

Physicochemical characterization of pig manure and its carbonaceous derivatives: Climate and sustainability impacts

Physikalisch-chemische Charakterisierung von Schweinegülle und ihrer kohlenstoffhaltigen Derivaten: Auswirkungen auf Klima und Nachhaltigkeit

Ifeanyi Charles Okoli¹, Friday Anegbode Edo², Albert Uzochukwu Chinenye Ohanaka^{1*}, Chidiogo Grace Okoli³

¹ Department of Animal Science and Technology, Federal University of Technology, P.M.B. 1526 Owerri, Imo State, Nigeria

² Department of Environmental Management, Federal University of Technology, P.M.B. 1526 Owerri, Imo State, Nigeria

³ Department of Environmental Health, National Open University, Plot 91, Cadastral Zone, Jabi, Abuja, Nigeria

* Corresponding author: ohanakaalbert@gmail.com

Received: 27 December 2024, received in revised form: 19 April 2025, accepted: 12 August 2025

Summary

Pig manure, a significant by-product of the swine industry, presents challenges and opportunities regarding management and environmental sustainability, especially in developing countries. The manure is composed of undigested feed remnants, including cellulose, proteins, minerals, and other excretory products, which makes it a nutrient-rich yet problematic resource. This review summarizes the state of knowledge up to the year 2024 by evaluating 201 relevant scientific articles on the physicochemical properties of pig manure and its biocarbon derivatives, highlighting their potential agricultural and environmental benefits. Understanding the factors influencing manure and biochar characteristics is critical in driving manure management and sustainability policies. Literature exploration showed that the carbon-rich products from carbonization have a higher pH (8–12), carbon (38%–75%), and ash (13%–72%) contents compared to the original manure, making them suitable for applications such as soil-crop improvement, renewable energy production, feed supplementation, and bioremediation. These biocarbon derivatives also exhibit enhanced surface area, porosity, and redox-active properties, fostering a beneficial soil or gut microbiome and overall environmental health improvements. The char characteristics are dependent on the manure quality and processing methods, with co-pyrolysis with other carbon-rich materials improving the char quality. However, the results from some of the selected studies on biochar properties and its production protocols were poorly characterized, which may be a major drawback for generalizing results. Overall, the thermal conversion of pig manure to biocarbon provides a sustainable solution to on-farm manure recycling, while mitigating pollution challenges in pig farming.

Keywords: Swine manure composition, thermo-carbonization, biochar properties, greenhouse gas emission, agro-sustainability, environmental health

Zusammenfassung

Schweinegülle, ein bedeutendes Nebenprodukt der Schweineindustrie, birgt Herausforderungen und Chancen hinsichtlich Management und ökologischer Nachhaltigkeit, insbesondere in Entwicklungsländern. Die Gülle besteht aus unverdauten Futterresten, darunter Zellulose, Proteine, Mineralien und andere Ausscheidungsprodukte, was sie zu einer nährstoffreichen, aber problematischen Ressource macht. Diese Übersicht fasst den Wissensstand bis zum Jahr 2024 zusammen, indem sie 201 relevante wissenschaftliche Artikel zu den physikochemischen Eigenschaften von Schweinegülle und ihren Biokohlederivaten auswertet und deren potenziellen landwirtschaftlichen und ökologischen Nutzen hervorhebt. Das Verständnis der Faktoren, die die Eigenschaften von Gülle und Biokohle beeinflussen, ist entscheidend für die Gestaltung von Güllemanagement- und Nachhaltigkeitsrichtlinien. Die Literaturrecherche zeigte, dass die kohlenstoffreichen Produkte aus der Karbonisierung im Vergleich zur ursprünglichen Gülle einen höheren pH-Wert (8–12), Kohlenstoffgehalt (38–75 %) und Aschegehalt (13–72 %) aufweisen. Dadurch eignen sie sich für Anwendungen wie Bodenverbesserung, Erzeugung erneuerbarer Energien, Futterergänzung und Bioremediation. Diese Biokohlenstoffe weisen zudem eine größere Oberfläche, Porosität und redoxaktive Eigenschaften auf, was zu einem positiven Boden- bzw. Darmmikrobiom und einer allgemeinen Verbesserung der Umweltgesundheit beiträgt. Die Eigenschaften der Kohle hängen von der Qualität des Düngers und den Verarbeitungsmethoden ab, wobei die Co-Pyrolyse mit anderen kohlenstoffreichen Materialien die Qualität der Kohle verbesserte. Die Ergebnisse einiger ausgewählter Studien zu den Eigenschaften von Biokohle und ihren Produktionsprotokollen waren jedoch unzureichend beschrieben, was die Verallgemeinerung der Ergebnisse erheblich erschweren könnte. Insgesamt bietet die thermische Umwandlung von Schweinegülle in Biokohle eine nachhaltige Lösung für das Recycling von Mist auf landwirtschaftlichen Betrieben und mindert gleichzeitig die Umweltbelastungen in der Schweinehaltung.

Schlagwörter: Zusammensetzung von Schweinegülle, Thermokarbonisierung, Eigenschaften von Biokohle, Treibhausgasemissionen, Agrarnachhaltigkeit, Umweltgesundheit

These massive volumes of manure generated globally from swine operations present critical environmental and public health challenges, including air and water pollution, soil degradation, and biodiversity loss when poorly managed (Machete and Chabo, 2020; Edo et al., 2021a). Potentially toxic gaseous emissions from swine facilities and manure storage tanks degrade air quality in nearby communities and contribute to social tensions and legal conflicts between producers and residents (Marszelek et al., 2019; Kadurumba et al., 2019; Edo et al., 2021b). In addition, the proximity of pig farms and manure disposal sites to human settlements raises serious public health concerns, including zoonotic disease transmission, odor nuisances, visual pollution, and environmental injustice (Edo et al., 2021b). Therefore, the challenge of handling swine manure becomes a key constraint to sustainable pig production (Kadurumba et al., 2019; Edo et al., 2021b).

Although producers have attempted to address pollution from swine operations through dietary strategies aimed at enhancing digestibility and reducing fecal volume, odor, and nutrient excretion, these measures alone are insufficient. Consequently, additional processes such as physical, chemical, or biological treatment steps are employed to transform or stabilize pig manure for various applications, including its use as fertilizer, animal feed, energy source, or in biocarbon production (Kroninger et al., 2021; AgriFarming, 2023; Edo, 2023). The thermochemical conversion of pig manure into environmentally friendly products such as biogas, bio-oil, syngas, and solid char biocarbon appears more promising as a waste management option with less environmental risk (Radenahmad et al., 2020; Ohanaka et al., 2021; Bolan et al., 2022). These products serve as adsorbents for soil and litter amendments, animal feed supplements, water purification, catalysis, or energy storage (Teoh et al., 2019; Ohanaka et al., 2021; Bolan et al., 2022; Ohanaka, 2022). The resultant char from thermal processing of the swine manure could serve as an energy source or chemical feedstock, thereby reducing the environmental impact of pig manure by decreasing its volume, odor, pathogens, and contaminants (Okoli, 2021a). More importantly, it exhibits improved physicochemical properties relative to the manure. However, most biocarbon products used in scientific studies are poorly characterized. Therefore, understanding the physicochemical properties of swine manure and its carbonaceous derivatives is required for proper characterization and utilization of derived carbon. This review focuses specifically on the physicochemical characteristics of pig manure and the characteristics of its char derivatives, exploring their potential impacts on agriculture, climate, and sustainability.

2. Methodology

Research papers predominantly published between 2003 and 2024, including non-peer-reviewed research (theses and conference proceedings), were selected for the study. Our study interest was on the physical and chemical properties of swine manure and its derived carbon as they affect agriculture and the environment. The literature search was performed using several electronic databases such as Science Direct, Scopus, Google Scholar, Web of Science, CAB abstracts, and ResearchGate. To identify the relevant publications, the following search keywords were included: pig dung, swine manure, slurry, biochar, charcoal, activated carbon, physicochemical, nutrient composition, proximate, ultimate analysis, heavy metals, microbial contamination, animal feed additives, adsorbents, soil amendment, odorous compounds, and greenhouse emission. While the search strategy was carefully designed to be as comprehensive as possible within the available time and resources, it is unlikely that any approach could capture every relevant study, and there is always a risk of missing key studies. Therefore, the references cited in the selected studies were also included in the search for relevant publications. No language or date restriction was applied. In total, 201 scientific studies were reviewed.

3. The Effect of Feed Composition on Pig Manure Characteristics

Animal manure is essentially the solid excreta of the animal and consists of the macerated undigested remains of the consumed feed, such as cellulose, hemicellulose, lignin, and other excretory products (Enyiukwu et al., 2021). The volume and composition of livestock manure differ significantly among animal species due to dietary composition, physiological factors, age-related changes, and nutritional approaches and practices (Makara and Kowalski, 2018). Feed composition refers to the physicochemical characteristics of feed ingredients, such as the content and quality of the protein, energy, fiber, minerals, and vitamin components. Compositional variations in different animal diets influence the consumption and utilization of feed by pigs. Feed composition affects the nutrient content and digestibility, water intake, energy utilization, and performance of pigs (Gaillard et al., 2020). Fibrous feedstuffs, for example, are usually cheaper than concentrates, thus reducing the cost of feed when incorporated into pig diets. They are, however, associated with dilution of dietary energy content

and increased feed intake to compensate for the energy requirement, impaired nutrient digestion and absorption, and therefore increased excreta volume (Okoli et al., 2009; Mpendulo et al., 2018). The fiber component of the diet is not easily digestible in the small intestine, but may undergo some level of fermentation in the large intestine, resulting in the release of bound nutrients. The fermentation process is, however, affected by the physical and chemical composition of the fiber, with soluble fibers being more amenable to fermentation than insoluble fibers (Jha et al., 2019).

The physical characteristics of the diet, such as bulk density (BD), swelling capacity, water-binding capacity, and viscosity, are dependent on the dietary fiber content, indicating that these characteristics can predict the digestibility of fiber *in vivo* in monogastric animals (Navarro et al., 2018). The authors further established that the total digestible fiber content is negatively correlated with digestible energy and metabolizable energy, indicating that feed composition and digestibility invariably influence the amount and composition in pig excreta and manure. Again, higher fiber, protein, and mineral contents in the feedstuff will usually result in increased dry matter, nitrogen, and phosphorus excretion, respectively, which invariably translates to more organic matter and volatile solids in the excreta and manure (Gailard et al., 2020; Lee et al., 2023). Thus, the high volume of manure generation during operations is associated with the high fiber content and low digestibility of high-fibrous feedstuffs (Okoli et al., 2009, 2011). Pigs fed fibrous feedstuffs produce an estimated 1132.53 kg of manure yearly per pig (Ewuziem, 2021), which is similar to the value published by Ngwabie et al. (2018). The nutrient composition and digestibility of feed ingredients are, therefore key determinants of the nature and volume of excreta from swine production and, by extension, its environmental impact.

4. Physicochemical Characteristics of Swine Manure

The most common form of animal manure in intensive production units is farmyard manure. Such animal manure consists of feces and plant materials such as straw, wood shaven, sawdust, and other bedding or litter material that has absorbed urine and fecal matter. Animal manure may contain other animal products, such as wool, hair, feathers, blood, bone, and spilt feed (Okoli et al., 2019). Most intensive livestock-rearing systems with slatted or concrete floors devoid of straw bedding produce animal manure in liquid form or slurry. Pig slurry is a combination of feces and urine in the

natural ratio of approximately 40% feces and 60% urine, in addition to the water used in cleaning the pen and the left-over fragments of feed (Marszelek et al., 2019). It contains mostly undigested and decomposing fibrous materials and minerals from feed, water, and excretions of the digestive tract, microorganisms, and their metabolites (Udebuani et al., 2018a; Okoli et al., 2019). Pig urine contains organic and inorganic compounds such as proteins, mineral, vitamins, hormones, and enzymes (Jakobsen et al., 2019). In Nigeria, small-scale pig farmers collect pig manure as solids and dispose of the urine by washing it into the adjoining gutter, which flows into the liquid manure pit (Okoli et al., 2019). The physicochemical characteristics of pig manure include its physical and chemical characteristics, such as color, odor, shape, size density, pH, moisture, nutrient and organic matter contents, and microbial activity in the manure (Okoli et al., 2007; Udebuani et al., 2018b; Anigbo et al., 2021). Researchers investigated the physical properties of pig manure, including odor, color, shape or contour, dimension or magnitude, and density, to develop more efficient methods for mitigating its environmental health impact, as well as to find the best storage, management, and treatment options. The density of pig slurry produced in Poland ranged between 900 and 1100 g/dm³ (Hus and Kutere cited by Kowalski et al., 2013). Recent studies in Nigeria reported varied density ranges of 500–800 and 1000–1500 g/dm³ for low-density and high-density swine manures, respectively (Udebuani et al., 2018a; Okoli et al., 2019; Edo, 2023). The density of pig manure varies in response to the type of feed, health status, age of the pigs, and storage and treatment conditions employed in managing the manure (Anigbo et al., 2021). Edo (2023) reported specific gravity (SG), water-holding capacity (WHC), and oil absorption capacity (OAC) ranges of 0.54–0.82, 122.29%–195.63%, and 1.12–1.59 g/g, respectively, for pig dung in southern Nigeria. The results indicate high aqueous and oil absorbance of manures and explain their potential uses in the bioremediation of crude oil-contaminated soils (Udebuani et al., 2012; Enyiukwu et al., 2021) and improvement of agricultural soils.

