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Use of poultry manure as an alternative to inorganic fertilizer: A review of potential human and environmental health risks

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ABSTRACT

Poultry manure has excellent potential to reduce overdependence on inorganic fertilizers for crop production among resource-constrained farming communities. However, its use on a large scale could possess short- and long-term risks. These risks fall into three main categories, namely human and other livestock, crop health, and environmental. This review research presented the potential value of chicken manure in soil health and food security stability. The review also presented the critical risks, such as pathogen transmission, heavy metal accumulation, and nutrient runoff, that are likely to hinder the large-scale use of poultry manure. Finally, this research has intensively presented scientifically proven strategies that could be adapted and adopted to help mitigate the current risks. Active government involvement through formulating and enacting appropriate policies and laws provides the first step in risk mitigation. Other practices, such as manure treatment and the adoption of better agronomic practices, are essential and have proved to be critical for the safe use of poultry manure. Poultry manure has excellent potential to reduce overdependence on inorganic fertilizers. To do this effectively, appropriate policies and laws should be enacted to encourage the use of safe products in the poultry sector, proper manure collection, and treatment and use. Farmers should choose and apply manure within the best agronomic principles.

Keywords: Environmental risks, human health risks, poultry manure, organic farming, organic fertilizer, soil health

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1 Introduction

Soil infertility is the leading cause of low crop productivity, especially among developing nations, resulting in increased food insecurity. The current poor state of farms and the increased rate of nutrient mining has been extensively reviewed by Otieno (2021). Of all nutrients required for growth and production, crops exhibit a high response to N, followed by P and K, and micro-nutrients (Otieno, 2019). However, farmers have struggled to meet the crop demands for those nutrients mainly due to the elevated cost of inorganic fertilizers currently experienced worldwide. To improve the situation, using poultry manure or litter as a source of plant nutrients is a more practical option and can be incorporated into most agricultural nutrient management plans. The term ’poultry litter’ refers to any dry form of poultry manure, including all types of bedding material, as well as waste such as feathers, soil, spilled feed, and all excrement produced by the birds; it is not limited to just the feces of the birds (Locatelli et al., 2017). Manure that has a solids content of over 20% (by weight) is considered dry manure and is treated as a solid substance, while manure with a solids content between 10% to 20% is referred to as semi-solid manure and is typically managed as a liquid (Bicudo, 2009). Due to its relatively elevated nutrient content, especially N and P, poultry manure has huge potential to reduce overdependence on inorganic fertilizers in crop production, increase crop yields and improve food security among resource-constrained and hungry farming communities. However, the main challenge is maximizing the benefits of poultry litter as an organic fertilizer while mitigating potential negative impacts on the environment. Large-scale use of manure may possess short- and long-term risks to crops, humans, and the environment. For the benefit of farmers, those risks must be considered and mitigated. Hence, this review aimed to identify evidence of the potential benefits of using poultry manure in soil health and food security stability. Also, it identified the potential crop, human, livestock, and ecological/environmental health risks that could be associated with the use of poultry manure. Lastly, it recommended potential strategies that could be used to manage those risks under extensive adoption of poultry manure for crop production.

2 Importance of PM in crop production and food security

Like other organic manures, chicken manure is very important and plays both direct and indirect roles in food production and security. Indirectly, organic manure works to improve crop-growing soil environments. Organic manures bind with soil particles, thereby improving particle aggregation and soil structure (Guo et al., 2019; Chen et al., 2021). Significant improvement in soil aggregate stability (17%), 2-3 times greater infiltration rate, saturated hydraulic conductivity, increased field capacity, and plant available water content by 20% as a result of poultry litter application has been reported (Feng et al., 2021). In clay soils, organic manures open the particles and help in aeration for better root growth and soil acidity management (Muhieldeen et al., 2014; Rauber et al., 2018). According to Otieno et al. (2018), applying manure can moderately increase soil pH by forming complex compounds that reduce the levels of aluminum, manganese, and iron ions in the soil. The bonding ability of organic matter in both the solid and liquid phases with aluminum is the cause of the complexation by manure (Otieno et al., 2018). Such amelioration of soil acidity provides favorable conditions for crop growth and makes nutrients available for uptake. Manures may also indirectly improve crop production by increasing microbial activities, which assists in the release of plant nutrients in their available forms. Increased soybean nodulation due to manure application, which is an effect of rhizobia bacteria, has been reported (Otieno et al., 2018). Rhizobia bacteria is important and responsible for biological nitrogen fixation for legumes growth and production. Due to organic compost application, increased soil microbial activity, dehydrogenase enzyme activity, and gene copies of bacteria, archaea, and ammonia-oxidizing bacteria have been reported (Watts et al., 2010; Tian et al., 2015).

