w) generally exhibited reduced methane emissions, and the cattle fed with 1% w/w bio-char had the lowest methane emissions (reduced by 6.96%, 12.6 L methane/animal/day). In addition, 3.8% w/w biochar added to a cattle diet reduced methane by 9.9% to 18.4% (Winders et al., 2018).

In conclusion, 0.5% to 9% biochar can effectively reduce enteric methane production from rumens by 0.5% to 18.4% in *in vitro* or *in vivo* conditions.

4.2. Removal of pollutants and toxins in animals

It is commonly known that biochar can adsorb and remove environmental pollutants and toxins such as heavy metals, organic and inorganic pollutants from water and soil (Tan et al., 2016). Pollutants and toxins in animals mainly come from their daily feed, which is subject to contamination from diverse sources such as environmental pollution, insects and the activities of microbes. Teleb, Hegazy, and Hussein (2004) found that supplementing broiler diets with 0.5% biochar reduced the detrimental effects of aflatoxins, lowering mortality and improving growth performance. Prasai et al. (2016) and Prasai, Walsh, Midmore, and Bhattarai (2018) revealed that biochar reduced the pathogenic bacterium *Campylobacter jejuni* in pullets' gut microbiota. In *in vitro* uremic toxin (urea and creatinine) adsorption model experiments, Jandosov et al. (2017) found that rice husk-derived carbon enterosorbents (biochar) modified by oxidation by ozone followed by ammonia treatment of the carbon surface were able to reduce clinically significant levels of uremic toxins, comparable to commercial enterosorbents.

The sorption capacity of biochar for organic contaminants is related to its surface area, carbon content and the hydrophobicity of the pollutants by adsorption isotherms (Oh & Seo, 2016). Biochar has been shown to have sorption affinity for pollutants at low pH (pH <7) (Oh & Seo, 2016; Shan et al., 2016; Tong, Li, Yuan, & Xu, 2011). Li et al. (2018) revealed that biochar pyrolyzed at high temperature ($\geq 500\ ^{\circ}C$) exhibited higher sorption capacity (41.2–42.4 mg g^{-1}) for the toxin microcystin-LR. This is greater than, or at least comparable to, the results from commercially available adsorbents such as carbon nanotubes (5.9 mg g^{-1}), mesoporous silica (5.99 mg g^{-1}) and activated charcoal (16.1–83.3 mg g^{-1}). These results indicate that biochar is able to remove pollutants and toxic substances in animals. There are knowledge gaps and research needs relating to how biochar can be applied in healthcare products, especially for human beings.

Activated charcoal has been used as a biomaterial promoting human embryonic stem cell differentiation and implemented in transplantation devices or scaffolds for therapeutic purposes (Chen et al., 2012). This indicates the efficacy of activated charcoal in biomedical applications (Ok, Chang, Gao, & Chung, 2015). The long-term use of activated charcoal for curing acute poisoning and digestive disorders in humans also indicates the potential for using biochar in health supplements (Cooney, 2016; Juurlink, 2016). It is important to explore the use of biochar as a medicine or health supplement for humans in the near future.

5. Conclusion

The application of biochar as feed supplements for animal farming is built on the use of activated charcoal in treating digestive disorders in humans and animals. Biochar can be produced from a wide range of biomass and organic materials, such as wheat straw, crop residues, corn cobs, stover and wood waste. After pyrolysis, chemical or physical activation, biochar can be applied as a feed supplement. The physiochemical properties of biochar are closely connected with their sources of feedstocks and pyrolysis temperature. Feedstock with high lignin content would usually produce higher biochar yield due to the formation of char. Some feedstocks, contain specific components (e.g. Jarrah wood contains organic molecules similar to those found in wood vinegar) and thus enhance the growth and taste of livestock. If the ash content of the non-wood feedstock (e.g. biochar derived from rice plant) is high, the surface area of the biochar could be low as a result of blockage of micropores. In general, the use of biochar as a feed supplement could provide benefits to the animal husbandry industry, agriculture, and the global environment. Biochar is a promising dietary supplement for livestock, with positive effects on animal growth (weight gain, feed conversion ratio, and nutrient intake) of cattle, goats, pigs, poultry and fish. Adding biochar derived from rice husk in animal feeds could increase the weight gain of cattle, pigs, chicken. Biochar can also reduce enteric methane emissions from ruminants by providing favorable habitats for methanogenic–methanotrophic microbial interactions in the gut, enhancing anaerobic methane oxidation. With similar properties to activated charcoal, with a porous structure and extensive surface area, biochar possess a high sorption ability to remove toxic substances from animal bodies, as well as from the farming environment. The sorption capability of toxicants depends on the preparation treatment of biochar and its physiochemical properties. Biochar produced from higher temperature usually illustrated higher sorption capability. The increased pyrolysis temperature also resulted in smaller biochar particles, which promoted forage digestibility and rumen fermentation kinetics. Biochar incorporated into feeds can improve poultry blood profiles and reduce pathogens through adsorption, which is a possible strategy for reducing usage of antibiotics. Undoubtedly, including biochar in animal diets appears to be an excellent strategy for animal husbandry. There are increasing biochar applications, and guideline criteria have been provided by FAO, WHO, IBI and EBF for classifying and certifying standard biochar as a feed supplement, as well as a soil amendment. This can help in regulating future utilization of biochar in animal feeds and further development of biochar for human usage.