The chemical profile of swine manure is summarized in Table 1, highlighting its proximate, ultimate, and elemental composition. The chemical characteristics primarily depend upon the nutrient composition of its diet, which it metabolizes to produce its nutrient needs, body tissues, and products. However, swine manure is usually high in moisture content and may be as high as 75%–90%, depending on the type of feeding and management practices adopted on the farm (Anigbo et al., 2021; Edo, 2023). It is also rich in essential minerals such as nitrogen, phosphorus, potassium, cal-

Table 1. Physicochemical properties of swine manure from different regions

Tabelle 1. Physikalisch-chemische Eigenschaften von Schweinemist aus verschiedenen Regionen

Location	Nigeria	China	Spain	Nigeria	Spain	China	USA	Nigeria	Taiwan	Poland
Manure type	Fresh	Fresh slurry	Dry separated solid	Fresh	Slurry	Fresh manure-sawdust compost	Freshly dewatered solid	Dry	Dry	Slurry
(%)										
pH	7.35	6.34		7.60	9.00	7.46	7.30	7.35		6.89
MC	12.02	73.60	94.50	12.02		12.54	8.6	11.79	13.6	42.02
Ash	23.24	19.86	23.60	23.70	47.22	27.56	25.30	23.07	18.10	
VM	5.32	73.75	63.40		41.72	58.18	58.90	13.17		
TC			35.60	1.69		34.79	54.3	65.35	42.2	
FC	18.08	6.39	13.00		11.06	3.40	7.20	52.18		
N	2.25	4.60	2.90	0.21	2.51	2.51	5.10	1.94	4.00	0.93
O	-	-	32.50	-	-	30.32	31.50		36.40	
H			4.80			4.83	7.50		6.60	
P	0.0024	0.13	3.07	1.93	-	1.15	0.03	2.51	3.02	12.06
K	8.27	2.64	3.54	0.03	-	13.2	0.11	0.70	0.80	0.20
Ca	0.03	5.58	3.12	6.05	0.15	3.32	0.05	1.38	4.97	24.91
Mg	0.01	1.31	1.31	0.47	0.07	0.61	0.03	1.12	1.12	0.47
Na	-	0.62	1.02	0.04	0.06	0.19	0.03	0.18	-	-
(mg/kg)										
Zn	89.70	998.59	256.20	26,280.00	988.00	793.42	-	180.18	0.12	181.00
Mn	67.90	630.15				354.40		499.05	0.08	81.00
Cu	27.30	986.18	137.10	810.00	227.00	536.37		33.43	0.08	31.00
Fe	1885.16				41.46			2052.38		876.00
Cr	60.4	22.05	9.80	530.00				8.46		48.20
Pb	9.60	8.58	3.60	40.00		0.95		26.60		1.40
Cd	9.70	0.29		830.00		0.35		0.99		2.50
Al	196.30		1400.00	1800.00						
As		2.1		0.002		48.17				5.2
References	Okoli et al., 2019	Song et al., 2020	Ipiates et al., 2023	Udebuani et al., 2018b	Cely et al., 2014	Meng et al., 2014	Lentz et al., 2019; Kumaraga- mage et al., 2016	Edo, 2023	Tsai et al., 2012	Makara and Kowalski, 2018

cium, and magnesium and organic matter contents, which represent the amount of carbon-containing compounds such as carbohydrates, proteins, lipids, and lignin. The pH of swine manure is usually alkaline and can affect its odor, nutrient availability, and microbial activity, depending on the nature and storage conditions of the manure (Udebuani et al., 2018a; Okoli et al., 2019; Anigbo et al., 2021). Swine manure also has high organic matter and gaseous (ammonia, nitrous oxide, hydrogen sulfide, and methane) contents, which constitute environmental and public health problems, affecting air quality and increasing the emission of greenhouse gases (Okoli et al., 2007; Anigbo et al., 2021; Chmielowiec-Korzeniowska et al., 2022).

4.1. Proximate composition

Okoli et al. (2019) published the mean proximate values of dried pig dung collected from different locations in Imo State, south-eastern Nigeria, as dry matter content (87.97%), crude protein (CP) (14.05%), crude fiber (23.33%), ether extract (8.27%), total ash (23.24%), and nitrogen-free extract (18.77%). Udebuani et al. (2018b) reported similar CP values, much higher total ash content (35.30%), lower ether extract, and nitrogen free extract (NFE) values (3.0% and 12.42%, respectively) at the same study location. However, in South Africa, Rapatsa and Moyo (2013) reported CP, crude fiber, ether extract, and ash content values of pig dung to be 18.60%, 20.90%, 8.30%, and 28.04%, respectively. The variations in these values could be attributed to the influence of the different feed components, especially the dietary levels of oily and gritty palm kernel cake and other fiber components in swine diets in the study areas (Okoli et al., 2009; 2011). Animal dung from diverse species exhibit remarkably high ash content and has been shown to affect the thermal behavior and characteristics of fertilizers and carbonaceous materials produced from them (Okoli et al., 2019; Okoli, 2021a). Sun et al. (2017), for example, reported a mean value of 38.98% ash in animal manure produced in China, which is similar to the 30.91% ash content reported by Edo (2023) in pig manure collected from the Okigwe zone in Imo State, Nigeria. Gunamantha and Widana (2018) reported a much higher ash content value of 53.88% in pig dung from Indonesia. A high ash content reduces the energy content of biomass materials and may create operational problems during the thermochemical char-forming process due to ash slag formation at elevated temperatures (Miguez et al., 2021).

4.2. Mineral concentrations

Minerals are a complex mixture of elements, and their concentrations in swine manure often reflect the swine's dietary composition, health status, and environmental factors. The type, age, and physiological status of the animal also influence the type and composition of diets offered to pigs and therefore influence the physicochemical composition of pig manure or slurry (Sharara and Sadaka, 2018). Manures from swine operations are heavily laden with macro and micro mineral nutrients such as phosphorus (P), nitrogen (N), and potassium (K) that are of economic benefit as biofertilizers when properly harnessed. Researchers observed high levels of potassium and phosphorus in dried swine manure collected from different farms in Imo State (Okoli et al., 2007, 2019). However, Udebuani et al. (2018b) reported much higher calcium, magnesium, and phosphorus concentrations than the values reported by Okoli et al. (2019). Song et al. (2020) equally reported higher concentrations of calcium (Ca), N, K, and magnesium (Mg) in swine manure produced in China. A study of dry swine manure samples from Imo State farms found consistently higher micro mineral concentrations of iron (Fe) and zinc (Zn) (Udebuani et al., 2018b; Okoli et al., 2019). Higher Zn, copper (Cu), and manganese (Mn) values were also reported in swine manure samples from China and Spain (Cely et al., 2014; Meng et al., 2014; Song et al., 2020). Okoli et al. (2019) observed the accumulation of heavy metals such as aluminum (Al) and chromium (Cr) in pig dung, while lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) were generally low. The values reported by these authors were similar to the values reported by Udebuani et al. (2018b) and Okoli et al. (2014) in poultry droppings.

The rich mineral concentrations of pig manure make it a valuable yet problematic nutrient resource when poorly managed. For example, high concentrations of mineral elements, particularly N and P, in swine manure contribute substantially to environmental injustice, affecting air quality, human health, and climate change. According to Gollenhon et al. (2016) as cited in Vanotti et al. (2020), animal manure could contain an estimate of 868,000 tons of nitrogen and 388,000 tons of phosphorus in excess for land application. Such levels of concentrations in manures are capable of polluting aquifers, causing soil degradation, and disrupting soil microbial communities when used as fertilizers without processing (Marszelek et al., 2019; Rashid et al., 2023). The higher concentrations of calcium, magnesium, sodium, potassium, sulfates, and chlorides in pig manures, signifying high electrical conductivity (EC), have the potential to induce higher soil salinity

and nutrient imbalance. Soil salinity induces oxidative stress in plants, inhibiting photosynthesis, nutrient synthesis, and nutrient uptake (Arif et al., 2020). There are also concerns regarding excretion of important microelements and heavy metals in manure, such as Zn, Cu, Cd, Pb, and As, probably resulting from the use of feed additives in intensive production units (Ding et al., 2021). Thus, there is a need for appropriate analysis of pig manure before any form of industrial application or processing (Lan et al., 2022).

4.3. Odorous compounds

In addition to the major compounds, reports also suggest that swine manure contains several volatile and odorous compounds that contribute to its unpleasant odor, including esters, alcohols, ketones, aldehydes, hydrocarbons, mercaptans, phenols, cyclic amines, hydrogen sulfide, ammonia, and nitric oxides, among others (Udebuani et al., 2018a; Song, 2024). The sources of the odor are mostly protein compounds, which are subject to anaerobic decomposition by putrefactive bacteria (Sharma et al., 2017). Ammonia is the main source of odor and air pollution from pig manure, and accounts for approximately 50% of the total volatile compounds released from manure (Cao et al., 2023). It is capable of causing acidification and eutrophication of soil and water bodies, in addition to animal and human health problems (Okoli et al., 2007; Marszelek et al., 2019; Ananna et al., 2021).

Methane, as the second source of odor and air pollution from pig manure, accounts for approximately 20% of the total volatile compounds and contributes to global warming and climate change as a potent greenhouse gas (Wang et al., 2017; Zhang et al., 2019). Hydrogen sulfide, as a source of odor and air pollution from pig manure, accounts for approximately 10% of the total volatile compounds and can cause corrosion and health problems to humans and animals (Okoli et al., 2007; Brglez, 2021).

Other major volatile organic compounds responsible for odor and air pollution in pig manure include alcohols and aldehydes, which account for approximately 5% and 3% of the total volatile compounds in the manure, respectively (Wang et al., 2017; Zhang et al., 2019). Aldehydes can also cause irritation and inflammation of sensitive tissues in humans and animals (Catalano et al., 2024). Compounds such as volatile fatty acids (acetic, propionic, and butyric acids), indole, phenolic, and sulfuric compounds contribute substantially to odor emission from swine manure (Song, 2024). Their

concentrations in manure vary with dietary levels of protein in feed rations, feed additives, storage conditions, and type of operation (Zhang et al., 2019; Trabue et al., 2021).

4.4. Microbial population

The different microorganisms present in pig manure include commensal and pathogenic bacteria such as *Clostridium*, *Bacillus*, *Lactobacillus*, *Enterobacter*, *Escherichia*, *Salmonella*, and *Proteus* species, as well as fungal organisms and parasites originating from the gut (Lim et al., 2018; Marszelek et al., 2019). A study investigating the microbial loads and profiles of pig dung reported that colony-forming units per milliliter for total heterogeneous bacteria ranged from 2.38×10^5 to 7.4×10^9 , total coliform count ranged from 2.25×10^5 to 1.5×10^9 , and fungal colony count ranged from 7.3×10^2 to 2.1×10^7 (Udebuani et al., 2018a). The bacterial organisms identified in the manure included *Pseudomonas* sp., *Salmonella typhi*, *Shigella* sp., *Escherichia coli*, *Streptococcus faecalis*, *Bacillus aureus*, and *Micrococcus luteus*, while the fungi were mainly *Rhizopus oryzae* and *Aspergillus niger*. However, Cho et al. (2015) reported a diverse community of bacteria in pig manure slurry, with Firmicutes, Bacteroidetes, and Proteobacteria dominating. Similar findings were also reported by He, L. et al. (2019) and Zhang, R. et al. (2021), suggesting the dominance of these bacterial genera in manure. The activities of these organisms are responsible for the degradation or metabolism of nutrients in manure, thus releasing odorous gases and other bacterial metabolites into the manure and the surrounding environment (Chmielowiec-Korzeniowska et al., 2022). The excessive land application of unprocessed swine manure can introduce microbial contaminants and antibiotic residues into the food chain through contaminated soil, water, and food crops (Marszelek et al., 2019).

4.5. The pH of pig manure

The pH of pig manure produced in southern Nigeria ranged from slightly acidic 6.60 to slightly basic 7.60 (Udebuani et al., 2018b), while European values ranged from 5.98 to 7.73 (Marszelek et al., 2019). However, Anigbo et al. (2021) published ranges of 9.33–10.06 and 11.57–12.10 for fresh and dry swine manures, respectively, in the Port Harcourt metropolis, southern Nigeria. Storage of pig slurry during a

warm period was found by Adamsen et al. (2021) to significantly increase the pH from 5.7 to 7.0 in 25 days, while under cold conditions, the increase was much less (5.5–6.1 in 25 days). Dai and Karring (2014) reported that the range of pH values in fresh pig manure suggests that the bacterial communities in the manure produce urease enzymes, which are most efficient for ammonia production and gas emission from the manure.

4.6. Fiber characteristics

Significant proportions of animal manure comprised fiber in the form of cellulose and lignin. The fibers that make up the organic matter fraction of pig manure are essentially cellulose, hemicellulose, lignin, and pectin. Fecal output is largest among pigs fed diets containing large proportions of fibrous feedstuffs, as practiced in many tropical countries, including Nigeria (Okoli et al., 2011; Mpendulo et al., 2018). For example, Xu et al. (2014) reported that in China, the amount of cellulose, hemicellulose, and lignin in sow pig manure was much higher than the amount in piglets and grower pig manures, probably reflecting the nutrient compositions of their diets. The composition of these fiber components and other extractives in biomass waste/swine manure is a key property that influences the biomass conversion process, since they decompose at distinct temperature spectra during combustion (Shah et al., 2018). For example, higher percentages of cellulose and hemicellulose in biomass increase the rate of thermal degradation during pyrolysis and may favor lower char formation and ash content (Tripathi et al., 2019).

Edo (2023) reported the mean values for neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), cellulose, and hemicellulose to be 53.49%, 25.44%, 6.36%, 19.08%, and 28.05%, respectively, in dried pig manure from Imo State, southern Nigeria. Trujillo et al. (2014) reported that fresh pig excreta from Mexico contained 334 g (33.40%) NDF, 126 g (12.60%) ADF, and 45 g (4.50%) ADL per kilogram of dry matter, while Zhao et al. (2020) reported much higher NDF, ADF, and ADL values for high-fiber cellulosic materials such as corn and wheat bran. A study of pig manure from Imo State, Nigeria found a significant cellulose:lignin ratio of 12.4:1, indicating its potential for bioenergy application (Edo, 2023). Woods from broad-leaved trees are composed of cellulose and lignin in appropriate ratios of 2:1 (Tullus et al., 2010; Guo et al., 2023). Sun et al. (2017) reported values of 3.1:1 and 1.9:1 for agricultural residues and livestock manure, respectively, from China. These published results show that the higher

(12.4:1) ratio recorded in pig dung from Imo State may affect the biomass conversion process of such manure since the cellulose:lignin ratio is an important thermochemical property that influences the carbon content of biomass-derived carbonaceous materials.