Additionally, poultry manure directly impacts crop production and food security by providing the much-needed macro (N, P, and K), secondary (S, Mg, and Ca), and trace (Zn, Pb, B, Cu, Cl, Fe, Mo, Ni, Mn, Co, Si, Cr) nutrients when applied. The nutritive quality of poultry manure/litter varies widely depending on feed type, bedding type, age of the chicken, sex, and production system (Van Horn, 1998; Ashworth et al., 2020). These nutrients become available to plants through the mineralization process, which is reported to be higher in poultry manure than other types of animal manure (Serna and Pomares, 1991). The highest nitrogen (N) and carbon mineralization rates are attained at about 90 days after poultry manure application (Sathya and Maheswari, 2017), although the bulk of organic N fraction is available and usable within 2-4 weeks after application (Ashworth et al., 2020). Generally, it is estimated that 50 to 60% of the organic-N in poultry litter becomes available through mineralization in the first year, with about 20% in the second year and 10% in the following year (Ashworth et al., 2020). With all these nutrients being made available for plant uptake, researchers have reported improved growth, development, and yields of various crops, including maize, beans, pepper, cassava, soybean, rice, spinach, melon, and sweet potatoes (Yeng et al., 2012; Ikeh et al., 2012; Enujeke, 2013; Biratu et al., 2018; Feng et al., 2021; Chen et al., 2021). Table 1 summarizes some selected research findings involving the impact of poultry manure on yields.

3 Health risks associated with the use of PM

The composition of poultry manure is influenced by the health status of the poultry, their age, and the type of feed given. Consequently, these manures have varying compositions and carry mineral and microbe components. Poultry manure enhances the multiplication and spread of nuisance flies in the house and compounds. Among those flies, the greatest nuisance includes Stable flies (*Stomoxys calcitrans* L.) and House flies (*Musca domestica* L) (Cook et al., 1999). Their breeding and population increase is associated with organic wastes, especially poultry manure and litter use. Research has shown that the use of poultry manure on the farm provides a favorable breeding for flies (1.5 and 0.2 million houseflies stable flies, respectively) from every hectare of poultry manure/litter applied as a surface pre-plant fertilizer (Watson et al., 1998; Cook et al., 1999).

Stomoxys calcitrans and *Musca domestica* L. are among the leading vectors of pathogens for human and livestock diseases. These insects obtain and trans-

Table 1. Summary of the effect of poultry manure/litter application on crop growth and yield

Country	Crops cultivated	Application rates (t/ha)	Crop yield increased (t/ha)	References
Nigeria	Pepper	6.0	17.03 vs. 8.22	Ikeh et al. (2012)
Nigeria	Watermelon	5.0	422.8 vs. 245.2	Enujeke (2013)
Zambia	Cassava	4.2	28.5 vs. 19.8	Biratu et al. (2018)
USA	Soybean	7.6	4.58 vs. 4.11	Feng et al. (2021)
China	Rice	0.45-0.90	12-16.6‡	Chen et al. (2021)
Botswana	Spinach	5-10†	42-300‡	Dikinya and Mufwanzala (2010)
Nigeria	Maize	10	4.8-6.31 vs. 0.38-0.64	Adeyemo et al. (2019)
Nigeria	Maize	8.0	2-3.47 vs. 0.72-1.36	Udom and Bello (2009)
Nigeria	Maize	5.0	2-2.19 vs. 0.85-0.95	Ayoola and Adeniyan (2006)
Nigeria	Melon	5.0	153-157 vs. 103-105.5	Ayoola and Adeniyan (2006)
Malawi	Maize	4.0	6.4 vs. 1.1	Ouma and Lelei (2017)
Ghana	Sweet potato	6.0	19-20 vs. 7-17.9	Yeng et al. (2012)
Nigeria	Cassava	5.0	23-24 vs. 10-14	Ayoola and Adeniyan (2006)