Acknowledgements

The authors would like to thank Ms. Ursula Absalom, MA, for improving the manuscript.

Funding

Financial support from the Innovative Technology Fund (Innovative Technology Commission, Hong Kong SAR): ITS/174/14FX, Green Valley Landfill Limited: EP/SP/10/91, the Dean's Research Fund: FLASS/DRF/IRS-1 from The Education University of Hong Kong and The Early Career Scheme, Research Grants Council of the Hong Kong SAR, China (Project no. 28300619) is gratefully acknowledged.

ORCID

Ming Hung Wong http://orcid.org/0000-0001-5615-471X

References

Abdel-Tawwab, M., Abdel-Rahman, A., & Ismael, N. (2008). Evaluation of commercial live baker's yeast, Saccharomyces cerevisiae as a growth and immunity promoter for Fry Nile tilapia Oreochromis niloticus challenge in situ with Aeromonas hydrophila. *Aquaculture*, *280*(1-4), 185–189. doi:10.1016/j.aquaculture.2008.03.055

Abechi, S. E., Gimba, C. E., Uzairu, A., & Dallatu, Y. A. (2013). Preparation and characterization of activated carbon from palm kernel shell by chemical activation. *Research Journal of Chemical Sciences*, *3*, 54–61.

Adrados, A., Lopez-Urionabarrenechea, A., Acha, E., Solar, J., Caballero, B. M., & de Marco, I. (2017). Hydrogen rich reducing gases generation in the production of charcoal from woody biomass carbonization. *Energy Conversion and Management*, *148*, 352–359. doi:10.1016/j.enconman.2017.06.010

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., … Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere*, *99*, 19–33. doi:10.1016/j.chemosphere.2013.10.071

Amin, F. R., Khalid, H., Zhang, H., Rahman, S. U., Zhang, R., Liu, G., & Chen, C. (2017). Pretreatment methods of lignocellulosic biomass for anaerobic digestion. *AMB Express*, *7*(1), 72. doi:10.1186/s13568-017-0375-4

Aworn, A., Thiravetyan, P., & Nakbanpote, W. (2008). Preparation and characteristics of agricultural waste activated carbon by physical activation having micro-and mesopores. *Journal of Analytical and Applied Pyrolysis*, *82*(2), 279–285. doi:10.1016/j.jaap.2008.04.007

Azargohar, R., Dalai, A. K. (2006). Biochar as a precursor of activated carbon. *Applied Biochemistry and Biotechnology*, *131* (1–3), 762–773.

Bartocci, P., Zampilli, M., Bidini, G., & Fantozzi, F. (2018). Hydrogen-rich gas production through steam gasification of charcoal pellet. *Applied Thermal Engineering*, *132*, 817–823. doi:10.1016/j.applthermaleng.2018.01.016

Bath, D. L. (2018). Feed by-products and their utilization by ruminants. In J. Tal Huber (Ed.), *Upgrading residues and by-products for animals* (pp. 1–16). Boca Raton, FL: CRC Press.

Beck, D. A., Johnson, G. R., & Spolek, G. A. (2011). Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution*, *159*(8-9), 2111–2118. doi:10.1016/j.envpol.2011.01.022

Břendová, K., Tlustoš, P., Száková, J., & Habart, J. (2012). Biochar properties from different materials of plant origin. *European Chemical Bulletin*, *1*, 535–539.

Bruun, E. W., Ambus, P., Egsgaard, H., & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry*, *46*, 73–79. doi:10.1016/j.soilbio.2011.11.019

Cao, X., Ma, L., Gao, B., & Harris, W. (2009). Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environmental Science & Technology*, *43*, 3285–3291. doi:10.1021/es803092k

Castillo-González, A. R., Burrola-Barraza, M. E., Domínguez-Viveros, J., & Chávez-Martínez, A. (2014). Rumen microorganisms and fermentation. *Archivos de Medicina Veterinaria*, *46*(3), 349–361. doi:10.4067/S0301-732X2014000300003

Cha, J. S., Park, S. H., Jung, S. C., Ryu, C., Jeon, J. K., Shin, M. C., & Park, Y. K. (2016). Production and utilization of biochar: A review. *Journal of Industrial and Engineering Chemistry*, *40*, 1–5. doi:10.1016/j.jiec.2016.06.002

Chen, B., & Chen, Z. (2009). Sorption of naphthalene and 1-naphthol by biochars of orange peels with different pyrolytic temperatures. *Chemosphere*, *76*(1), 127–133. doi:10.1016/j.chemosphere.2009.02.004