5. Pig Manure Carbonization Processes and Derivatives

When biomass materials are heated to 350–650°C, their chemical bonds break and rearrange to form new functional groups typical of oxygenated hydrocarbons such as carboxyl, lactones, quinone, chromene, anhydride, phenol ether, and pyrone. This is reflective of the carbohydrate structures of their cellulose and hemicellulose contents (Mia et al., 2017). Carbonization is thus a thermochemical degradation of biomass materials in a furnace under an oxygen-controlled environment, which leads to the loss of volatile gases such as alkanes, alkenes, carbon monoxide, alcohols, etc., with an increased propagation of carbon in the char residue (Yahya et al., 2018; Okoli, 2021b). This irreversible process transforms the physicochemical characteristics of biomass at elevated temperatures. There are, however, certain important factors that influence the process and quality of the final carbon product, such as the carbonization temperature, activation cum retention time, impregnation ratio, and nitrogen flow rate (Bedia et al., 2018; Reza et al., 2020). The carbonization temperature has the most critical influence on the percentage yield, morphology, ash, and fixed carbon (FC) contents of biocarbon products (Ohanaka et al., 2021; Okoli, 2021b). Organic waste such as pig manure could serve as a potential precursor to produce biocarbon for industrial and farm use (Ohanaka et al., 2021) due to its rich cellulose, lignin, carbon, and volatile matter (VM) contents. The processes involved in the biotransformation of swine manure into carbon usually require different pretreatment steps before the actual carbonization and activation processes (Cantero et al., 2019). For example, there may be the need to remove impurities such as metals, plastics, and waste fabrics from manure. There is also the need to standardize the moisture content and particle size of manure before carbonization (Iwanow et al., 2020; Reza et al., 2020). Again, the amount of ash and minerals in the manure feedstock could be reduced by pretreatment with acidic or basic solutions, especially when activated chars of low ash content are targeted, particularly those used in catalytic applications (Reza et al., 2020). Activated char/charcoal is a carbonaceous solid product of biomass pyrolysis produced under similar production con-

ditions as biochar, except for the activation process, with increased surface area for adsorption compared to biochar. The activation process modifies the surface chemistry of the resultant char, which influences its sorption characteristics (Man et al., 2021). The activation process could either be physical or chemical activation. In the physical activation method, the biochar obtained from the carbonization process undergoes steam, carbon dioxide, or nitrogen gas activation at high temperatures (400–1000 °C), enhancing its porosity and surface area (Xu et al., 2021). Activation of the char through CO₂ activity results mostly in the creation of microporosity, while steam activity widens the microporosity starting from the early stages of the activation process (Mopoung and Dejang, 2021). However, reports suggest that steam-activated carbon have higher surface area, pore distribution, and surface oxygen-containing functional groups than those obtained by CO₂ activation (Yang et al., 2016). Ohanaka (2022) and Okey et al. (2022) specifically reported the significant additive effects of steam-activated charcoal on the growth, physiological, and egg-laying performance of chickens when incorporated into their diets. Edo (2023) also produced activated chars from dried pig manure co-pyrolyzed with blends of either palm kernel shell (PKS) or waste plastic water sachets using a steam activation procedure, which enhanced the physicochemical characteristics and soil amendment value of the final products. The production of activated char using the chemical activation method involves a single-step pyrolysis method, which requires treatment of the organic raw materials with dehydrating chemical agents (usually acids or bases) before carbonization. The process begins with the impregnation or soaking of the raw material with an appropriate chemical reagent, followed by a simultaneous carbonization and activation process (Hidayu and Muda, 2016). The common chemical catalysts usually employed in chemical activation are dehydrating agents such as sulfuric acid (H₂SO₄), phosphoric acid (H₃PO₄), zinc chloride (ZnCl₂), potassium sulfide (K₂S), carbonates of alkali metal, and metal chlorides (Heidainejad et al., 2020; Ho, 2022). The impregnation of precursor materials lowers the temperature requirement during pyrolysis and restricts the formation of tars, thereby resulting in a much richer carbon product with more porosity and char yield (Leng et al., 2021). The resultant char is subjected to post-activation treatment such as cooling and washing with hot distilled water to remove and possibly recover the impregnation chemical, while enhancing the porosity of the char (Takaya et al., 2016).

Several studies have shown that chemical activation has more benefits than physical activation in terms of lower pro-

cess temperature, higher carbon yield, and enhanced surface chemistry and surface area for adsorption (Ho, 2022). However, there are some disadvantages associated with chemical activation, such as the need to wash the product to remove impurities arising from the activating reagents. Several factors, including the catalytic agent, time and temperature of activation, nature of biomass, and time and temperature of carbonization, influence the properties of activated charcoal (Hirunpraditkoon et al., 2011; Ho, 2022). Researchers have recently explored alternative biomass carbonization methods, expanding beyond traditional techniques. For example, microwave-assisted pyrolysis has emerged as a novel method for biocarbon production, integrating carbonization and activation process into a single step (Iwanow et al., 2020). Similarly, hydrothermal carbonization has gained prominence as an efficient and cost-effective single-step bio-carbonization technology for high moisture, manure management that requires no prior pre-drying process or high energy input for char production (He et al., 2019; Zubbri et al., 2021).

6. Co-pyrolysis of pig dung and other waste materials

Freshly voided pig dung has relatively high moisture and ash contents, low bulk and energy densities, and variable chemical compositions, which may affect its value as an energy feedstock (Ro et al., 2019). Generally, swine manure is inorganic and low in energy density (Cheng et al., 2020), but may contain higher concentrations of nitrogenous substances, which significantly lower its fuel-grade properties during pyrolysis (Li et al., 2020; Ipiates et al., 2023). Iregbu (2014) observed that dry pig manure burns inefficiently or smolders during open-air combustion, producing a thick smoke that keeps burning until all manure is charred, and forms a whitish or grayish ash that does not crumble easily, suggesting the presence of metallic oxide components. Okoli et al. (2019) showed that pig manure ash contains high phosphorus and potassium levels, while part of the nitrogen is lost. The high concentration of phosphorus usually found in pig manure may also contribute to the smoky, sluggish burning of dry manure owing to the formation of phosphorus-oxy acids, which catalyze the char-forming reaction once ignited and could impede the smooth burning of manure (Iregbu, 2014). Again, the aluminum metal in the dung most likely forms alumina (Al₂O₃) during combustion, which conducts heat away from the burning surface (Okoli et al., 2019), and therefore decreases the heat budget of the burning ma-

nure, thus diminishing the heat propagation rate. Equally, the relatively high levels of potassium and sulfur in pig dung could result in the formation of potassium sulfate (K_2SO_4), which again is a good heat conductor that deflects heat away from the burning surface of the manure. However, improved flammability of pig dung can be achieved through blending or co-pyrolysis with carbon-rich flame accelerants such as sawdust, PKS, bamboo wood, and plastics (Ohanaka et al., 2021; Edo 2023).

Co-pyrolysis is a process that involves the use of two or more biomass materials for the production of biocarbon with improved physicochemical properties, based on the principle of synergistic effects, which comes from the reactions of the different materials during the thermochemical process (Ohanaka et al., 2021; Ipiales et al., 2023). The high oxygen and nitrogen contents of pig manure that impede its caloric value and flammability could be overcome by blending with oxygen- and nitrogen-deficient feedstock to dilute the nitrogen content during pyrolysis (Li et al., 2020a). In practical terms, the choice should be because biomass with a higher lignin content generates chars with relatively higher carbon yield in proximate analysis. The type of product derived from co-pyrolysis will depend on the nature of the carbonized biomass materials, blending ratios, pyrolysis temperature, and duration of pyrolysis (Ohanaka et al. 2021; Edo 2023). The blending ratios of the chosen feedstock are, however, the major factor that significantly influences the synergistic effects of co-pyrolysis (Ipiales et al., 2023). The co-pyrolysis of pig manure and sewage sludge resulted in a reduction in heavy metal and antibiotic levels in manure (Li et al. 2020b), while Vuppaladadiyam et al. (2019) reported an increased cracking reaction and a decrease in gas formation resulting from the co-pyrolysis of pig manure and microalgae. Bernado et al. (2012) studied the synergistic effect of the co-carbonization of plastic, pine biomass, and tire wastes, which significantly increased the carbon yield and calorific value of the resultant char. Similarly, the co-pyrolysis of biomass and plastic waste resulted in the production of solid products with higher heating values than coal due to the elemental composition of the char (Paradeca et al., 2009). Co-pyrolysis of swine manure and plastic wastes resulted in an increase in the FC content of the biochar from 44.60% in the swine manure-derived biochar to a 52.40%–64.70% range in the different manure–plastic char products (Ro et al., 2014). The authors also observed decreased ash concentration from 44.4% in the swine manure-derived biochar to 27.60% in swine manure–plastic biochar. However, biochar yield decreased from the 39.00% obtained from swine manure alone to 28.00% obtained from the manure–plastic AC. Again,

the study showed that all the biochar produced from this process had similar surface areas, VM contents, and chemical structures, suggesting similar functionalities when applied to soils.

Edo (2023) reported that on carbonization, pig manure yielded relatively high carbon products (29.50% and 35.00%) for biochar and activated charcoal, respectively. The percentage yield of the swine manure-derived biochar and activated charcoal products significantly decreased (16.33% and 19.67%, respectively) when blended with waste plastic water sachets. Nevertheless, the char yields slightly increased (35.50% and 41.00%) when blended with PKSs. Ohanaka et al. (2021) reported a higher activated charcoal yield (46.54%) from the co-pyrolysis of pig dung, PKS, and bamboo wood chips. Generally, co-pyrolysis of swine manure with carbon-rich materials enhances the high heating value, combustion properties, and stability of carbon, while decreasing the heavy metal content of the resulting char. These results highlight the potential value of using the co-pyrolysis approach to manage swine manure disposal and environmental pollution problems, while producing value-added biocarbon products.

7. Characteristics of Pig Manure-Derived Carbonaceous Materials

The pyrogenic conversion of animal manure into carbonaceous materials remains one of the sustainable approaches to agricultural waste reduction, biomass energy production, and the development of carbon-rich products for applications in agronomy, animal farming, anaerobic digestion, soil remediation, carbon sequestration, and construction (Reza et al., 2020; Sarfaraz et al., 2020; Osman et al., 2022). Although several study reports exist on the pyrogenic conversion of pig manure to biochar (Tsai et al., 2012; Gnamantha and Widana, 2018; Qiu et al., 2022), a limited number of such studies have been undertaken in Nigeria (Ohanaka et al., 2021; Okey et al., 2022; Edo 2023). The large volumes of pig manure produced in the country and the disposal challenges faced by smallholder farmers, however, make it a viable feedstock to produce biocarbon products as a waste management and pollution mitigation approach. It is, however, important to understand the characteristics of the manure-derived carbonaceous products since their physicochemical composition is heavily dependent on the nature and characteristics of the manure and, by extension, the feedstuff offered to the animals (Cely et al., 2014; Okoli et al., 2019). Table 2 highlights the physicochemical properties

of swine manure-derived biocarbon from different regions. The physical and proximate characteristics, ultimate and elemental composition, pH, cation exchange capacity (CEC), and EC are key properties of biocarbon driving its usage and applications in various agro-industrial operations.

7.1. Physical characteristics

Carbonaceous materials prepared from different biomass precursors exhibited varying physical characteristics, especially in their BD, porosity, and specific surface area values. Structurally, biochar or activated char contains micropores, mesopores, and macropores that play significant roles in their capacity to absorb substances of varied nature. Carbonaceous materials are characterized by their physical and structural properties including density, surface area, and pore volume (Iwanow et al., 2020). The total pore volume and porosity of biocarbon products are usually higher than the values obtained from the original precursor material (Tomczyk et al., 2020). Activated char and biochar can possess a surface area range of 300–2000 m²/g, while values as high as 5000 m²/g have been reported (Hidayu and Muda, 2016). The enormous surface area and porosity of biocarbon confer unique adsorptive capacity and habitation for desirable microbiota proliferation (Abhishek et al., 2022). Reports suggest that activated char or biochar can adsorb toxins, gases, anti-nutrients, and bacteria in contaminated livestock feeds, manure, soil, and pollutants in industrial effluents (Borchard et al., 2019; Ohanaka et al., 2021). As a litter amendment in livestock farms, biochar can mitigate litter moisture content and odor emission, particularly ammonia, methane, nitrogen sulfide, urea, and nitrous oxide (Xu et al., 2021; Malyan et al., 2021). Reduced litter moisture and odorous gases in rearing systems are significant health improvements for intensively reared animals, farm workers, and the global environment. The BD, WHC, and SG values of activated charcoal derived from the blend of pig manure, PKS, and bamboo wood chips were reported by Ohanaka et al. (2021) to be 0.87 g/cm³, 89.90%, and 0.73, respectively. Edo (2023), however, reported the BD and WHC values of pig manure-derived activated charcoal and biochar to be 1.02 and 1.05 g/ml and 59.86 and 63.41%, respectively. These values were significantly altered by the co-carbonization of swine manure with either PKS or waste plastic water sachet. WHC and BD of activated carbon and biochar reportedly increase agricultural soil aeration and retention of soil nutrients and water for crop production when used for soil amendment purposes (Kumar et al., 2022). As a feed or litter amendment additive, Ohanaka (2022) report-

ed BD reduction and increased WHC of laying hen ration amended with 1% AC derived from a blend of swine manure, PKS, and bamboo chips. Studies have indicated that the internal surfaces of biocarbon are inundated with organic nutrients as they travel through the gut or within manure matrix, thus increasing its capacity to hold water and exchangeable nutrients (Schmidt et al., 2019). This also reduces nutrient loss in manure through volatilization or nutrient leaching.

OAC is another physical property of biocarbon that can help remediate oil-polluted soil or water surfaces (Nguyen and Pignatello et al., 2013; Mukome et al., 2020). Ohanaka et al. (2021) reported an OAC value of 1.25 g/g for AC derived from pig dung-PKS-bamboo wood chip co-pyrolysis at 400°C carbonization temperature. Edo (2023) reported OAC values for pig manure-derived activated char and biochar to be 0.84 and 0.85 g/g, respectively, while Sohaimi and Ngadi (2016) reported 0.12 g/g OAC for cooking oil with the application of textile sludge-derived biochar. However, potassium hydroxide (KOH)-activated coconut shell biochar produced at a much higher temperature (1000°C) had sorption capacities of 5.54 and 9.33 g/g for used/premium motor oil (Raj and Joy 2015). Higher OAC ranges have been reported for woody (6–120 g/g), rice (6.85–10.88 g/g), and date palm (11–33 g/g) biochar produced under varying temperature and activation conditions (Nguyen and Pignatello, 2013; Štefelová et al., 2017; Nasir et al., 2018; Huang et al., 2021).