† w/w (%); ‡ values are percentage

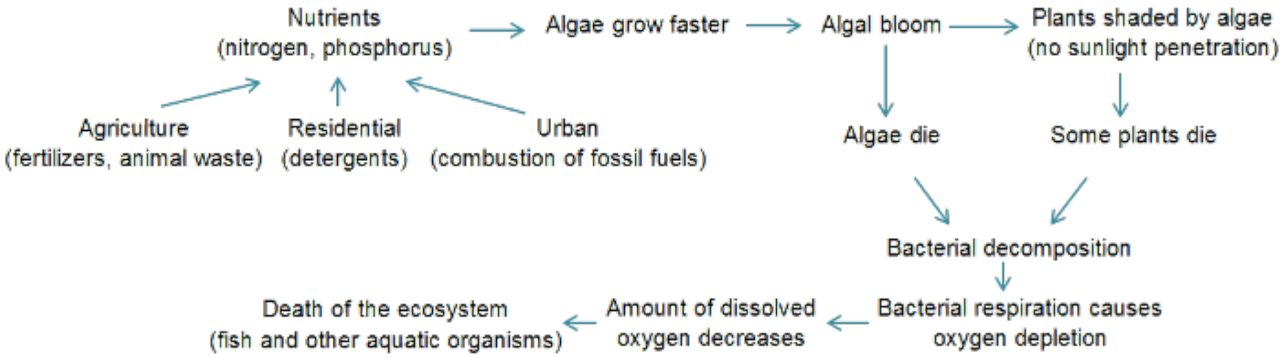

Figure 1. An overview of the eutrophication process and its causes and consequences. Source: Knockaert (2021)

Table 2. Fishery loss due to the impact of harmful algal blooms of some toxic algal species in different marine habitats (Dorgham, 2014)

Species	Year	Area	Loss	Type of loss
Chattonella antiqua	1972	Seto Inland Sea	Fish	60 × 10^6 US$
Chattonella antiqua	1979– 2004	Seto Inland Sea	Fish	100 × 10^6 Yen
Heterocapsa circularisquama	1998	Seto Inland Sea	Oysters	3.9 × 10^9 Yen
Gonyaulax polygramma	1994	Seto Inland Sea	Fishery	80 × 10^6 Yen
C. polykrikoides	2000	Yatsushiro Sea	Fishery	4 × 10^9 Yen
C. polykrikoides	1995	Korean coastal waters	Fishery	76.4 × 10^9 Won

port many pathogens on their mouthparts and legs (Williams, 2009). For instance, adult houseflies are mechanical vectors of more than 100 devastating diseases that severely affect human and animal health (Scott et al., 2014). Therefore, any slight increase in their population around the homestead could increase the chances of diseases outbreak. Using untreated poultry manure from unhealthy flocks could also lead to antibiotic-resistant pathogens. Considering the increased use of antibiotics in poultry rearing, large quantities of those drugs, resistant bacteria, and other pathogens are excreted with the fecal matter. Eventually, those pathogens get into human and other livestock bodies through drinking contaminated water and foods after manure application leading to increased resistance to current drugs used for treatment. Resistant *Salmonella*, *Escherichia coli*, *Enterococci*, *Staphylococci*, and other bacteria have been reported (Kyakuwaire et al., 2019; Ngogang et al., 2020).

Along with feed additives, certain metals such as As, Co, Cu, Cr, Fe, Mn, Se, and Zn are added to prevent illnesses, enhance weight gain, improve feed efficiency, and raise egg production (Miller et al., 1991). Unfortunately, some of those elements are classified as heavy metals and could have detrimental health impacts on humans and livestock (Balali-Mood et al., 2021). The heavy metal components are passed out with fecal matter, which then gets into the crops through root absorption and eventually accumulates in the system. The metals will eventually enter human and animal bodies during the food chain, posing significant potential health threats (Sprynskyy et al., 2007). The build-up of heavy metals in plants depends on the type of plant and its ability to absorb the metals, which can be assessed through the plant's uptake of the metals or by determining the soil-to-plant transfer factors of the metals (Khan et al., 2008; Singh and Kalamdhad, 2011). The absorption of heavy metals by plants and their subsequent build-up in the food chain poses a potential risk to animal and human health. In some countries, food crops have been found to accumulate high concentrations of metals (such as., Cu= 0.81-247 mg/kg and Cr= 0.18-9.81 mg/kg) exceeding the levels set by regulating bodies after application of manure (Muhammad et al., 2020). The absorption and high build-up of Cd, Cu, Ni, Zn, Cr, Mn, and Pb have been reported in commonly consumed vegetables, including *Beta vulgaris* (Spinach) (Sharma et al., 2007). When such crop products are consumed continually, and in large quantities, the accumulation of residuals in the body could get to harmful levels.