Chen, E. Y., Wang, Y. C., Mintz, A., Richards, A., Chen, C. S., Lu, D., … Chin, W. C. (2012). Activated charcoal composite biomaterial promotes human embryonic stem cell differentiation toward neuronal lineage. *Journal of Biomedical Materials Research Part A*, *100*, 2006–2017. doi:10.1002/jbm.a.34201

Chu, G. M., Jung, C. K., Kim, H. Y., Ha, J. H., Kim, J. H., Jung, M. S., … Cho, J. H. (2013). Effects of bamboo charcoal and bamboo vinegar as antibiotic alternatives on growth performance, immune responses and fecal microflora population in fattening pigs. *Animal Science Journal*, *84*(2), 113–120. doi:10.1111/j.1740-0929.2012.01045.x

Chu, G. M., Kim, J. H., Kang, S. N., & Song, Y. M. (2013). Effects of dietary bamboo charcoal on the carcass characteristics and meat quality of fattening pigs. *Korean Journal for Food Science of Animal Resources*, *33*(3), 348–355. doi:10.5851/kosfa.2013.33.3.348

Chu, G. M., Kim, J. H., Kim, H. Y., Ha, J. H., Jung, M. S., Song, Y., … Song, Y. M. (2013). Effects of bamboo charcoal on the growth performance, blood characteristics and noxious gas emission in fattening pigs. *Journal of Applied Animal Research*, *41*(1), 48–55. doi:10.1080/09712119.2012.738219

Cooney, D. O. (2016). *Activated charcoal: Antidote, remedy and health aid*. Brushton, NY: TEACH Services, Inc.

Danielsson, R., Dicksved, J., Sun, L., Gonda, H., Müller, B., Schnürer, A., & Bertilsson, J. (2017). Methane production in dairy cows correlates with rumen methanogenic and bacterial community structure. *Frontiers in Microbiology*, *8*, 226. doi:10.3389/fmicb.2017.00226

Danish, M., & Ahmad, T. (2018). A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application. *Renewable and Sustainable Energy Reviews*, *87*, 1–21. doi:10.1016/j.rser.2018.02.003

Deusch, S., Camarinha-Silva, A., Conrad, J., Beifuss, U., Rodehutscord, M., & Seifert, J. (2017). A structural and functional elucidation of the rumen microbiome influenced by various diets and microenvironments. *Frontiers in Microbiology*, *8*, 1605. doi:10.3389/fmicb.2017.01605

Dim, C. E., Akuru, E. A., Egom, M. A., Nnajiofor, N. W., Ossai, O. K., Ukaigwe, C. G., & Onyimonyi, A. E. (2018). Effect of dietary inclusion of biochar on growth performance, haematology and serum lipid profile of broiler birds. *Agro-Science*, *17*(2), 9–17. doi:10.4314/as.v17i2.2

Edmunds, J. L., Worgan, H. J., Dougal, K., Girdwood, S. E., Douglas, J. L., & McEwan, N. R. (2016). In vitro analysis of the effect of supplementation with activated charcoal on the equine hindgut. *Journal of Equine Science*, *27*(2), 49–55. doi:10.1294/jes.27.49

Eger, M., Graz, M., Riede, S., & Breves, G. (2018). Application of MootralTM reduces methane production by altering the archaea community in the rumen simulation technique. *Frontiers in Microbiology*, *9,* 2094. doi:10.3389/fmicb.2018.02094

Elghandour, M. M., Adegbeye, M. J., Barbabosa-Pilego, A., Perez, N. R., Hernández, S. R., Zaragoza-Bastida, A., & Salem, A. Z. (2018). Equine contribution in methane emission and its mitigation strategies. *Journal of Equine Veterinary Science*, *72*, 56–63. doi:10.1016/j.jevs.2018.10.020

European Biochar Foundation (EBF). (2012). European Biochar Certificate—Guidelines for a sustainable production of biochar. European Biochar Foundation (EBF), Arbaz, Switzerland. Retrieved from http://www.europeanbiochar.org/en/download

European Commission (EC). (2019). Animal feed. Retrieved from https://ec.europa.eu/food/safety/animal-feed_en

Evans, A. M., Boney, J. W., & Moritz, J. S. (2017). The effect of poultry litter biochar on pellet quality, one to 21 d broiler performance, digesta viscosity, bone mineralization, and apparent ileal amino acid digestibility. *Journal of Applied Poultry Research*, *26*(1), 89–98. doi:10.3382/japr/pfw049

FAO/WHO. (2010). *Joint FAO/WHO Expert Committee on Food Additives (JECFA) Compendium of food additive specifications*. 73rd Meeting 2010, Rome.