7.2. Carbon contents

In addition to the operating conditions for biochar production, the chemical and compositional structure of the biomass feedstock influences its carbon content values (Tomczyk et al., 2020). Variations in the lignocellulose proportions in the manure affect the biochar carbon content, as a higher lignin content of manure results in a higher carbon content of the manure-derived biochar (Kloss et al., 2012). A higher cellulose content of the biomass feedstock favors tar formation, while a higher lignin content favors char production, and higher carbon and ash contents during carbonization (Tripathi et al., 2016). Gunamantha and Widana (2018) reported a lower carbon content (18.88%) in pig manure-derived biochar than the 27.31% recorded in cow manure-derived biochar. In contrast, Sarfaraz et al. (2020) reported higher total carbon content (38.27%) in the pig manure-derived biochar compared to the 22.11% and 16.42% recorded in poultry litter- and cow dung-derived biochar, respectively. Tsai et al. (2012) reported a range of 41.10%–43.90%

Table 2. Physicochemical properties of swine manure-derived char products from different regions

Tabelle 2. Physikalisch-chemische Eigenschaften von aus Schweinemist gewonnenen Char-Produkten aus verschiedenen Regionen

Location	Nigeria	China	Spain	Brazil	Spain	China	USA	Nigeria	Nigeria	Taiwan	Denmark
Char type	Activated charcoal	Hydrochar	Hydrochar	Biochar	Biochar	Biochar	Hydrochar	Activated char	Biochar	Biochar	Biochar
Activation method	Steam	Acid	Steam	Nil	Nil	Nil	N2	steam	Nil	Nil	N2
CT	400°C	220°C	180°C	450°C	300°C	400°C	220°C	300°C	300°C	700°C	600°C
pH	8.49	5.29	-	10.24	7.8	9.86	6.85	9.44	8.96	11.98	
(%)											
MC						3.36	1.70	5.42	4.96	2.50	
Ash	13.13	24.03	31.60	50.33	50.25	46.35	38.20	50.80	35.79	52.8	31.80
VM		5.33	53.9		31.25	38.00	44.60	5.65	5.32		10.70
TC	75.35		37.50			35.86	70.00	44.13	41.11	49.30	62.20
FC			14.50	38.27	18.5	12.11	15.40	38.15	53.71		57.50
N		4.30	2.40	3.00	2.24	2.57	4.30	1.56	1.61	2.00	1.18
O			23.10			13.09	17.10			14.90	3.7
H			4.70			2.12	7.70			0.90	1.12
P	2.51	1.20		4.88	0.28	1.83		2.48	2.22	7.50	3.34
K	0.93	1.50		3.67	0.08	2.52		1.66	1.22	2.70	1.55
Ca	0.56	5.50		7.02	0.13	5.30		0.56	0.38	5.00	6.10
Mg	0.44	1.00		5.84	0.09	1.25		0.51	0.42	3.40	0.80
Na	0.14	0.20			0.06	0.36		0.17	0.16		1.18
(mg/kg)											
Zn	103.48	970.96		508.60	1213.00	1558.08		120.15	16.33	0.34	660
Mn	671.33	568.32		462.60		760.91		602.85	706.55	0.18	580
Cu	39.46	885.82		20.70	348.00	1135.62		99.60	58.66	0.05	140
Fe	1304.65			282.80	60.94			8446.66	6498.15		11,300
Cr		21.63						15.46	16.10		450
Pb		4.17				1.47		18.09	14.13		1.90
Cd		0.17			0.00	0.53		0.09	0.09		<0.90
Al								0.00	0.00		620
As		0.45				55.47					
BD	0.87							1.02	1.00		
SG	0.73							1.11	1.09		
WHC	89.90							59.86	63.41		
CEC				170.00	35.60						
EC				4.08	102.00	730.00					
SA				12.36		3.68				59.00	22.90
References	Ohanaka et al., 2021	Song et al., 2020	Ipiates et al., 2023	Sarfraz et al., 2020	Cely et al., 2014	Menger et al., 2014	Lenz et al., 2019	Edo, 2023	Edo, 2023	Tsai et al., 2012	Whettrzak et al., 2014

carbon contents of swine manure-derived biochar, similar to the 41.11% and 44.13% reported by Edo (2023) in activated charcoal and biochar derived from pig manure, respectively. However, reports suggest that dung-derived biochar has relatively lower carbon concentrations than their plant-derived counterparts (Tomczyk et al., 2020). This is due to the presence of more labile organic compounds in animal manures, which are rapidly lost at high temperatures before the formation of recalcitrant carbon products (Domingues et al., 2017; Sarfaraz et al., 2020).

Co-pyrolysis of pig manure with other carbon-rich materials could influence the carbon contents of biochar in response to the blending ratios and pyrolysis conditions. Ohanaka et al. (2021) reported a much higher carbon content of 75.35% from a blend of pig dung, PKS, and bamboo sticks (4:3:3 ratio). Edo (2023) reported a significant increase in the total carbon contents (64.81% and 54.31%, respectively) of activated charcoal and biochar derived from the co-pyrolysis of pig manure and PKS compared to that derived from the manure alone (44.13% vs. 41.11%, respectively). The carbon values, however, decreased (33.77% and 30.4%, respectively) due to co-pyrolysis with waste plastic water sachets. Qiu et al. (2022) reported a 1.5-fold increase in the FC contents in biochar produced from the combination of pig manure and invasive Japanese knotweed at varying blending ratios and pyrolysis temperatures (400–600°C). Carbonization of pig manure with cellulose and glucose reportedly increased the carbon content from 20.00% to 46.50% and 43.00%, respectively (Li et al., 2020a). Carbonization of swine manure and other carbon-rich biomass increases the stability and concentration of carbon in the final char product and therefore becomes a better agent for long-term soil carbon sequestration compared to its original manure biomass. Reports suggest an increase in fecal carbon concentration and slower fecal decomposition by soil organisms due to dietary biochar supplements in animal diets (Al-Kindi et al., 2016). The resultant fecal output from such dietary amendment has the capacity to increase soil carbon storage and therefore, a useful soil conditioner with emission mitigation properties.

7.3. pH

The pH of biochar is usually alkaline since it positively correlates with the formation of carbonates and other base cations during the carbonization process. Cely et al. (2014) reported that biochar pH could vary from 7.8 to 10.6 in response to pyrolysis temperature. Tsai et al. (2012) reported a range of pH values from swine manure-derived biochar produced at

different carbonization temperatures. The pH values averaged 7.65 at 400°C to 11.98 at 700 °C. Ohanaka et al. (2021) reported a pH value of 8.49 in AC derived from the blend of pig dung, PKS, and bamboo sticks at 400°C, while Cely et al. (2014) obtained pH values of 7.80 and 8.20 in swine manure-derived biochar at 300 and 500°C pyrolysis temperatures. Edo (2023) recorded pH values of 9.44 and 8.96 in pig manure-derived activated charcoal and biochar, respectively. Co-pyrolysis with PKS or wastewater sachet plastics, however, yielded lower pH (8.50 and 8.35) values in the AC products compared to the manure alone. The increase in the alkalinity of manure biochar was associated with the increased pyrolytic temperature and biomass characteristics (Guo et al., 2021). The alkalinity of biochar products has been leveraged as a natural liming agent to reduce the acidity of agricultural soils, while improving their productivity. However, lower pH (2–5) or acidic chars derived from pig manure when specifically activated using mineral/organic acids have been reported (Meng et al., 2014; Jiang et al., 2018). The acidification process enhances the surface functional groups on the carbonaceous surface, increasing its hydrophilic, adsorptive, and redox-active properties, and thus its affinity for microbial interaction. This could improve nutrient utilization and decontamination in crop–livestock production, while potentially reducing enteric methane emissions (Schmidt et al., 2019; Lonappan et al., 2019; Teoh et al., 2019).

7.4. Proximate characteristics

Proximate analysis data are typically reported on a dry weight basis, except for moisture content. The major proximate constituents of the biochar are usually FC, ash, and VM, which are the gases, oil, and tar released during the pyrolysis process at 300°C (Amer and Elwardany, 2020). During pyrolysis, hydrogen and oxygen are lost from the dung in greater amounts than carbon, thus resulting in biochar containing a lower VM value than the original manure (Gunamantha and Widana, 2018). According to Antal and Gronli (2003), these volatile gases are initially lost as water and later as hydrocarbons and slowly as evaporating agents such as H₂, CO, and CO₂. Gunamantha and Widana (2018) reported that VM in pig manure is approximately 39.9% but decreases to 13.62% in biochar. Edo (2023) recorded a mean VM of 13.17% in dried pig manure, which further reduced to 5.65% and 5.32% in activated charcoal and biochar products, respectively. A swine slurry hydrochar exhibited a similar VM value (5.33%) (Song et al., 2020). Deenik et al. (2010) stated that a VM value above 35.00% is high and will

trigger nitrogen deficiency in the soil, disrupting nutrient cycling and ecosystem health. Therefore, the carbonization of pig manure lowers the VM content in the derived biochar within limits suitable for agronomic operations.

The residual organic matter in biochar after evaporation of VM is FC, suggested as a potential measure of biochar recalcitrance (Crombie et al., 2013). The pyrolytic process also modifies and increases the FC content of the manure waste biomass. For example, Gunamantha and Widana (2018) reported an FC value of 14.24% for pig manure-derived biochar, while the value in the feedstock was lower (6.46%), indicating a substantial increase during the carbonization process. The co-pyrolysis of pig manure with PKS resulted in a higher FC value (60.42) in AC beyond the value reported for swine manure alone (Edo, 2023). The higher FC content of biochar relative to its original manure emits lower CO₂ emissions compared to manure or chemical fertilizer (Sarfaraz et al., 2020). However, the FC content of biocarbon products is influenced by their ash concentrations.

Ash is the leftover inorganic fraction after the complete combustion of a feedstock. Generally, the ash yield from pyrolysis positively correlates with the ash content of the biomass feedstock (Cely et al., 2014). Again, manure-derived biochar has higher ash concentrations compared to the original manure. Gunamantha and Widana (2018) reported a 72.41% ash content in pig manure-derived biochar compared to 53.58% in manure. Edo (2023) reported a mean ash content of 23.07% in dried pig manure, which increased to 50.80% and 53.71% in activated charcoal and biochar derived from it, respectively. Co-pyrolysis of the manure with sachet water plastic waste resulted in higher ash contents of derived biochar (65.95%), while PKS reduced the ash contents to 41.31%. Ohanaka et al. (2021), in contrast, reported a much lower total ash content (13.13%) in activated charcoal produced from a 4:3:3 blending ratio of dried pig manure, PKS, and bamboo wood chips. The high ash content in manure-derived biochar is usually due to the high concentration of nutrients in the biomass feedstock. The ash component of the biomass hinders the formation of aromatic structures that contribute to FC during the carbonization process and reduces the absorptive capacity of biochar and activated charcoal, indicating that it is an impurity (Yargicoglu et al., 2015).

7.5. Elemental composition

Biomass-derived carbonaceous materials are composed of carbon, moisture, VM, and elemental composition such as

hydrogen, oxygen, nitrogen, phosphorus, and sulfur on their surface, which are key determinants of biochar chemical properties and quality characteristics (Yahyah et al., 2015; Okoli et al., 2021b). The mineral concentrations of biochar from animal manure are influenced by the nutrient concentrations in their diets, manures, and pyrolytic conditions. For example, biochars derived from cow manure had lower macro mineral concentrations than biochar of pig manure origin (Sarfaraz et al., 2020). Specifically, pig dung-derived biochar contained much higher levels of N, P, K, Ca, Mg, Zn, and Fe than the poultry litter- and cattle dung-derived biochar, while the ash values followed the opposite trend. The elemental composition of manure-derived biochar, such as Ca, P, K, and Mg, increases substantially compared to their original manure biomass (Song et al., 2020). The nutrient-rich mineral concentration of biocarbon increases its electrochemical behavior and could serve as additional sorption sites or catalysts in biotic and abiotic reactions (Schmidt et al., 2019). This increases its application as a biofertilizer or supercapacitor, while reducing the usage of chemical fertilizers (Lentz et al., 2019). Co-pyrolysis of pig manure with other carbon-rich materials could alter the order of mineral concentrations (Ohanaka et al. 2021; Edo 2023).

Generally, animal manure-derived biochar contains more phosphorus than plant-derived biochars (Shi et al., 2023), while the latter contains more potassium than manure-derived biochar (Zhao et al., 2013). Some studies have indeed characterized the higher concentration of phosphorus entrapped in the matrix of the char to be polyphosphate anions, which can improve their adsorption capacity for heavy metals (Xu et al., 2013; Lima et al., 2015). Meng et al. (2014) reported increased adsorption for Cu (II) metal by sawdust-composted pig manure biochar pyrolyzed at 400°C. Wnetrzak et al. (2014) and Wang et al. (2018) also reported improved sorption of Cr (III) and Pb heavy metals, respectively, on various swine manure biochars. This is possibly due to the high P concentration on the surface of pig manure biochar that reacts with heavy metals to form insoluble metal phosphates, thereby immobilizing them for uptake or leaching into underground water/soil, thus reducing their potential toxicity (Liu et al., 2020).

7.6. Heavy metal content

Endogenous toxic heavy metals such as nickel (Ni), Cr, Pb, Cd, Al, and As have also been identified within the structure of carbonaceous materials and were essentially derived from the feedstock (Gunamantha and Widana 2018; Zhang, J.

et al., 2021; Edo 2023). These metals may accumulate and concentrate in the ash fraction during pyrolysis. Hydrochar produced from pig dung recorded varying concentrations of Pb, Cd, Cr, and As, depending on the temperature of carbonization (Song et al., 2020). Heavy metal concentrations in biocarbon were higher when produced under very high pyrolytic temperatures compared to low-temperature carbon. Again, the endogenous heavy metals in biochar are considered more stable than those from its manure source and therefore exhibit low bioavailability in soils (Cheng et al., 2018; Li et al., 2020). In a study investigating the contrasting effects of composting and pyrolysis on bioavailability and speciation of Cu and Zn in pig manure, heavy metals were less bioavailable in the manure-derived biochar compared to the original manure (Meng et al., 2017). Edo (2023) reported low concentrations of Pb (18.09 and 14.13 mg/kg) in pig manure-derived activated charcoal and biochar, respectively. The co-pyrolysis of the manure with PKS or waste plastic water sachet, however, recorded lower Pb concentrations in manure-PKS (15.55 and 10.89 mg/kg), and manure-plastic (12.78, and 10.08 mg/kg) derived activated charcoal and biochar respectively. The Cd, Hg, Al, and Ni concentrations were very low or untraceable. Gunamantha and Widana (2018) reported 7.28% and 13.65% Al_2O_3 in pig- and cow manure-derived biochar, respectively, indicating relatively very high values. The maximum allowable thresholds of heavy metals and other elements in biochar by the European Biochar Foundation (2012) are Pb <150 mg/kg, Cu <50 mg/kg, Zn <400 mg/kg, Ni <30 mg/kg, Cd <1.5 mg/kg, Ar <30 mg/kg, and Cr <90 mg/kg. This, therefore, suggests that biochar from swine manure is safe with reduced environmental risk.