Poultry manures are great sources of pest and disease pathogens to humans and other livestock. Chicken litter or chicken litter-based organic fertilizers can contain various types of pathogens. Commonly reported pathogens are *Actinobacillus*, *Bordetalla*, *Campylobacter*, *Clostridium*, *Corynebacterium*, *Escherichia coli*, *Globicatella*, *Listeria*, *Mycobacterium*, *Salmonella*, *Staphylococcus* and *Streptococcus* (Chen and Jiang, 2014). According to Bolan et al. (2010), the concentration of these microbes in chicken manure can be very high, reaching up to 1010 CFU/g, and Gram-positive bacteria account for nearly 90% of the diversity. These pathogens can cause various human illnesses when they come into contact with the body, whether through direct contact with poultry litter or manure, indirectly through contaminated poultry products, or through drinking water contaminated with these pathogens. The level of contamination and concentration of these foodborne pathogens vary depending on pathogen species and serotype, chicken age, season, geographic area, and farm handling practice (Renwick et al., 1992; Stern and Robach, 2003). For instance, the highest prevalence of Salmonella was found in fecal samples taken from 18-week-old layer birds, at 55.6%, followed by 25- to 28-week birds at 41.7%, 75- to 78-week birds at 16.7%, and 66- to 74-week birds at 5.5% (Li et al., 2007). This implies that the age of the poultry is a critical factor in determining the level of safety required when using raw poultry manure.

4 Crop risks associated with the use of PM

Like animals, crops also require nutrients at safe concentrations, especially heavy metals such as As, Co, Cu, Cr, Fe, Mn, Se, Cr, and Zn. The impact of these metals on crop growth and development could be exogenous, endogenous, or both. Application of poultry manure with high concentrations of heavy metals could contaminate the soil environment, adversely influencing soil fertility and negatively impacting crop growth, development, and production (Reeves, 2000). Accumulation of heavy metals such as Pb, As, and Cu could reach levels that are toxic to the growth and production of various crops. The accumulation of those heavy metals has been associated with long-term manure application (Bolan et al., 2004). At a concentration of 500 µM, Cu cause a reduction in the length and fresh and dry weights of the embryonic axis of germinating dry bean seeds in addition to a decreased growth by 50% (Karmous et al., 2015). Elevated levels of Fe concentration decrease the growth, photosynthesis, and development of sweet potatoes (*Ipomoea batatas* L.) and potatoes (*Solanum tuberosum* L.) (Chatterjee et al., 2006; Adamski et al., 2012). Negative effects on growth and development due to Mo, Mn, and Zn were reported in previous studies in chickpeas (*Cicer arietinum* L.) (Nautiyal et al., 2005), tomatoes (*Lycopersicon esculentum*) (Kleiber et al., 2015), black gram (*Vigna mungo* L.) (Gopal et al., 2015) and wheat (*Triticum aestivum*) seedling (Li et al., 2013). In addition, applying manure with higher Cu concentrations

Table 3. Summary of key roles by each stakeholder in the chicken manure industry

Government	Suppliers	Researchers & Extn agents	Farmers
• Poultry feed law enactment and enforcement. • Poultry manure collection, processing, and storage law • Manure treatment and use guidelines.	• Proper record • Sharing records and information with the government, manure retailers, and farmers • Manure treatment and storage • Carry out key nutrient and pathogen tests	• Manure treatment • Determine economically optimum application rates • Training farmers on treatments, storage, and application	• Manure treatment and storage • Implement best practices

Table 4. Summary of critical pathogen components of poultry manure that should be considered during testing†