Fellet, G., Marchiol, L., Delle Vedove, G., & Peressotti, A. (2011). Application of biochar on mine tailings: Effects and perspectives for land reclamation. *Chemosphere*, *83*(9), 1262–1267. doi:10.1016/j.chemosphere.2011.03.053

Feng, Y., Xu, Y., Yu, Y., Xie, Z., & Lin, X. (2012). Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biology and Biochemistry* , *46*, 80–88. doi:10.1016/j.soilbio.2011.11.016

Gerlach, A., & Schmidt, H. P. (2012a). The use of biochar in cattle farming. *Ithaka Journal*, *2012*, 281–285.

Gerlach, H., & Schmidt, H. P. (2012b). Biochar in poultry farming. *Ithaka Journal*, *2012*, 262–264.

Giffard, C. J., Collins, S. B., Stoodley, N. C., Butterwick, R. F., & Batt, R. M. (2001). Administration of charcoal, Yucca schidigera, and zinc acetate to reduce malodorous flatulence in dogs. *Journal of the American Veterinary Medical Association*, *218*(6), 892–896. doi:10.2460/javma.2001.218.892

Hagemann, N., Spokas, K., Schmidt, H. P., Kägi, R., Böhler, M., & Bucheli, T. (2019). Activated carbon, biochar and charcoal: Linkages and synergies across pyrogenic carbon's ABCs. *Water*, *10*(2), 182. doi:10.3390/w10020182

Hansen, H. H., Storm, I. D., & Sell, A. M. (2012). Effect of biochar on in vitro rumen methane production. *Acta Agriculturae Scandinavica, Section A - Animal Science*, *62*(4), 305–309. doi:10.1080/09064702.2013.789548

Hien, N. N., Dung, N. N. X., Manh, L. H., & Le Minh, B. T. (2018). Effects of biochar inclusion in feed and chicken litter on growth performance, plasma lipids and fecal bacteria count of Noi lai chicken. *Livestock Research for Rural Development*, *30*, 131. http://www.lrrd.org/lrrd30/7/nnxdu30131.html

Hook, S. E., Wright, A. D. G., & McBride, B. W. (2010). Methanogens: Methane producers of the rumen and mitigation strategies. *Archaea*, *2010*, 1–11. doi:10.1155/2010/945785

International Biochar Initiative (IBI). (2015). Biochar Certification Program manual-requirements and procedures for IBI Biochar Certification. Retrieve from https://www.

biochar-international.org/wp-content/uploads/2018/05/IBI_Biochar_Certification_Program_Manual_V2.1_Final.pdf

Islam, M. M., Ahmed, S. T., Kim, Y. J., Mun, H. S., Kim, Y. J., & Yang, C. J. (2014). Effect of sea tangle (*Laminaria japonica*) and charcoal supplementation as alternatives to antibiotics on growth performance and meat quality of ducks. *Asian-Australasian Journal of Animal Sciences*, *27*(2), 217–224. doi:10.5713/ajas.2013.13314

Jandosov, J., Mikhalovska, L., Howell, C., Chenchik, D., Kosher, B., Lyubchik, S., … Mikhalovsky, S. (2017). Synthesis, morphostructure, surface chemistry and preclinical studies of nanoporous rice husk-derived biochars for gastrointestinal detoxification. *Eurasian Chemico-Technological Journal*, *19*(4), 303–313. doi:10.18321/ectj678

Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M. A., & Sonoki, T. (2014). Physical and chemical characterizations of biochars derived from different agricultural residues. *Biogeosciences*, *11*(23), 6613–6621. doi:10.5194/bg-11-6613-2014

Joseph, S., Pow, D., Dawson, K., Mitchell, D. R. G., Rawal, A., Hook, J., … Solaiman, Z. M. (2015). Feeding biochar to cows: An innovative solution for improving soil fertility and farm productivity. *Pedosphere*, *25*(5), 666–679. doi:10.1016/S1002-0160(15)30047-3

Juurlink, D. N. (2016). Activated charcoal for acute overdose: A reappraisal. *British Journal of Clinical Pharmacology*, *81*(3), 482–487. doi:10.1111/bcp.12793

Kammann, C., Ippolito, J., Hagemann, N., Borchard, N., Cayuela, M. L., Estavillo, J. M., … Wrage-Mönnig, N. (2017). Biochar as a tool to reduce the agricultural greenhouse-gas burden–knowns, unknowns and future research needs. *Journal of Environmental Engineering and Landscape Management*, *25*(2), 114–139. doi:10.3846/16486897.2017.1319375

Kaye, B. M., Elliott, C. R. B., & Jalim, S. L. (2012). Methiocarb poisoning of a horse in Australia. *Australian Veterinary Journal*, *90*(6), 221–224. doi:10.1111/j.1751-0813.2012.00910.x

Khaki, N. D., Malcevschi, A., Voccia, A., & Marzano, F. (2017). *Interaction of Dietary biochar (black carbon) on the growth performance and survival rate of early stage larvae of brown trout (Salmo trutta)*. Aquaculture Europe 2017 Dubrovnik, Croatia.