7.7. CEC and EC

CEC of soil is a measure of its ability to absorb cation nutrients. Accordingly, Cely et al. (2014) reported that mineral soils generally have CEC values lower than 15 cmol_c/kg , while humic substances may have CEC values greater than 100 cmol_c/kg (Sposito, 1989). Soils with high CEC values are usually able to retain cationic nutrients such as K^+ and NH_4^+ in the root zone, thereby preventing nutrient leaching. Therefore, the addition of amendments with high CEC improves soil biogeochemical nutrient cycling and reduces the rate at which nutrients leach into the groundwater (Kuo et al., 2020). The pyrolysis of manures into biochar increases the CEC beyond the values in the manure feedstock, which converts it into a high-value product. This is due to the nutri-

ent-rich content of minerals, particularly Ca, K, P, Mg, and Na, in the dung biomass, which promotes the formation of oxygen-containing functional groups on the biochar surface during pyrolysis (Cely et al., 2015; Domingues et al., 2017; Borhan et al., 2018). For example, Sarfaraz et al. (2020) reported 170.00, 117.50, and 127.50 cmol_c/kg for pig-, poultry-, and cow manure-derived biochar, respectively. Cely et al. (2014) reported a CEC of 35 cmol_c/kg for a swine slurry-derived biochar, while Zornoza et al. (2016) reported a 46.1 cmol_c/kg from pig manure-derived biochar produced at 300°C. High-CEC biochars can remediate disturbed ecosystems or wastelands, hence restoring plant growth (Ghosh and Maiti 2020). This is possible due to the increase in the presence of redox-active functional groups, which increases the availability and retention of nutrients, microbial activity, and exchangeable cations in such soils. A study conducted by Liu et al. (2018) reported a significant increase in the level of N (97%), K (66%), and total available P (90%) in a newly reclaimed coalmine sink due to biochar application. EC is a measure of the amount of total dissolved salts in the biochar. It is the amount of soluble alkaline cation content in a biochar (Zhang et al., 2020). Cely et al. (2015) reported EC values of 102 and 59 $\mu\text{S}/\text{cm}$ at 300°C and 500°C pyrolysis temperatures of biochar, respectively, in agreement with Hossain et al. (2011) who reported that the EC of biochar from sewage sludge decreases with increasing pyrolysis temperature. This is, however, in contrast to the reports of Zornoza et al. (2016) who reported increasing EC range values (2700–8010 $\mu\text{S}/\text{cm}$) of swine manure-derived biochar produced at increasing carbonization temperature ranges of 300–700°C. Similarly, biochar produced from sawdust-composted pig dung at a higher temperature (700°C) had higher EC (1835 $\mu\text{S}/\text{cm}$) than that (730–1655 $\mu\text{S}/\text{cm}$) produced at a lower temperature (400°C) (Meng et al., 2014). Sarfaraz et al. (2020), however, reported higher EC value for poultry manure-derived biochar (9.56 $\mu\text{S}/\text{cm}$) compared to pig- (4.08 $\mu\text{S}/\text{cm}$) and cattle manure-derived biochar (3.60 $\mu\text{S}/\text{cm}$), even though the values are much lower than those reported for dairy manure- (997–1025 $\mu\text{S}/\text{cm}$) and corn stover-derived biochar (286–327 $\mu\text{S}/\text{cm}$) at 1050°C under varying residence times (Borhan et al., 2018). The EC property of biochar confers on it the ability to function as an electron mediator in biochemical redox reactions and thus can transfer, accept, or store electrons between microbial species or systems (Sun, T. et al., 2017; Yuan et al., 2022). This is especially significant when considering the role of biochar in the mitigation of anthropogenic greenhouse gas emissions. For example, the ability of biochar to serve as a sink (electron acceptor) for H_2 ions during rumen

fermentation may inhibit the activities and proliferation of hydrogen-producing and methanogenic bacteria, thus limiting the production of methane as a by-product (Kolganova et al., 2023). This also improves digestive efficiency, while reducing energy loss in the form of methane (Teoh et al., 2019; Qomariyah et al., 2023). However, the exact mechanism of action remains to be elucidated through additional research.

8. Limitations, Prospects, and Future Research Perspectives

This study highlights the dual nature of pig manure as a valuable organic resource and a significant environmental liability. While thermochemical conversion of manure into biocarbon offers promising waste management and sustainability prospects by offering pathways for odor reduction, volume minimization, energy production, and nutrient recycling, several limitations, however, limit its full-scale adoption. A major constraint is the inconsistent and often poor characterization of manure-derived biocarbon. Variations in feed composition, pyrolysis temperature, and co-processing materials influence the resultant biochar properties. These inconsistencies complicate comparisons across studies and hinder standardization for agricultural or industrial applications. More so, the study primarily referenced data from specific regions such as Africa, China, USA, and a few EU countries. These contexts may not be entirely representative of global scenarios, especially in developing countries where pig farming conditions and resources can differ significantly. Again, the presence of endogenous heavy metals such as Pb, Cd, and Cr in biocarbon also raises concerns regarding environmental safety and long-term soil accumulation and toxicity. Future research should, therefore, focus on developing standardized protocols for the physicochemical characterization of swine manure and its pyrolyzed derivatives. This includes determining the influence of different feedstock blends, optimizing pyrolysis conditions, and post-processing treatments on biochar properties (Reza et al., 2020). Research into efficient and cost-effective conversion technologies is essential to make biocarbon production more accessible and viable for smallholder farmers in rural areas.

There is also a need to explore the interactions of biochar with the gut microbiome and soil microbial communities and its efficacy to sequester carbon, retain nutrient, and mitigate greenhouse gas emissions (Xu et al., 2021; Kolganova et al., 2023). More data is required to provide more insights on how biocarbon affects ecosystems and human health over time. Therefore, the expansion of longitudinal

field-based studies, particularly in regions like sub-Saharan Africa, where localized data is scarce, is critical in assessing its long-term effects on soil health, nutrient cycling, and livestock performance. This will drive the formulation of adaptable, context-specific policies and solutions for the sustainable valorization of pig manure. Overall, refining biochar production and utilization processes could transform pig manure from a pollution burden into a valuable asset for sustainable agriculture, energy, and climate resilience.

9. Conclusion

Disposing of large volumes of pig manure produced in pig farms has become a major environmental and pollution problem in many countries, and it is more predominant in technologically constrained and underdeveloped ones. Cost-effective low-tech approaches such as the thermal conversion of manure into valuable carbonaceous products, especially at small-scale farms, are possible. The solid char products are highly alkaline in pH, have moderate carbon contents, and are high in ash and elemental compositions, compared to their original manure, indicating their suitability as adsorbents in soil and feed amendments. Other physicochemical properties of biocarbon, like the surface area, pore volume, EC, and carbon content, create a rich microenvironment favorable for microbiome proliferation for improved soil or gut health. It could serve as a dietary supplement for improved livestock production and as a slow-release biofertilizer for remediation, anthropogenic greenhouse emission mitigation, and improvement of soils for agronomic benefits. The co-carbonization of swine manure with other carbon-rich materials or change in the pyrolysis conditions reportedly improved the quality characteristics of the char products and enhanced their industrial value. Thus, the thermal conversion of manure to biocarbon offers a significantly enhanced technique for the environmentally sustainable recycling of surplus and nutrient-rich on-farm manure and residue biomass for multipurpose operations in a rural economy.

References

- Abhishek, K., Shrivastava, A., Vimal, V., Gupta, A.K., Bhujbal, S.K., Biswas, J.K., Singh, L., Ghosh, P., Pandey, A., Sharma, P., Kumar, M., 2022. Biochar application for greenhouse gas mitigation, contaminants immobilization and soil fertility enhancement: A state-of-the-art review. *Science of the Total Environment* 853, 158562. <https://doi.org/10.1016/j.scitotenv.2022.158562>

- Adamsen, A.P., Nyord, T., Hafner, S., 2021. The stability of pH of acidified stored manure slurry. Advisory note from DCA-Danish Center for Food and Agriculture, Aarhus University, Aarhus, Denmark. 2021 https://pure.au.dk/portal/files/216960350/Fasts_ttelse_af_syrebehov_190521.pdf
- AgriFarming, 2023. Pig Waste Management and Sustainable Manure Utilization. <https://www.agrifarming.in/pig-waste-management-and-sustainable-manure-utilization>
- Al-Kindi, A., Schlecht, E., Schiborra, A., Joergensen, R.G., 2016. Effects of quebracho tannin extract (*Schinopsis balansae*) and activated charcoal on feed intake and digestibility by goats and their faecal microbial biomass. *Biological Agriculture & Horticulture* 32(3), 159–169. <https://doi.org/10.1080/01448765.2015.1108869>
- Amer, M., Elwardany, A., 2020. Biomass carbonization. In: AlQubeissi, M., El-kharouf, A., Soyhan, H.S. (Eds.). Renewable energy resources, challenges, and application. IntechOpen <https://doi.org/10.5772/intechopen.90480>
- Ananna, F.H., Amin, M.G.M., Islam, D., Ahmed, T., Ashrafuzzaman, M., Aziz, M.G., 2021. Groundwater contamination risks with manure-borne microorganisms under different land-application options. *Water Science and Engineering* 14(4), 314–322. <https://doi.org/10.1016/j.wse.2021.11.001>
- Anigbo, N.J., Okpokwasili, G.C., Ogugbue, C.J., 2021. The physicochemical characteristics of fresh and old pig dung collected from three pig farms in Port Harcourt metropolis. *GSC Biological and Pharmacological Sciences* 16(3), 013–018. <https://doi.org/10.30574/gscbps.2021.16.3.0254>
- Antal, M.J., Grønli, M., 2003. The art, science, and technology of charcoal production. *Industrial Engineering and Chemical Research* 42, 1619–1640. <https://doi.org/10.1021/ie0207919>
- Arif, Y., Singh, P., Siddiqui, H., Bajguz, A., Hayat, S., 2020. Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiology and Biochemistry* 156, 64–77. <https://doi.org/10.1016/j.plaphy.2020.08.042>
- Bedia, J., Peñas-Garzón, M., Gómez-Avilés, A., Rodríguez, J.J., Belver, C., 2018. A review of the synthesis and characterization of biomass-derived carbons for adsorption of emerging contaminants from water. *C – Journal of Carbon Research* 4(4), 63. <https://doi.org/10.3390/c4040063>
- Bernado, M., Lapa, N., Goncalves, M., Mendes, B., Pinto, F., Fonseca I., 2012. Physicochemical properties of char obtained in the co-pyrolysis of the waste mixture. *Journal of Hazardous Materials* 219–220, 196–202. <https://doi.org/10.1016/j.jhazmat.2012.03.077>
- Bolan, N., Hoang, S.A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., Joseph, S., Jung, S., Kim, K., 2022. Multiple applications of biochar beyond carbon storage. *International Materials Reviews* 67(2), 150–200. <https://doi.org/10.1080/09506608.2021.1922047>
- Borchard, N., Schirrmann, M., Cayuela, M.L., Kammann, C., Wrage-Mönnig, N., Estavillo, J.M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J.A., Novak, J., 2019. Biochar, soil and land-use interactions that reduce nitrate leaching and N₂O emissions: a meta-analysis. *Science of the Total Environment* 651, 2354–2364. <https://doi.org/10.1016/j.scitotenv.2018.10.060>
- Borhan, M.S., Rahman, S., Sarker, N.C., 2018. Characterizing corn and cattle manure-derived biochars relevant to their use as soil additives. *Transactions of the ASABE* 61(4), 1335–1349. <https://doi.org/10.13031/trans.12753>
- Brglez, S., 2021. Risk of toxic hydrogen sulfide concentrations on swine farms. *Journal of Cleaner Production* 312, 127746. <https://doi.org/10.1016/j.jclepro.2021.127746>
- Cantero, D., Jara, R., Navarrete, A., Pelaz, L., Queiroz, J., Rodríguez-Rojo, S., Cocero, M.J., 2019. Pretreatment processes of biomass for biorefineries: current status and prospects. *Annual Review of Chemical and Biomolecular Engineering* 10, 289–310. <https://www.annualreviews.org/doi/abs/10.1146/annurev-chembio-eng-060718-030354>
- Cao, T., Zheng, Y., Dong, H., 2023. Control of odour emissions from livestock farms: A review. *Environmental Research* 225, 115545. <https://doi.org/10.1016/j.envres.2023.115545>
- Catalano, A., Mariconda, A., D'Amato, A., Iacopetta, D., Ceramella, J., Marra, M., Saturnino, C., Sinicropi, M.S., Longo, P., 2024. Aldehydes: What We Should Know About Them. *Organics* 5(4), 395–428. <https://doi.org/10.3390/org5040021>
- Cely, P., Gascó, G., Paz-Ferreiro, J., Méndez, A., 2015. Agronomic properties of biochars from different manure wastes. *Journal of Analytical & Applied Pyrolysis* 111, 173–182. <https://doi.org/10.1016/j.jaap.2014.11.014>
- Cely, P., Tarquis, A.M., Paz-Ferreiro, J., Mendez, A., Gasco, G., 2014. Factors driving the carbon mineralization priming effect in a sandy loam soil amended with different types of biochar. *Solid Earth* 5, 585–594. <https://doi.org/10.5194/se-5-585-2014>
- Cheng, D., Gao, A., Cen, K., Zhang, J., Ca, X.Z., 2018. Investigation of biomass torrefaction based on three major