Parameter	Maximum allowable concentrations	References
Actinobacillus		Kyakuwaire et al. (2019)
Campylobacter		Kyakuwaire et al. (2019)
Clostridium	<100 MPN/g	Scantling et al. (1995); Rothrock et al. (2008)
Corynebacterium		Chen and Jiang (2014)
Escherichia coli	<1000 MPN/g	Kyakuwaire et al. (2019); Ngogang et al. (2020)
Globicatella		Kyakuwaire et al. (2019); Miller et al. (2017)
Mycobacterium		Chen and Jiang (2014)
Salmonella	<1000 MPN/g	Kyakuwaire et al. (2019); Ngogang et al. (2020)
Streptococcus	<500 MPN/g	KEBS (2018)

† Due to lack of consistency in information about poultry manure, occasionally, maximum allowable concentrations and annual pollutant loading rates were adapted from compost and general manure. Also, a range of numbers was used where common figures were missing. Based on available information, all the listed micro-organisms cause ill-health conditions in humans, animals, or both.

could increase Cu-resistant soil bacteria pathogens. For instance, an increase in the Cu-resistant bacteria population with increasing Cu content after manure application in the soil has been reported (Bolan et al., 2004). The impact of these could be increased crop yield losses on farmers' fields and high cost of production.

5 Environmental risks associated with the use of PM

Apart from humans, livestock, and crops, inconsiderate use of untreated poultry manure could negatively impact the quality of water bodies, soil, microbes, and air. Increased accumulation of heavy metals and nutrients leaching into the soils and water bodies affect soil microbes leading to ecological imbalances. As previously mentioned, feed additives and metals elements such as As, Co, Cu, Fe, Mn, Se, and Zn are added to prevent diseases, improve weight gains and feed conversion, and increase egg production in the case of poultry rearing (Miller et al., 1991). Significant portions of those metals ingested by animals are excreted as feces and urine (manure by-products), which are then applied to crops. Short and long-term application of manure has been reported to result in the accumulation of heavy metals, leaching of nutrients into water bodies, and eventual bioaccumulation in the animals (Kingery et al., 1994; Bolan et al., 2004). Eutrophication of surface water is another negative impact arising from the use of poultry manure (Fig. 1). Eutrophication is a complicated process and

Table 5. Summary of maximum allowable concentration and annual pollutant loading rate of various nutrient elements in poultry manure

Parameter	MAL	Annual PLR	Reference
pH	8-12		Ritz and Vendrell (2014); KEBS (2018)
MC	15-35%		KEBS (2018)
OMC	>70%		KEBS (2018)
N	No restriction†		KEBS (2018)
P	No restriction		KEBS (2018)
K	No restriction		KEBS (2018)
Ca	No restriction		KEBS (2018)
Mg	No restriction		KEBS (2018)
As	10-25 mg/kg	2 kg/ha/yr	Nevels et al. (2001); Kyakuwaire et al. (2019); KEBS (2018);Bellows (2005);Chastain et al.
Co	10-34 mg/kg	150 kg/ha/yr	Bellows (2005)
Cu	90-1750 mg/kg	75 kg/ha/yr	Chastain et al.; Nevels et al. (2001); Bellows (2005); Ritz and Vendrell (2014); KEBS (2018)
Cr	50-750 mg/kg	150 kg/ha/yr	Nevels et al. (2001); KEBS (2018)
Pb	150-1200 mg/kg	15 kg/ha/yr	Bellows (2005); Nevels et al. (2001); KEBS (2018)
Se	2 mg/kg	5 kg/ha/yr	Bellows (2005); Nevels et al. (2001)
Zn	300-9000 mg/kg	140 kg/ha/yr	Chastain et al.; Nevels et al. (2001); Bellows (2005); Ritz and Vendrell (2014); KEBS (2018)

† No restriction but requires >1%; MAL: maximum allowable limit; PLR: pollution loading rate; OMC: organic matter content (%); MC: moisture content (%)

a significant human-caused source of harm to aquatic ecosystems (Dorgham, 2014). Eutrophication is the process by which water is enriched with nitrogen and phosphorous compounds, causing an increase in algae and plant growth, leading to negative impacts on the stability of both macro and micro-organisms and the quality of the water (CEC, 1991). High application of poultry manure has been associated with elevated leaching and drainage of its rich N and P contents into water bodies (Moore et al., 1995). At higher concentrations, those nutrients can lead to excessive plant and algal growth on water surfaces, which are harmful to aquatic life (Fig. 1).