Khoa, M. A., Quang, N. H., Thang, T. V., Phung, T. V., & Kien, T. T. (2018). Effect of tannin in green tea by-product in combination with bio-char supplemented into basal beef cattle diet on nutrient digestibility, methane production and animal performance. *Open Journal of Animal Sciences*, *08*(03), 206–214. doi:10.4236/ojas.2018.83015

Kim, K. H., Kim, J. Y., Cho, T. S., & Choi, J. W. (2012). Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). *Bioresource Technology*, *118*, 158–162. doi:10.1016/j.biortech.2012.04.094

Koltowski, M., Charmas, B., Skubiszewska-Zięba, J., & Oleszczuk, P. (2017). Effect of biochar activation by different methods on toxicity of soil contaminated by industrial activity. *Ecotoxicology and Environmental Safety*, *136*, 119–125. doi:10.1016/j.ecoenv.2016.10.033

Kook, K., & Kim, K. H. (2003). The effects of supplemental levels of bamboo vinegar on growth performance, serum profile and meat quality in fattening Hanwoo cow. *Journal of Animal Science and Technology*, *45*, 57–68.

Kupper, T., Fischlin Häni, C., & Spring, P. (2015). TC-P_09 Use of a feed additive based on biochar for mitigation of ammonia emissions from weaned piglets and broilers. In: RAMIRAN, 2015–16th International Conference Rural-Urban Symbiosis. Hamburg: Advances in Emission Prevention. 424–427.

Kutlu, H. R., Ünsal, I., & Görgülü, M. (2001). Effects of providing dietary wood (oak) charcoal to broiler chicks and laying hens. *Animal Feed Science and Technology*, *90*(3-4), 213–226. doi:10.1016/S0377-8401(01)00205-X

Kwapinski, W., Byrne, C. M. P., Kryachko, E., Wolfram, P., Adley, C., Leahy, J. J., … Hayes, M. H. B. (2010). Biochar from biomass and waste. *Waste and Biomass Valorization*, *1*(2), 177–189. doi:10.1007/s12649-010-9024-8

Lan, T. T., Preston, T. R., & Leng, R. A. (2016). Feeding biochar or charcoal increased the growth rate of striped catfish (Pangasius hypophthalmus) and improved water quality. *Livestock Research for Rural Development*, *28*, 84.

Lehmann, J., & Joseph, S. (Eds.) (2015). *Biochar for environmental management: Science, technology and implementation*. London: Routledge.

Leng, R. A. (2018). Unravelling methanogenesis in ruminants, horses and kangaroos: The links between gut anatomy, microbial biofilms and host immunity. *Animal Production Science*, *58*(7), 1175–1191. doi:10.1071/AN15710

Leng, R. A., Inthapanya, S., & Preston, T. R. (2012a). Biochar lowers net methane production from rumen fluid in vitro. *Livestock Research for Rural Development*, *24*(6), 103.

Leng, R. A., Inthapanya, S., & Preston, T. R. (2012b). Methane production is reduced in an in vitro incubation when the rumen fluid is taken from cattle that previously received biochar in their diet. *Gas*, *1050*(1488), 1367.

Leng, R. A., Inthapanya, S., & Preston, T. R. (2013). All biochars are not equal in lowering methane production in in vitro rumen incubations. *Livestock Research for Rural Development*, *25,* 106. Retrieved from http://www.lrrd.org/lrrd25/6/leng25106.htm

Leng, R. A., Preston, T. R., & Inthapanya, S. (2012). Biochar reduces enteric methane and improves growth and feed conversion in local "Yellow" cattle fed cassava root chips and fresh cassava foliage. *Livestock Research for Rural Development*, *24*: Article#199.

Li, J., Cao, L., Yuan, Y., Wang, R., Wen, Y., & Man, J. (2018). Comparative study for microcystin-LR sorption onto biochars produced from various plant-and animal-wastes at different pyrolysis temperatures: Influencing mechanisms of biochar properties. *Bioresource Technology*, *247*, 794–803. doi:10.1016/j.biortech.2017.09.120

Liu, P., Liu, W. J., Jiang, H., Chen, J. J., Li, W. W., & Yu, H. Q. (2012). Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresource Technology*, *121*, 235–240. doi:10.1016/j.biortech.2012.06.085

Mabe, L. T., Su, S., Tang, D., Zhu, W., Wang, S., & Dong, Z. (2018). The effect of dietary bamboo charcoal supplementation on growth and serum biochemical parameters of juvenile common carp (*Cyprinus carpio L.*). *Aquaculture Research*, *49*(3), 1142–1152. doi:10.1111/are.13564

Martin, C., Morgavi, D. P., & Doreau, M. (2010). Methane mitigation in ruminants: From microbe to the farm scale. *Animal*, *4*(03), 351–365. doi:10.1017/S1751731109990620

Maurer, D., Koziel, J., Kalus, K., Andersen, D., & Opalinski, S. (2017). 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. *Sustainability*, *9*(6), 929–946. doi:10.3390/su9060929

McFarlane, Z., Myer, P., Cope, E., Evans, N., Carson Bone, T., Biss, B., & Mulliniks, J. (2017). Effect of biochar type and size on in vitro rumen fermentation of Orchard Grass Hay. *Agricultural Sciences*, *08*(04), 316–325. doi:10.4236/as.2017.84023

Mo, W. Y., Man, Y. B., & Wong, M. H. (2018). Use of food waste, fish waste and food processing waste for China's aquaculture industry: Needs and challenge. *Science of the Total Environment*, *613*, 635–643.