- components: Hemicellulose, cellulose, and lignin. *Energy Conversion and Management* 169, 228–237. <https://doi.org/10.1016/j.enconman.2018.05.063>
- Cheng, F., Bayat, H., Jena, U., Brewer, C.E. 2020. Impact of feedstock composition on pyrolysis of low-cost, protein- and lignin-rich biomass: A review. *Journal of Analytical and Applied Pyrolysis* 147, 104780. <https://doi.org/10.1016/j.jaap.2020.104780>
- Chmielewicz-Korzeniowska, A., Tymczyna, L., Wlazło, Ł., Trawińska, B., Ossowski, M., 2022. Emissions of gaseous pollutants from pig farms and methods for their reduction – A review. *Annals of Animal Science* 22(1), 89–107. <https://www.proquest.com/openview/432cfb6169f56136caa82c841acd75be/1?pq-origsite=gscholar&cbl=1976406>
- Cho, S., Hwang, O., Park, S., 2015. Effect of dietary protein levels on the composition of odorous compounds and bacterial ecology in pig manure. *Asian-Australasian Journal of Animal Sciences* 28(9), 13. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4554878/>
- Crombie, K., Masek, O., Sohi, S., Brownsort, P., Cross, A. 2013. The effect of pyrolysis conditions on biochar stability is determined by three methods. *GCB Bioenergy* 5, 122–131. <https://doi.org/10.1111/gcbb.12030>
- Dai, X., Karring, H., 2014. A determination and comparison of urease activity in the feces and fresh manures of pigs and cattle in relation to ammonia production and pH changes. *Plos One* 9(11), e110402. <https://doi.org/10.1371/journal.pone.0110402>
- Deenik, J.L., McClellan, T., Uehara, G., Antal, M.J., Campbell, S., 2010. Charcoal volatile matter content influences plant growth and soil nitrogen transformations. *Soil Science Society of America Journal* 7, 1259–1270. <https://doi.org/10.2136/sssaj2009.0115>
- Ding, H., Zhang, Q., Zu, H., Vu, X., Chen, L., Wang, Z., Fang, J., 2021. Selection of copper and zinc, dosages in pig diets based on mutual protection. *Ecotoxicology and Environmental Safety* 216, 112177. <https://doi.org/10.1016/j.ecoenv.2021.112177>
- Domingues, R. R., Trugilho, P.F., Silva, C.A., de Melo, I.C.N.A., Melo, L.C.A., Magriotis, Z.M., Sanchez-Monedero, M.A., 2017. Properties of biochar derived from wood and high-nutrient biomass with the aim of agronomic, and environmental benefits. *PLoS ONE* 12, e0176884. <https://doi.org/10.1371/journal.pone.0176884>
- Ebc, H., 2012. European biochar certificate–guidelines for a sustainable production of biochar. European Biochar Foundation (EBC), Arbaz, Switzerland.
- Edo, F.A., 2023. Assessment of the socioenvironmental impacts of pig production and development of value-added products from piggery waste. PhD Thesis, Federal University of Technology Owerri, Nigeria.
- Edo, F.A., Ihejirika, C.E., Okoli, C.G., Okoli, I.C., 2021a. Sociocultural and production practices of pig farmers in relation to waste generation and disposal challenges in Imo state, Nigeria. *International Journal of Agriculture and Rural Development* 24(2), 6020–6030. [https://www.ijard.com/journalarticles/Vol%2024\(2\)%202021/37%20Socio-Cultural%2C%20and%20Production%20Practices%20of%20Pig%20Farmers%20in%20Relation%20to%20Waste%20Generation%20and%20Disposal%20Challenges%20in%20Imo%20State%2C%20Nigeria.pdf](https://www.ijard.com/journalarticles/Vol%2024(2)%202021/37%20Socio-Cultural%2C%20and%20Production%20Practices%20of%20Pig%20Farmers%20in%20Relation%20to%20Waste%20Generation%20and%20Disposal%20Challenges%20in%20Imo%20State%2C%20Nigeria.pdf)
- Edo, F.A., Ihejirika, C.E., Okoli, C.G., Okoli, I.C., 2021b. Sociocultural and environmental impact of pig farming on nearby residents in Imo state, Nigeria. *Nigerian Journal of Animal Science and Technology* 4(3), 93–104. <http://njast.com.ng/index.php/home/article/view/162>
- Enyiukwu, D.N., Bassey, I.N., Nwaogu, G. A., Asamudo, N.U., Chukwu, L.A., Monday, E.A., Maranzu, J.O. 2021. Pig (*Sus scrofa domesticus*) dung and their associated fungi: Potential candidates for bioremediation and nutrient improvement of crude oil contaminated soils. *Biodiversitas* 22(8), 3276–3286. <https://doi.org/10.13057/biodiv/d220822>
- Ewuziem, E., 2021. Pollution and resource use efficiency among pig farmers in Imo state, Nigeria (Thesis). Repository.mouau.edu.ng. <https://repository.mouau.edu.ng/work/view/pollution-and-resource-use-efficiency-among-pig-farmers-in-imo-state-nigeria-7-2>
- FAOSTAT, 2023. Crops and livestock products. Food and Agriculture Organization of the United Nations, Rome, Italy. <https://www.fao.org/faostat/en/#data/QCL>
- Gaillard, C., Brossard, L., Dourmad, J., 2020. Improvement of feed and nutrient efficiency in pig production through precision feeding. *Animal Feed Science and Technology* 268, 114611. <https://doi.org/10.1016/j.anifeeds-ci.2020.114611>
- Ghosh, D., Maiti, S.K., 2020. Can biochar reclaim coal mine spoil? *Journal of Environmental Management* 272, 111097. <https://doi.org/10.1016/j.jenvman.2020.111097>
- Gunamantha, I.M., Widana, G.A.B., 2018. Characterization of the potential of biochar from cow and pig manure for geo-ecology application. *IOP Conference Series: Earth and Environmental Science* 131(1), 012055. <https://iopscience.iop.org/article/10.1088/1755-1315/131/1/012055>

- Guo, J., Zheng, L., Li, Z., Zhou, X., Cheng, S., Zhang, L., Zhang, Q., 2021. Effects of various pyrolysis conditions and feedstock compositions on the physicochemical characteristics of cow manure-derived biochar. *Journal of Cleaner Production* 311, 127458. <https://doi.org/10.1016/j.jclepro.2021.127458>
- Guo, P., Zhao, X., Feng, Q., Yang, Y., 2023. Branchwood properties of two *Tilia* species collected from natural secondary forests in Northeastern China. *Forests* 14(4), 760. <https://doi.org/10.3390/f14040760>
- He, C., Zhang, Z., Ge, C., Liu, W., Tang, Y., Zhuang, X., Qiu, R., 2019. Synergistic effect of hydrothermal co-carbonization of sewage sludge with fruit and agricultural wastes on hydrochar fuel quality and combustion behavior. *Waste Management* 100, 171–181. <https://doi.org/10.1016/j.wasman.2019.09.018>
- He, L. Y., He, L. K., Liu, Y. S., Zhang, M., Zhao, J. L., Zhang, Q. Q., Ying, G. G., 2019. Microbial diversity and antibiotic resistome in swine farm environments. *Science of the Total Environment* 685, 197–207. <https://doi.org/10.1016/j.scitotenv.2019.05.369>
- Heidainejad, Z., Dehghani, M. H., Heidari, M., Javedan, G., Ali, I., Sillanpää, M., 2020. Methods for preparation and activation of activated carbon: A review. *Environmental Chemistry Letters* 18, 393–415. <https://doi.org/10.1007/s10311-019-00955-0>
- Hidayu, A. R., Muda, N., 2016. Preparation of impregnated activated carbon from palm kernel shell and coconut shell for CO₂ capture. *Procedia Engineering* 148, 106–113. <https://doi.org/10.1016/j.proeng.2016.06.463>
- Hirunpraditkoon, S., Tunthong, N., Ruangchai, A., Nuithitku, K., 2011. Adsorption capacities of activated carbons prepared from bamboo by KOH activation. *World Academy of Science, Engineering, and Technology* 78, 711–715. <https://doi.org/10.5281/zenodo.1055445>
- Ho, S. M., 2022. A review of chemical activating agents on the properties of activated carbon. *International Journal of Chemistry and Research* S1(1), 1–13. <https://mail.madridge.org/journal-of-chemistry-and-research/special-issue/ijcr-s1-001.pdf>
- Hossain, M. K., Strezov, V., Chan, K. Y., Ziolkowski, A., Nelson, P. F., 2011. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management* 92(1), 223–228. <https://doi.org/10.1016/j.jenvman.2010.09.008>
- Huang, X., Jiang, Y., Yu, R., 2021. Popped rice biochar and superhydrophobic SiO₂ / Popped rice biochar for oil adsorption. *Silicon* 13, 2661–2669. <https://doi.org/10.1007/s12633-020-00621-z>
- Ipiates, R. P., Mohedano, A. F., Diaz-Portuondo, E., Diaz, E., De la Rubia, M. A., 2023. Co-hydrothermal carbonization of swine manure and lignocellulosic waste: a new strategy for the integral valorization of biomass wastes. *Waste Management* 169, 267–275. <https://doi.org/10.1016/j.wasman.2023.07.018>
- Iregbu, G. U., 2014. Evaluation of the energy and combustion value of pig dung in its pure and combustion accelerants blended states. MSc Thesis: Department of Animal Science Technology, Federal University of Technology Owerri, Imo State, Nigeria.
- Iwanow, M., Gärtner, T., Sieber, V., König, B., 2020. Activated carbon as catalyst support: Precursors, preparation, modification, and characterization. *Beilstein Journal of Organic Chemistry* 16, 1188–1202. <https://doi.org/10.3762/bjoc.16.104>
- Jakobsen, L. K., Andersson, K. E., Norregaard, R., Olsen, L. H., 2019. Urine composition in pigs is regulated in both the ureter and the bladder. *Physiological Research* 68, 785–792. <https://doi.org/10.33549/physiolres.934086>
- Jha, R., Foughse, J. M., Tiwari, U. P., Li, L., Willing, B. P., 2019. Dietary fiber and intestinal health of monogastric animals. *Frontiers in Veterinary Science* 6, 48. <https://doi.org/10.3389/fvets.2019.00048>
- Jiang, B., Lin, Y., Mbog, J. C., 2018. Biochar derived from swine manure digestate and applied on the removals of heavy metals and antibiotics. *Bioresource Technology* 270, 603–611. <https://doi.org/10.1016/j.biortech.2018.08.022>
- Kadurumba, C., Kadurumba, O. E., Enekwachi, M. E., 2019. Piggery waste management practices and environmental implication on human health in Rivers State, Nigeria. *International Journal of Agricultural and Rural Development* 22(1), 4161–4166.
- Kim, S. W., Gormley, A., Jang, K. B., Duarte, M. E., 2023. Current status of global pig production: an overview and research trends. *Animal Bioscience* 37(4), 719. <https://doi.org/10.5713/ab.23.0367>
- Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M. H., Soja, G., 2012. Characterization of slow pyrolysis biochars: effects of feedstocks and pyrolysis temperature on biochar properties. *Journal of Environmental Quality* 41(4), 990–1000. <https://doi.org/10.2134/jeq2011.0070>
- Kolganova, A., Lal, R., Firkins, J., 2023. Biochar's Electrochemical Properties Impact on Methanogenesis: Ruminant vs. Soil Processes. *Journal of Agricultural Chemistry and*

- Environment 12(1), 28–43. <https://doi.org/10.4236/jacen.2023.121003>
- Kowalski, Z., Makara, A., Fijorek, K., 2013. Changes in the properties of pig manure slurry. *Acta Biochimica Polonica* 60(4), 845–850. https://doi.org/10.18388/abp.2013_2070
- Kroninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., Briones, M.J.I., 2021. Manure management and soil biodiversity: Toward more sustainable food production system in EU. *Agricultural Systems* 194, 103251. <https://doi.org/10.1016/j.agry.2021.103251>
- Kumar, A., Bhattacharya, T., Mukherjee, S., Sarkar, B., 2022. A perspective on biochar for repairing damages in the soil–plant system caused by climate change-driven extreme weather events. *Biochar* 4(1), 22. <https://doi.org/10.1007/s42773-022-00148-z>
- Kumaragamage, D., Akinremi, O.O., Racz, G.J., 2016. Comparison of nutrient and metal loadings with the application of swine manure slurries and their liquid separates to soils. *Journal of Environmental Quality* 45(5), 1769–1775. <https://doi.org/10.2134/jeq2016.04.0130>
- Kuo, Y. L., Lee, C.H., Jien, S.H., 2020. Reduction of nutrient leaching potential in coarse-textured soil by using biochar. *Water* 12(7), 2012. <https://doi.org/10.3390/w12072012>
- Lan, W., Yao, C., Lou, F., Jin, Z., Lu, S., Li, J., Wang, X., Hu, A., 2022. Effects application of pig manure on the accumulation of heavy metals in rice. *Plants* 11(2), 207. <https://doi.org/10.3390/plants11020207>
- Lee, S.A., Lopez, D.A., Stein, H.H., 2023. Mineral composition and phosphorus digestibility in feed phosphates fed to pigs and poultry. *Animal Bioscience* 36(2), 167–174. <https://doi.org/10.5713/ab.22.0322>
- Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., Jiang, S., Li, H., Huang, H., 2021. An overview on engineering the surface area and porosity of biochar. *Science of the Total Environment* 763, 144204. <https://doi.org/10.1016/j.scitotenv.2020.144204>
- Lentz, Z., Kolar, P., Classen, J.J., 2019. Valorization of swine manure into hydrochars. *Processes* 7(9), 560. <https://doi.org/10.3390/pr7090560>
- Li, C., Xie, S., Wang, Y., Pan, X., Yu, G., Zhang, Y., 2020b. Simultaneous heavy metal immobilization and antibiotics removal during synergistic treatment of sewage sludge and pig manure. *Environmental Science and Pollution Research*, 27 30323–30332. <https://doi.org/10.1007/s11356-020-09230-0>
- Li, C., Zhang, C., Gao, G., Gholizadeh, M., Zhang, S., Xu, L., Zhang, L., Li, Q., Hu, X., 2020a. Interaction of volatile from co-pyrolysis of pig manure with cellulose/glucose and their effects on char properties. *Journal of Environmental Chemical Engineering* 8(6), 104583. <https://doi.org/10.1016/j.jece.2020.104583>
- Li, F., Wu, X., Ji, W., Gui, X., Chen, Y., Zhao, J., Zhou, C., Ren, T., 2020. Effects of pyrolysis temperature on properties of swine manure biochar and its environmental risks of heavy metals. *Journal of Analytical and Applied Pyrolysis*, 152, 104945. <https://doi.org/10.1016/j.jaap.2020.104945>
- Lim, J., Yang, S.H., Kim, B.S., Lee, E.Y., 2018. Comparison of microbial communities in swine manure at various temperatures and storage time. *Asian-Australian Journal of Animal Science* 31(8), 1373–1380. <https://doi.org/10.5713%2Fajas.17.0704>
- Lima, I., Ro, K., Reddy, G., Boykin, D., Klasson, K., 2015. Efficacy of chicken litter and wood biochars and their activated counterparts in heavy metal clean up from wastewater. *Agriculture* 5(3), 806–825. <https://doi.org/10.3390/agriculture5030806>
- Liu, Y., Wang, F., Yin, Z., Jia, W., Xiao, H., Lin, Q., Feng, Y., 2020. Immobilization of lead and cadmium in soil using biochars derived from pig manure and Suaeda glauca. *Bulletin of Environmental Contamination and Toxicology*, 105, 146–154. <https://doi.org/10.1007/s00128-020-02886-x>
- Liu, Y., Zhu, J., Ye, C., Zhu, P., Ba, Q., Pang, J., Shu, L., 2018. Effects of biochar application on the abundance and community composition of denitrifying bacteria in a reclaimed soil from coal mining subsidence area. *Science of the Total Environment* 625, 1218–1224. <https://doi.org/10.1016/j.scitotenv.2018.01.003>
- Lonappan, L., Rouissi, T., Liu, Y., Brar, S. K., Surampalli, R.Y., 2019. Removal of diclofenac using microbiobiochar fixed-bed column bioreactor. *Journal of Environmental Chemical Engineering* 7(1), 102894. <https://doi.org/10.1016/j.jece.2019.102894>
- Machete, J.B., Chabo, R.G., 2020. A review of piggery manure management: Generally, across Western, Asian, and African countries. *Botswana Journal of Agriculture and Applied Sciences* 14(1), 17–27. <https://bojaas.buan.ac.bw/index.php/jaas/article/view/17>
- Makara, A., Kowalski, Z., 2018. Selection of pig manure management strategies: A case study of Polish farms. *Journal of Cleaner Production* 172, 187–195. <https://doi.org/10.1016/j.jclepro.2017.10.095>
- Malyan, S.K., Kumar, S.S., Fagodiya, R.K., Ghosh, P., Kumar, A., Singh, R., Singh, L., 2021. Biochar for environmental sustainability in the energy-water-agroecosystem