The effects of eutrophication on the ecosystem and phytoplankton community have been intensively reviewed by Dorgham (2014) (Table 2). Some of the negative effects on water bodies include deterioration of water quality leading to serious threats to the biotic components of this ecosystem, increased number of suspended particles leading to a decrease in water clarity, increased rate of precipitation into water bodies leading to hypoxia, and enhanced water acidification (Dorgham, 2014). Increased emission of greenhouse gases such as nitrous oxide (N_2O) and carbon dioxide (CO_2) is another potential impact on the environment. Poultry manure is among the leading emitters of N_2O and CO_2 gases. Those gases are released during the fresh application or composting of poultry manure. Higher N_2O and CO_2 emissions have been reported with poultry manure than with inorganic fertilizer (NPK) application (Sistani et al., 2019) which have contributed to climate change which is characterized by reduced rainfall, unpredictable weather patterns, unreliable rainfall, high temperatures, and the outbreak of pests and diseases. Volatilization of N_2O and CO_2 can also contribute to atmospheric deposition and acid rain (Walker et al., 2000).

Air quality has been one of the major environmental concerns in the poultry industry. The most common cause of objections against animal-based industries is the bioaerosols, dust, and unpleasant odor produced during the production and storage of chicken manure and its application on farms (Millner, 2009). Uncontrolled decomposition and application of unprocessed poultry manure produce bad odorous gases, including amines, amides, mercaptans, sulfides, and disulfides (Bolan et al., 2010). These harmful gases can lead to respiratory illnesses in both animals and humans (Schiffman and Williams, 2005).

6 Risk management strategies

6.1 Policy formulation and law enactment

This involves developing and enacting better policies and laws that control the use of organic fertilizers, including poultry manure. Such policies and laws must cover even the poultry sector, including the feed industry (Table 3). For example, laws should be enacted and enforced to regulate the quality of the feeds, specifically looking into the tolerable levels of concentrations for heavy metals such as As, Co, Cu, Cr, Fe, Mn, Se, and Zn in poultry feeds. This ensures that all heavy metals are within acceptable limits for consumption and concentrations in the manure that could be used for crop production. Also, a separate law enactment and enforcement should be on poultry manure collection, processing, and storage. This will ensure that manure is properly treated, stored, and applied, thereby reducing pollution, human and livestock pathogens transfer, and leaching (Table 3). It should also provide guidelines on when and how to use poultry manure. Based on the available information, most countries do not have detailed manure-specific policies, especially those that regulate the commonly used poultry manure in crop production. For instance, in Africa, (a) policies that exist do not always explicitly mention livestock manure management, but it is often considered a component of waste management; (b) animal waste is often regarded as a source of pollution and a potential human health risk, not as a resource to be utilized; (c) even when policies exist, enforcement can be a challenge as countries take limited action to promote good practices or to enforce legislation on manure management (Ndambi et al., 2019). Suppliers play important roles in ensuring compliance with the laws and regulations.

6.2 PM collection, treatment and storage

The safety and quality of manure are largely controlled at this stage, and therefore producers' and suppliers' commitment and compliance are highly demanded. There are several scientifically proven processes that could be used to reduce the negative impacts of poultry manure during crop production.

6.2.1 Chemical treatment

Chemical treatment of manure using Alum (aluminum sulfate) or sodium bisulfite is commonly recommended in the management of the above risks. Application of these chemical amendments suppresses NH_3 emissions, removing bad odor and altering pH to unfavorable breeding levels for the compound and house flies (Rothrock et al., 2010; Cook et al., 2011; Tomlinson et al., 2014). Alum is commonly used to decrease the presence of pathogens in chicken litter prior to its application on land. The addition of alum (10% wt/wt) effectively decreased the populations of *C. jejuni*, *E. coli*, and *Clostridium*/*Eubacterium* by the end of the first month (Scantling et al., 1995; Rothrock et al., 2008). The addition of alum to poultry litter in chicken houses can decrease the volatilization of ammonia and runoff of water-soluble phosphorus, reducing ecological contamination from leaching of nitrogen and phosphorus and volatilization of various forms of nitrogen.