Moe, T., Ishikawa, M., Koshio, S., & Yokoyama, S. (2009). Effects of dietary bamboo charcoal on growth parameters and nutrient utilization of tiger puffer fish, *Takifugu rubripes*. *Aquaculture Science*, *57*, 53–60.

Mohan, D., Pittman, C. U., Jr., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels*, *20*, 848–889. doi:10.1021/ef0502397

Mohan, D., Rajput, S., Singh, V. K., Steele, P. H., & Pittman, C. U. (2011). Modeling and evaluation of chromium remediation from water using low cost bio-char, a green adsorbent. *Journal of Hazardous Materials*, *188*(1-3), 319–333. doi:10.1016/j.jhazmat.2011.01.127

Moss, A. R., Jouany, J. P., & Newbold, J. (2000). Methane production by ruminants: Its contribution to global warming. *Annales de Zootechnie*, *49*(3), 231–253. doi:10.1051/animres:2000119

Mukherjee, A., & Zimmerman, A. R. (2013). Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma*, *193*, 122–130. doi:10.1016/j.geoderma.2012.10.002

Mullen, C. A., Boateng, A. A., Goldberg, N. M., Lima, I. M., Laird, D. A., & Hicks, K. B. (2010). Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. *Biomass and Bioenergy*, *34*(1), 67–74. doi:10.1016/j.biombioe.2009.09.012

Naeem, M. A., Khalid, M., Arshad, M., & Ahmad, R. (2014). Yield and nutrient composition of biochar produced from different feedstocks at varying pyrolytic temperatures. *Pakistan Journal of Agricultural Sciences*, *51*, 1.

Naka, K., Watarai, S., Inoue, K., Kodama, Y., Oguma, K., Yasuda, T., & Kidama, H. (2001). Adsorption effect of activated charcoal on enterohemorrhagic *Escherichia coli*. *Journal of Veterinary Medical Science*, *63*, 281–285. doi:10.1292/jvms.63.281

Oh, S. Y., & Seo, Y. D. (2016). Sorption of halogenated phenols and pharmaceuticals to biochar: Affecting factors and mechanisms. *Environmental Science and Pollution Research*, *23*(2), 951–961. doi:10.1007/s11356-015-4201-8

Ok, Y. S., Chang, S. X., Gao, B., & Chung, H. J. (2015). SMART biochar technology—A shifting paradigm towards advanced materials and healthcare research. *Environmental Technology & Innovation*, *4*, 206–209. doi:10.1016/j.eti.2015.08.003

Oliveira, F. R., Patel, A. K., Jaisi, D. P., Adhikari, S., Lu, H., & Khanal, S. K. (2017). Environmental application of biochar: Current status and perspectives. *Bioresource Technology*, *246*, 110–122. doi:10.1016/j.biortech.2017.08.122

O'Toole, A., Andersson, D., Gerlach, A., Glaser, B., Kammann, C., Kern, J., … Srocke, F. (2016). Current and future applications for biochar. In: S. Shackley, G. Ruysschaert, K. Zwart, B. Glaser (Eds.), *Biochar in European soils and agriculture. Science and practice* (pp. 253–280). Abington: Taylor & Francis Group.

Pereira, R. C., Muetzel, S., Arbestain, M. C., Bishop, P., Hina, K., & Hedley, M. (2014). Assessment of the influence of biochar on rumen and silage fermentation: A laboratory-scale experiment. *Animal Feed Science and Technology*, *196*, 22–31. doi:10.1016/j.anifeedsci.2014.06.019

Phanthavong, V., Viengsakoun, N., Sangkhom, I., & Preston, T. R. (2015). Effect of biochar and leaves from sweet or bitter cassava on gas and methane production in an in vitro rumen incubation using cassava root pulp as source of energy. *Livestock Research for Rural Development*, *27*, 72. Retrieved from http://www.lrrd.org/lrrd27/4/phan27072.html

Phongpanith, S., Inthapanya, S., & Preston, T. R. (2013). Effect on feed intake, digestibility and N balance in goats of supplementing a basal diet of Muntingia foliage with biochar and water spinach (Ipomoea aquatica). *Livestock Research for Rural Development*, *25*, 35.