- nexus. *Renewable and Sustainable Energy Reviews* 149, 111379. <https://doi.org/10.1016/j.rser.2021.111379>
- Man, K.Y., Chow, K.L., Man, Y.B., Mo, W.Y., Wong, M.H., 2021. Use of biochar as feed supplements for animal farming. *Critical Reviews in Environmental Science and Technology* 51(2), 187–217. <https://doi.org/10.1080/10643389.2020.1721980>
- Marszelek, M., Kowalski, Z., Makara, A., 2019. The possibility of contamination of the water-soil environment as a result of the use of pig slurry. *Ecological Chemistry and Engineering Science* 26(2), 313–330. <https://intapi.sciendo.com/pdf/10.1515/eces-2019-0022>
- Mateos, G.G., Corrales, N.L., Talegón, G., Aguirre, L., 2024. Pig meat production in the European Union-27: Current status, challenges, and future trends. *Animal Bioscience* 37(4), 755. <https://doi.org/10.5713/ab.23.0496>
- Meng, J., Feng, X., Dai, Z., Liu, X., Wu, J., Xu, J., 2014. Adsorption characteristics of Cu (II) from aqueous solution onto biochar derived from swine manure. *Environmental Science and Pollution Research* 21, 7035–7046. <https://doi.org/10.1007/s11356-014-2627-z>
- Meng, J., Wang, L., Zhong, L., Liu, X., Brookes, P.C., Xu, J., Chen, H., 2017. Contrasting effects of composting and pyrolysis on bioavailability and speciation of Cu and Zn in pig manure. *Chemosphere* 180, 93–99. <https://doi.org/10.1016/j.chemosphere.2017.04.009>
- Mia, S., Singh, B., Dijkstra, F.A., 2017. Aged biochar affects gross nitrogen mineralization and recovery: a 15 N study in two contrasting soils. *GCB Bioenergy* 9(7), 1196–1206. <https://doi.org/10.1111/gcbb.12430>
- Míguez, J. L., Porteiro, J., Behrendt, F., Blanco, D., Patiño, D., Dieguez-Alonso, A., 2021. Review of the use of additives to mitigate operational problems associated with the combustion of biomass with high content in ash-forming species. *Renewable and Sustainable Energy Reviews* 141, 110502. <https://doi.org/10.1016/j.rser.2020.110502>
- Mopoung, S., Dejang, N., 2021. Activated carbon preparation from eucalyptus wood chips using continuous carbonization-steam activation process in a batch intermittent rotary kiln. *Scientific Report* 11, 13948 (2021). <https://doi.org/10.1038/s41598-021-93249-x>
- Mpendulo, T., Chimonyo, M., Ndou, S.P., Bakare, A.G., 2018. Fiber source and inclusion level affect characteristics of excreta from growing pigs. *Asia-Australia Journal of Animal Science* 31(5), 755. <https://doi.org/10.5713/2Fajas.14.0611>
- Mukome, F.N., Buelow, M.C., Shang, J., Peng, J., Rodriguez, M., Mackay, D.M., Pignatello, J.J., Sihota, N., Hoelen, T.P., Parikh, S.J., 2020. Biochar amendment as a remediation strategy for surface soils impacted by crude oil. *Environmental Pollution* 265, 115006. <https://doi.org/10.1016/j.envpol.2020.115006>
- Nasir, M.I., Hossain, M.Z., Charpentier, P.A. 2018. Synthesis and Characterization of Date Palm Fiber-Based Bio-Char and Activated Carbon and its Utilization for Environmental Remediation. *Journal of Petroleum Research and Studies* 8(2), 209–222. <https://www.iasj.net/iasj/download/9490ba1c55d66f89>
- Navarro, D.M., Bruininx, E.M., de Jong, L., Stein, H.H., 2018. Effects of physicochemical characteristics of feed ingredients on the apparent total tract digestibility of energy, DM, and nutrients by growing pigs. *Journal of Animal Science* 96(6), 2265–2277. <https://doi.org/10.1093/jas/sky149>
- Nguyen, H.N., Pignatello, J.J., 2013. Laboratory tests of biochars as absorbents for use in recovery or containment of marine crude oil spills. *Environmental Engineering Science* 30(7), 374–380. <https://doi.org/10.1089/ees.2012.0411>
- Ngwabie, N.M., Wirten, Y.L., Yinda, G.S., Vanderzaag, A.C., 2018. Quantifying greenhouse gas emissions from municipal solid waste dumpsites in Cameroun. *Waste Management* 87, 947–953. <https://doi.org/10.1016/j.wasman.2018.02.048>
- Ohanaka A.U.C., 2022. Morpho-physiological responses and performance of chicken fed activated charcoal-palm sap (ACAPS) supplemented diets. PhD Thesis, Federal University of Technology, Owerri, Nigeria.
- Ohanaka, A.U.C., Ukonu, E.C., Ogbuewu, I.P., Etuk, I.F., Okoli, I.C., 2021. Evaluation of the physic-chemical properties of agro-waste derived activated charcoal as potential feed additives in livestock production. *International Journal of Agriculture and Rural Development* 24(1), 5711–5719. <https://www.ijard.com/Vol%2024%20No1%202021>
- Okey, S.N., Ogbu, C.C., Okoli, I.C., Okey, O.N., Akpa, C.A.N., Afolabi, K.D., Udo, U.J., 2022. Effect of dietary inclusion of agricultural waste-derived activated charcoal on hematological and serum biochemical indices of layer chickens. *Asian Journal of Research in Animal and Veterinary Sciences* 10(4), 11. <http://go7publish.com/id/eprint/1626/1/220-Article%20Text-385-1-10-20221119.pdf>
- Okoli, C.G., Edo, F.A., Ogbuewu, I.P., Nwajiobi, I.J., Enemor, V.H.A., Okoli, I.C., 2019. Biochemical Values of Pig Dung Collected from Different Locations in Imo state, Southern Nigeria. *Asian Journal of Biological Science* 12, 470-476. <https://scialert.net/fulltext/?doi=ajbs.2019.470.476&org=12>

- Okoli, I.C., 2021a. Activated charcoal 1: Historical overview, current, and future uses. <https://researchtropica.com/activated-charcoal-1-historical-overview-current-and-future-uses/>. Accessed 22/9/2021.
- Okoli, I.C., 2021b. Activated charcoal 3: Production from biomass wastes. <https://researchtropica.com/activated-charcoal-3-production-from-biomass-wastes/>. Accessed 22/9/2021.
- Okoli, I.C., Alachie, D.A., Okoli, C.G., Akano, E.C., Ogundu, U.E., Akujobi, C.T., Onyicha, I.D., Chinweze, C.E., 2007. Aerial pollutant gases concentrations in tropical pig pen environment in Nigeria. *Nature and Science* 4(4), 1–5. <https://scialert.net/fulltext/?doi=rjes.2007.110.115>
- Okoli, I.C., Alaoma, O.R., Opara, M.N., Uchegbu, M.C., Ezeokeke, C.T., Durunna, C.S., Nnadi, F.N., Iheukwumere, F.C., Okeudo, N.J., 2009. Sociocultural characteristics of educated smallholder pig farmers and the effects of their feeding practices on the performance of pigs in Imo State, Nigeria. *Report and Opinion* 1(4), 59–65. <http://www.sciencepub.net/report/0104/report0104.pdf#page=62>
- Okoli, I.C., Nwogu, C.M., Etuk, I.F., Omede, A.A., Ogbuewu, I.P., Aladi, N.O., Okoro, V.M.O., Opara, M.N., Ezema, C., Uchegbu, M.C., Madubuike, F.N., 2014. Plantain ash enhances dietary mineral element absorption in pullets. *Iranian Journal of Applied Animal Science* 4(2), 351–360. https://journals.iaui.ir/article_513683.html
- Okoli, I.C., Uchegbu, M.C., Alaoma, O.R., Omede, A.A., Opara, M.N., Ekenyem, B.U., 2011. Compositional and biochemical characteristics of grower pig rations compounded by smallholder pig farmers in Imo State, Nigeria. *Proceedings of the 3rd International Conference on Sustainable Animal Agriculture for Developing Countries*, July 26–29, 2011, Nakhon Ratchasima Thailand. <https://www.cabidigitallibrary.org/doi/pdf/10.5555/20113387219>
- Okorogbona, A., Adebisi, L.O., 2012. Animal manure for smallholder agriculture in South Africa. In: Lichtfouse, E. (Ed.). *Farming for Food and Water Security. Sustainable Agriculture Review*, 10 Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4500-1_9
- Osman, A.I., Fawzy, S., El-Azazy, M.F.M., Elgarahy, A.M., Fahim, R.A., Abdel Maksoud, M.I.A., Ajlan, A.A., Yousry, M., Saleem, Y., Rooney, D.W., 2022. Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: A review. *Environmental Chemistry Letters* 20, 2385–2485. <https://doi.org/10.1007/s10311-022-01424-x>
- Paradeca, F., Pinto, F., Gulyurtlu, I., Cabrita, I., Lapa, N., 2009. Study of the copyrolysis of biomass and plastic wastes. *Clean Technologies and Environmental Policy* 11(1), 115–122. <https://doi.org/10.1007/s10098-008-0176-1>
- Qiu, J., Souza, M., Robles Aguilar, A. A., Ghysels, S., Ok, Y.S., Ronsse, F., Meers, E., 2022. Improving biochar properties by co-pyrolysis of pig manure with bioinvasive weed for use as the soil amendment. *Chemosphere* 312(Pt 1), 137229. <https://doi.org/10.1016/j.chemosphere.2022.137229>
- Qomariyah, N., Ella, A., Ahmad, S.N., Yusriani, Y., Sholikin, M.M., Prihambodo, T.R., Retnani, Y., Jayanegara, A., Wina, E., Permana, I.G., 2023. Dietary biochar as a feed additive for increasing livestock performance: A meta-analysis of in vitro and in vivo experiment. *Czech Journal of Animal Science* 68(2), 72–86. <https://www.agriculturejournals.cz/pdfs/cjs/2023/02/04.pdf>
- Radenahmad, N., Tasfiah, A., Saghir M., Taweekun, J., Saifullah, M., Bakar, A., Kalam, A., 2020. A review on biomass-derived syngas for SOFC-based combined heat and power application. *Renewable and Sustainable Energy Reviews* 119, 109560. <https://doi.org/10.1016/j.rser.2019.109560>
- Raj, K.G., Joy, P.A., 2015. Coconut shell-based activated carbon–iron oxide magnetic nanocomposite for fast and efficient removal of oil spills. *Journal of Environmental Chemical Engineering* 3(3), 2068–2075. <https://doi.org/10.1016/j.jece.2015.04.028>
- Rapatsa, M.M., Moyo, G., 2013. Performance evaluation of chicken, cow, and pig manure in the production of natural fish food in aquadams stocked with *Oreochromis mossambicus*. *Physics and Chemistry of the Earth, Parts A/B/C* 66, 68–74. <https://doi.org/10.1016/j.pce.2013.08.009>
- Rashid, A., Schutte, B.J., Ulery, A., Deyholos, M.K., Sanogo, S., Lehnhoff, E.A., Beck, L., 2023. Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. *Agronomy* 13(6), 1521. <https://doi.org/10.3390/agronomy13061521>
- Reza, M.S., Yun, C.S., Afroze, S., Radenahmad, N., Abu Bakar, M.S., Saidur, R., Taweekun, J., Azad, A.K., 2020. Preparation of activated carbon from biomass and its applications in water and gas purification. A review. *Arab Journal of Basic and Applied Sciences* 27(1), 208–238. <https://doi.org/10.1080/25765299.2020.1766799>
- Ro, K.S., Hunt, P.G., Jackson, M.A., Compton, D.L., Yates, S.R., Cantrell, Chang, S., 2014. Copyrolysis of swine manure with agricultural plastic waste: Laboratory-scale study. *Waste Management* 34(8), 1520–1528. <https://doi.org/10.1016/j.wasman.2014.04.001>