Phongphanith, S., & Preston, T. R. (2016). Effect of rice-wine distillers' byproduct and biochar on growth performance and methane emissions in local "Yellow" cattle fed ensiled cassava root, urea, cassava foliage and rice straw. *Livestock Research for Rural Development*, *28*, 178. Retrieved from http://www.lrrd.org/lrrd28/10/seng28178.html

Prasai, T. P., Walsh, K. B., Bhattarai, S. P., Midmore, D. J., Van, T. T., Moore, R. J., & Stanley, D. (2016). Biochar, bentonite and zeolite supplemented feeding of layer chickens alters intestinal microbiota and reduces Campylobacter load. *PLoS One*, *11*(4), e0154061. doi:10.1371/journal.pone.0154061

Prasai, T. P., Walsh, K. B., Midmore, D. J., & Bhattarai, S. P. (2018). Effect of biochar, zeolite and bentonite feed supplements on egg yield and excreta attributes. *Animal Production Science*, *58*(9), 1632–1641. doi:10.1071/AN16290

Prasai, T. P., Walsh, K. B., Midmore, D. J., Jones, B. E., & Bhattarai, S. P. (2018). Manure from biochar, bentonite and zeolite feed supplemented poultry: Moisture retention and granulation properties. *Journal of Environmental Management*, *216*, 82–88. doi:10.1016/j.jenvman.2017.08.040

Preston, T. R. (2014). Role of biochar in farming systems producing food and energy from biomass. In: T. J. Goreau, R. W. Larson, J. Campe (Eds.), *Geotherapy: Innovative methods of soil fertility restoration, carbon sequestration, and reversing CO2 increase* (Vol. 283), (pp. 284–298), Boca Roton: CRC Press, Taylor & Francis Group.

Quaiyum, M. A., Jahan, R., Jahan, N., Akhter, T., & Sadiqul, I. M. (2014). Effects of bamboo charcoal added feed on reduction of ammonia and growth of Pangasius hypophthalmus. *Journal of Aquaculture Research & Development*, *5*, 269–273. doi:10.4172/2155-9546.1000269

Saleem, A. M., Ribeiro, G. O., Jr., Yang, W. Z., Ran, T., Beauchemin, K. A., McGeough, E. J., … McAllister, T. A. (2018). Effect of engineered biocarbon on rumen fermentation, microbial protein synthesis, and methane production in an artificial rumen (RUSITEC) fed a high forage diet. *Journal of Animal Science*, *96*, 3121–3130. doi:10.1093/jas/sky204

Sanchez-Monedero, M. A., Cayuela, M. L., Roig, A., Jindo, K., Mondini, C., & Bolan, N. (2018). Role of biochar as an additive in organic waste composting. *Bioresource Technology*, *247*, 1155–1164. doi:10.1016/j.biortech.2017.09.193

Saroeun, K., Preston, T. R., & Leng, R. A. (2018). Rice distillers' byproduct and molasses-urea blocks containing biochar improved the growth performance of local Yellow cattle fed ensiled cassava roots, cassava foliage and rice straw. *Livestock Research for Rural Development*, *30*, 162. Retrieved from http://www.lrrd.org/lrrd30/9/saroe30162.html

Schmidt, H. P., Wilson, K., & Kammann, C. (2017). *Using biochar in animal farming to recycle nutrients and reduce greenhouse gas emissions.* EGU General Assembly Conference Abstracts, Vienna, Austria (Vol. 19, p. 5719).

Shan, D., Deng, S., Zhao, T., Wang, B., Wang, Y., Huang, J., … Wiesner, M. R. (2016). Preparation of ultrafine magnetic biochar and activated carbon for pharmaceutical adsorption and subsequent degradation by ball milling. *Journal of Hazardous Materials*, *305*, 156–163. doi:10.1016/j.jhazmat.2015.11.047

Silivong, P., & Preston, T. R. (2015). Growth performance of goats was improved when a basal diet of foliage of Bauhinia acuminata was supplemented with water spinach and biochar. *Livestock Research for Rural Development*, *27*, 58. Retrieved from http://www.lrrd.org/lrrd27/3/sili27058.html

Sivilai, B., Preston, T. R., Leng, R. A., Hang, D. T., & Linh, N. Q. (2018). Rice distillers' byproduct and biochar as additives to a forage-based diet for growing Moo Lath pigs; effects on growth and feed conversion. *Livestock Research for Rural Development*, *30*, 111.

Suliman, W., Harsh, J. B., Abu-Lail, N. I., Fortuna, A. M., Dallmeyer, I., & Garcia-Perez, M. (2016). Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass and Bioenergy*, *84*, 37–48. doi:10.1016/j.biombioe.2015.11.010

Tan, X. F., Liu, Y. G., Gu, Y. L., Xu, Y., Zeng, G. M., Hu, X. J., … Li, J. (2016). Biochar-based nano-composites for the decontamination of wastewater: A review. *Bioresource Technology*, *212*, 318–333. doi:10.1016/j.biortech.2016.04.093

Teleb, H. M., Hegazy, A. A., & Hussein, Y. A. (2004). Efficiency of kaolin and activated charcoal to reduce the toxicity of low level of aflatoxin in broilers. *Scientific Journal of King Faisal University*, *5*, 1425.

Thu, M., Koshio, S., Ishikawa, M., & Yokoyama, S. (2009). Effects of dietary bamboo charcoal on growth parameters, apparent digestibility and ammonia nitrogen excretion of tiger puffer fish, Takifugu rubripes. *Aquaculture Science*, *57*(1), 53–60.

Thu, M., Koshio, S., Ishikawa, M., & Yokoyama, S. (2010). Effects of supplementation of dietary bamboo charcoal on growth performance and body composition of juvenile Japanese flounder, Paralichthys olivaceus. *Journal of the World Aquaculture Society*, *41*, 255–262. doi:10.1111/j.1749-7345.2010.00365.x

Tong, X. J., Li, J. Y., Yuan, J. H., & Xu, R. K. (2011). Adsorption of Cu (II) by biochars generated from three crop straws. *Chemical Engineering Journal*, *172*(2-3), 828–834. doi:10.1016/j.cej.2011.06.069

Toth, J. D., & Dou, Z. (2016). Use and impact of biochar and charcoal in animal production systems. In M. Guo, Z. He, & M. Uchimiya (Eds.), *Agricultural and environmental applications of biochar: Advances and barriers* (pp. 199–224). Madison, WI: Soil Science Society of America, Inc.

Uchimiya, M., Lima, I. M., Klasson, K. T., & Wartelle, L. H. (2010). Contaminant immobilization and nutrient release by biochar soil amendment: Roles of natural organic matter. *Chemosphere*, *80*(8), 935–940. doi:10.1016/j.chemosphere.2010.05.020

Uchimiya, M., Wartelle, L. H., Klasson, K. T., Fortier, C. A., & Lima, I. M. (2011). Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. *Journal of Agricultural and Food Chemistry*, *59*(6), 2501–2510. doi:10.1021/jf104206c

United States Department of Agriculture (USDA). (2018). Meat – Production and value 2017 summary, National Agricultural Statistics Service, April 2018.

US Environmental Protection Agency (USEPA). (2016). Global greenhouse gas emissions data. Retrieved from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

Van Zwieten, L., Singh, B., Joseph, S., Kimber, S., Cowie, A., & Chan, K. Y. (2009). Biochar and emissions of non-CO_2 greenhouse gases from soil. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 227–250). London: Routledge.

Waheed, Q., Nahil, M., & Williams, P. (2013). Pyrolysis of waste biomass: Investigation of fast pyrolysis and slow pyrolysis process conditions on product yield and gas composition. *Journal of the Energy Institute*, *86*(4), 233–241. doi:10.1179/1743967113Z.00000000067

Wang, L., Skreiberg, Ø., Van Wesenbeeck, S., Grønli, M., & Antal, M. J. Jr. (2016). Experimental study on charcoal production from woody biomass. *Energy & Fuels*, *30*, 7994–8008. doi:10.1021/acs.energyfuels.6b01039

Watarai, S. & Tana . (2005). Eliminating the carriage of Salmonella enterica serovar enteritidis in domestic fowls by feeding activated charcoal from bark containing wood vinegar liquid (Nekka-Rich). *Poultry Science*, *84*, 515–521. doi:10.1093/ps/84.4.515

Willson, N. L., Van, T. T., Bhattarai, S. P., Courtice, J. M., McIntyre, J. R., Prasai, T. P., … Stanley, D. (2019). Feed supplementation with biochar may reduce poultry pathogens, including Campylobacter hepaticus, the causative agent of spotty liver disease. *PLoS One*, *14*(4), e0214471. doi:10.1371/journal.pone.0214471

Winders, T. M., Jolly-Breithaupt, M. L., Freeman, C. B., Mark, B. M., Erickson, G. E., & Watson, A. K. (2018). *Evaluating the Effect of Feeding Biochar to Cattle on Methane Production and Diet Digestibility*. In 10th International Livestock Environment Symposium (ILES X) (p. 1). American Society of Agricultural and Biological Engineers, Omaha, Nebraska. doi:10.13031/iles.18-148

Yahya, M. A., Al-Qodah, Z., & Ngah, C. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. *Renewable and Sustainable Energy Reviews*, *46*, 218–235. doi:10.1016/j.rser.2015.02.051

Yu, T., Abudukeranmu, A., Anniwaer, A., Situmorang, Y. A., Yoshida, A., Hao, X., … Guan, G. (2019). Steam gasification of biochars derived from pruned apple branch with various pyrolysis temperatures. *International Journal of Hydrogen Energy*. doi:10.1016/j.ijhydene.2019.02.226

Zervas, G., & Tsiplakou, E. (2011). The effect of feeding systems on the characteristics of products from small ruminants. *Small Ruminant Research*, *101*(1-3), 140–149. doi:10.1016/j.smallrumres.2011.09.034