- Ro, K.S., Libra, J.A., Bae, S., Berge, N.D., Flora, J.R., V., Pacenka, R., 2019. Combustion behavior of animal-manure-based hydrochar and pyrochar. *A.C.S. Sustainable Chemistry and Engineering* 7, 470–478. <https://doi.org/10.1021/acssuschemeng.8b03926>
- Sarfaraz, O., da Silva, L.S., Drescher, G.L., Zafar, M., Severo, F.F., Kokkonen, A., Molin G.D., Shafi, M.I., Shafique, Z., Solaiman, Z., 2020. Characteristics and carbon mineralization of biochars produced from different animal manures and plant residues. *Scientific Report* 10, 955. <https://doi.org/10.1038/s41598-020-57987-8>
- Schmidt, H.P., Hagemann, N., Draper, K., Kammann, C., 2019. The use of biochar in animal feeding. *PeerJ* 7, e7373. <https://peerj.com/articles/7373/>
- Shah, M.S., Khan, M.N.S., Kumar, V., 2018. Biomass residue characterization for their potential application as biofuels. *Journal of Thermal Analysis and Calorimetry* 134, 2137–2145. <https://doi.org/10.1007/s10973-018-7560-9>
- Sharara, M.A., Sadaka, S.S., 2018. Opportunities and barriers to bioenergy conversion techniques and their potential implementation on swine manure. *Energies* 11(4), 957. <https://doi.org/10.3390/en11040957>
- Sharma, N.K., Choct, M., Wu, S., Swick, R.A., 2017. Nutritional effects on odour emissions in broiler production. *World's Poultry Science Journal* 73(2), 257–280. <https://doi.org/10.1017/S0043933917000046>
- Shi, W., Lian, W., Tian, S., Gong, X., Yu, Q., Guo, Z., Zhang, X., Ma, B., Bian, R., Zheng, J., Pan, G., 2023. A review of agronomic and environmental properties of inorganic compounds in biochars. *Current Research in Environmental Sustainability* 5, 100226. <https://doi.org/10.1016/j.crsust.2023.100226>
- Sohaimi, K.S.A., Ngadi, N., 2016. Removal of oil using activated carbon from textile sludge biochars. *Applied Mechanics and Materials* 818, 237–241. <https://doi.org/10.4028/www.scientific.net/AMM.818.237>
- Song, C., Yuan, W., Shan, S., Ma, Q., Zhang, H., Wang, X., Niazi, N.K., Wang, H., 2020. Changes of nutrients and potentially toxic elements during hydrothermal carbonization of pig manure. *Chemosphere* 243, 125331. <https://pubmed.ncbi.nlm.nih.gov/31995863/>
- Song, J.M., 2024. Emission characteristics of odorous compounds from a swine farm on Jeju island, Korea. *Atmosphere* 15(3), 327. <https://doi.org/10.3390/atmos15030327>
- Sposito, G., 1989. *The chemistry of soils*. Oxford University Press, New York.
- Statista, 2023. Leading countries in pork production in Africa 2020. <https://www.statista.com/statistics/1290476/production-volume-of-pork-meat-in-africa-by-countries/>
- Stefelová, J., Slovák, V., Siqueira, G., Olsson, R.T., Tingaut, P., Zimmermann, T., Sehaqui, H., 2017. Drying and pyrolysis of cellulose nanofibers from wood, bacteria, and algae for char application in oil absorption and dye adsorption. *ACS Sustainable Chemistry & Engineering* 5(3), 2679–2692. <https://doi.org/10.1021/acssuschemeng.6b03027>
- Sun, T., Levin, B.D.A., Guzman, J.J.L., Enders, A., Muller, D.A., Angenent, L.T., Lehmann, J., 2017. Rapid electron transfer by the carbon matrix in natural pyrogenic carbon. *Nature Communications* 8(1), 14873. <https://doi.org/10.1038/ncomms14873>
- Sun, X., Shan, R., Li, X., Pan, J., Liu, X., Deng, R., Song, J., 2017. Characterization of 60 types of Chinese biomass waste and resultant biochars in terms of their candidacy for soil application. *GCB Bioenergy* 9, 1423–1435. <https://doi.org/10.1111/gcbb.12435>
- Takaya, C.A., Fletcher, L.A., Singh, S., Okwuosa, U.C., Ross, A.B., 2016. Recovery of phosphate with chemically modified biochars. *Journal of Environmental Chemical Engineering* 4(1), 1156–1165. <https://doi.org/10.1016/j.jece.2016.01.011>
- Teoh, R., Caro, E., Holman, D.B., Joseph, S., Meale, S.J., Chaves, A.V., 2019. Effects of hardwood biochar on methane production, fermentation characteristics, and the rumen microbiota using rumen simulation. *Frontiers in Microbiology* 10, 1534. <https://doi.org/10.3389/fmicb.2019.01534>
- Tomczyk, A., Sokolowska, Z., Boguta, P., 2020. Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. Review in *Environmental Science and Technology* 19, 191–215. <https://doi.org/10.1007/s11157-020-09523-3>
- Trabue, S.L., Kerr, B.J., Scoggin, K.D., Andersen, D., Van Weelden, M., 2021. Swine diets impact manure characteristics and gas emissions: Part I protein level. *Science of the Total Environment* 755, 142528. <https://doi.org/10.1016/j.scitotenv.2020.142528>
- Tripathi, M., Sahu, J.N., Ganesan, P., 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Review* 55, 467–481. <https://doi.org/10.1016/j.rser.2015.10.122>
- Tripathi, N., Hills, C.D., Singh, R.S., Atkinson, C.J., 2019. Biomass waste utilization in low-carbon products: harnessing a major potential resource. *NJP Climate and Atmospheric Science* 2(1), 35. <https://doi.org/10.1038/s41612-019-0093-5>
- Trujillo, G.D., Borquez, G.J.L., Pinos-Rodriguez, J.M., Dominguez-Vara, I.A., Rojo, R.R., 2014. Nutritive value

- of ensiled pig excreta, poultry litter, or urea with molasses or bakery byproducts in diets for lambs. *South African Journal of Animal Science* 44(2), 114–122. <https://doi.org/10.4314/sajas.v44i2.3>
- Tsai, W.T., Liu, S.C., Chen, H.R., Chang, Y.M., Tsai, Y.L., 2012. Textural and chemical properties of swine-manure-derived biochar pertinent to its potential use as a soil amendment. *Chemosphere* 89(2), 198–203. <https://doi.org/10.1016/j.chemosphere.2012.05.085>
- Tullus, A., Mandre, M., Soo, T., Tullus, H., 2010. Relationships between cellulose, lignin, and nutrients in the stem wood of hybrid aspen in Estonian plantations. *Cellulose Chemistry & Technology* 44(4), 101. [https://www.cellulosechemtechnol.ro/pdf/CCT44,4-6\(2010\)/101-109.pdf](https://www.cellulosechemtechnol.ro/pdf/CCT44,4-6(2010)/101-109.pdf)
- Udebuani, A.C., Nwajiobi, I.J., Okoli, I.C., Ozor, P.T.E., 2018b. Proximate and elemental compositions of animal dung collected from Owerri, Southeast Nigeria. In: *Exploring Science and Technology: Innovations for Sustainable Livestock Development*. 43rd Annual Conference of the Nigerian Society for Animal Production, March 18–22, 2018, FUT Owerri, pp. 1439–1441. <https://njap.org.ng/index.php/njap/article/view/6586>
- Udebuani, A.C., Nwajiobi, I.J., Ozor, P.T.E., 2018a. Microbial loads and profiles of poultry, cattle and pig dung produced: In Owerri, Southeast Nigeria. In: *Exploring Science and Technology: Innovations for Sustainable Livestock Development*. Proceedings of 43rd Annual Conference of the Nigerian Society for Animal Production, March 18–22, 2018, FUT Owerri, pp. 1442–1444. <https://njap.org.ng/index.php/njap/article/view/6582>
- Udebuani, A.C., Okoli, I.C., Nwigwe, H.C., Ozoh, P.T.E., 2012. The value of animal manure in the enhancement of bioremediation processes in petroleum hydrocarbon contaminated agricultural soils. *Journal of Agricultural Technology* 8(6), 1935–1952. <https://www.cabidigitallibrary.org/doi/full/10.5555/20133001837>
- Vanotti, M.B., García-González, M.C., Szögi, A.A., Harrison, J.H., Smith, W.B., Moral, R., 2020. Removing and recovering nitrogen and phosphorus from animal manure. In: Waldrip, H.M., Pagliari, P.H., He, Z. (Eds.). *Animal manure: Production, characteristics, environmental concerns, and management* 67, 275–321. <https://doi.org/10.2134/adaspecpub67.c22>
- Vuppaladadiyam, A.K., Liu, H., Zhao, M., Soomro, A.F., Memon, M.Z., DuPont, V., 2019. Thermogravimetric and kinetic analysis to discern synergy during the co-pyrolysis of microalgae and swine manure digestate. *Biotechnology for Biofuels and Bioproducts* 12, 170. <https://doi.org/10.1186/s13068-019-1488-6>
- Wang, L., Li, D., 2024. Current status, challenges and prospects for pig production in Asia. *Animal Bioscience* 37(4), 742. <https://doi.org/10.5713/ab.23.0303>
- Wang, Y., Dong, H., Zhu, Z., Gerber, P. J., Xin, H., Smith, P., Opio, C., Steinfeld, H., Chadwick, D. 2017. Mitigating greenhouse gas and ammonia emissions from swine manure management: A system analysis. *Environmental Science and Technology* 51, 4503–4511. <https://doi.org/10.1021/acs.est.6b06430>
- Wnetrzak, R., Leahy, J.J., Chojnacka, K. W., Saeid, A., Novotny, E., Jensen, L.S., Kwapinski, W., 2014. Influence of pig manure biochar mineral content on Cr (III) sorption capacity. *Journal of Chemical Technology & Biotechnology* 89(4), 569–578. <https://doi.org/10.1002/jctb.4159>
- Wu, Q., Wang, H., Zheng, X., Liu, F., Wang, A., Zou, D., Yuan, J., Xiao, Z., 2020. Thermochemical liquefaction of pig manure: Factors influencing on oil. *Fuel* 264, 116884. <https://doi.org/10.1016/j.fuel.2019.116884>
- Xu, D., Wen, L., Xue, L., Jang, Z., 2014. Analysis of direct combustion characteristics of pig manure based on thermogravimetry. *Transactions of the Chinese Society of Agricultural Engineering* 30(5), 162–168. <https://www.cabidigitallibrary.org/doi/full/10.5555/20143179382>
- Xu, X., Cao, X., Zhao, L., 2013. Comparison of rice husk and dairy manure-derived biochars for simultaneously removing heavy metals from aqueous solutions: Role of mineral components in biochars. *Chemosphere* 92(8), 955–961. <https://doi.org/10.1016/j.chemosphere.2013.03.009>
- Xu, Z., He, M., Xu, X., Cao, X., Tsang, D.C., 2021. Impacts of different activation processes on the carbon stability of biochar for oxidation resistance. *Bioresource Technology* 338, 125555. <https://doi.org/10.1016/j.biortech.2021.125555>
- Yahya, M.A., Mansor, M.H., Zolkarnaini, W.A.A.W., Rusli, N.S., Aminuddin, A., Mohamad, K., Sabhan, F.A.M., Atik, A.A.A., Ozair, L.N., 2018. A brief review on activated carbon derived from agriculture byproducts. *AIP Conference Proceedings* 2018. <https://doi.org/10.1063/1.5041244>
- Yang, L., Huang, T., Jiang, X. X., Jiang, W., 2016. Effect of steam and CO₂ activation on characteristics and desulfurization performance of pyrolusite modified activated carbon. *Adsorption* 22, 1099–1107. <https://doi.org/10.1007/s10450-016-9832-7>
- Yargicoglu, E.N., Sadasivam, B.Y., Reddy, K.R., Spokas, K., 2015. Physical and chemical characterization of waste

- wood-derived biochar. *Waste Management* 36, 256–268. <https://doi.org/10.1016/j.wasman.2014.10.029>
- Yuan, J., Wen, Y., Dionysiou, D.D., Sharma, V.K., Ma, X., 2022. Biochar as a novel carbon-negative electron source and mediator: electron exchange capacity (EEC) and environmentally persistent free radicals (EPFRs): a review. *Chemical Engineering Journal* 429, 132313. <https://doi.org/10.1016/j.cej.2021.132313>
- Zhang, J., Li, C., Li, G., He, Y., Yang, J., Zhang, J., 2021. Effect of biochar on heavy metal bioavailability and uptake by tobacco (*Nicotiana tabacum*) in two soils. *Agriculture, Ecosystem and Environment* 317, 107453. <https://doi.org/10.1016/j.agee.2021.107453>
- Zhang, R.M., Liu, X., Wang, S. L., Fang, L. X., Sun, J., Liu, Y.H., Liao, X.P., 2021. Distribution patterns of antibiotic resistance genes and their bacterial hosts in pig farm wastewater treatment systems and soil fertilized with pig manure. *Science of the Total Environment* 758, 143654. <https://doi.org/10.1016/j.scitotenv.2020.143654>
- Zhang, X., Zhang, P., Yuan, X., Li, Y., Han, L., 2020. Effect of pyrolysis temperature and correlation analysis on the yield and physicochemical properties of crop residue biochar. *Bioresource Technology* 29, 122318. <https://doi.org/10.1016/j.biortech.2019.122318>
- Zhang, Y., Zhu, Z., Zheng, Y., Chen, Y., Yin, F., Zhang, W., Dong, H., Xin, H., 2019. Characterization of volatile organic compound (VOC) emissions from swine manure biogas digestate storage. *Atmosphere* 10(7), 411. <https://doi.org/10.3390/atmos10070411>
- Zhao, J., Bai, Y., Zhang, G., Liu, L., Lai, C., 2020. Relationship between dietary fiber fermentation and volatile fatty acids concentration in growing pigs. *Animals* 10(2), 263. <https://doi.org/10.3390/ani10020263>
- Zhao, L., Cao, X., Masek, O., Zimmerman, A., 2013. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials* 256, 1–9. <https://doi.org/10.1016/j.jhazmat.2013.04.015>
- Zubabri, N.A., Mohamed, A.R., Lahijani, P., Mohammadi, M., 2021. Low-temperature CO₂ capture on biomass-derived KOH-activated hydrochar established through hydrothermal carbonization with water-soaking pretreatment. *Journal of Environmental Chemical Engineering* 9(2), 105074. <https://doi.org/10.1016/j.jece.2021.105074>
- Wang, T., Sun, H., Ren, X., Li, B., Mao, H., 2018. Adsorption of heavy metals from aqueous solution by UV-mutant *Bacillus subtilis* loaded on biochars derived from different stock materials. *Ecotoxicology and Environmental Safety* 148, 285–292. <https://doi.org/10.1016/j.ecoenv.2017.10.039>
- Zornoza, R., Moreno-Barriga, F., Acosta, J.A., Muñoz, M.A., Faz, A., 2016. Stability, nutrient availability and hydrophobicity of biochars derived from manure, crop residues, and municipal solid waste for their use as soil amendments. *Chemosphere* 144, 122–130. <https://doi.org/10.1016/j.chemosphere.2015.08.046>