6.2.2 Composting

Composting is a process through which organic matter is transformed into a nutrient-rich soil supplement or mulch through aerobic (requires oxygen) degradation, which is carried out in a controlled manner (US EPA, 2022). Proper composting of poultry manure before selling and/or applying it to crops is recommended in managing risks associated with poultry manure. However, composting requires labor and time to turn on-farm organic waste materials into valuable farm resources (Inckel et al., 2005). During composting, heat (temperature rising as high as 45 to 75 °C) (Lin et al., 2012; Sarkar et al., 2016), capable of killing all non-thermophilic pathogens is produced. However, it is worth noting that composting usually leads to losses of nitrogen from manure if not well protected. Therefore, to reduce the release of ammonia during composting, producers may need to add substances such as straw, peat, wood chips, paper waste, aluminum sulfate, and zeolite to the litter (Moore et al., 2000).

6.2.3 Lime application

Application of lime is an important practice in manure production and treatment as it regulates pH and adds essential Ca and Mg nutrients. Adding quicklime (CaO) or hydrated lime ($Ca(OH)_2$) at rates between 5% and 20% has shown effective towards disinfecting and stabilizing chicken litter by raising the pH to 12 or increasing the temperature through an exothermic reaction, thus killing most enteric pathogens (Bennett et al., 2003; Stringfellow et al., 2010). The use of quicklime effectively eliminates pathogens in poultry litter by raising the pH to levels beyond their tolerance and also through the drying process, rendering the environment inhospitable for their survival. The addition of lime to the manure also plays additional roles, such as enriching manure with additional Ca and Mg and the capacity to moderate pH, thereby improving nutrient use efficiency.

6.2.4 Biological treatment

Insect-based treatment of manure and organic waste management is increasingly recognized as a low-cost and environmentally friendly method for recycling resources (Kim et al., 2021). Among the insects, black soldier flies (*Hermetia illucens*) larvae (BSFL) are gaining significant attention (Lalander et al., 2019). In addition, such insects can be an excellent protein source through a certain procedure of extraction (Kim et al., 2021). Production and efficient usage of BSFL depends on several factors such as; optimal rearing temperature of 26–27 °C, relative humidity of 60–70%, substrates moisture content of substrates of 52–70%, and optimal light intensity of135–200 $\mu mol/m^2$ (Barragan-Fonseca et al., 2017; Kim et al., 2021). Soldier fly larva has an inactivation effect on Salmonella population decreasing the population by 4-6-log CFU/g after 2-3 days (Erickson et al., 2004). Using an anaerobic biodigester to digest contaminated chicken manure for about 38 days produces biogas and pathogen-free fertilizer for farm use (Yongabi et al., 2009).

6.3 Integrated best agronomic practices

Like other nutrient sources and soil amendments, efficient and safe use of manure requires strict adherence to best practices. These practices should be applied both during storage and application. Proper nutrient management using agronomic rates of N and P should form the basis of manure management. Before application, soil tests should be done to determine the levels of N and P deficiencies that should be bridged by manure application. That will reduce the risks associated with excess N and P washing into water streams and bodies. It also reduces the risks of heavy metals building up in the soil. Manure incorporation into the soil is always encouraged as it hastens mineralization. This can be done during the final land preparation when the manure heaps are spread and incorporated with a plow or at planting when the manures are spot-applied and covered with soil. Subsurface application of poultry manure helps to reduce air pollution. It also prevents nuisance flies, such as house and stable flies, from breeding and increasing their population. According to Cook et al. (1999), band application of poultry manure reduced the populations of house and stable flies to 0.5 million and 45,000, respectively, per hectare.

Manure can also be mixed with other materials like biochar during the application or composting to reduce the production of gases such as N_2O and CO_2 and the leaching of nutrients. Several studies have reported significant decreases in the emission of N_2O and CO_2 gases when poultry manure is mixed and applied or composted with biochar (Agyarko-Mintah et al., 2017; Awasthi et al., 2020). Under such practice, biochar rates as low as 10% have been recommended for co-application (Agyarko-Mintah et al., 2017). The decrease in N_2O emission is likely due to the conversion of different N forms from poultry manure by micro-organism activities that occur with biochar presence. To reduce the leaching of N and P nutrients that may cause eutrophication, it is advisable to maintain a vegetative buffer of at least 7-30 m between the area applied and streams or water bodies (Kulesza, 2020).

7 Tests and standards

Poultry litter/manure can be a valuable resource when properly applied as a fertilizer to pasture, hay, small grains, and row crops. However, if not well handled, the resource could pose risks ranging from low to high, as summarized in Table 4. To effectively and eco-efficiently use poultry litter as a fertilizer, the nutrient and microbial content of the litter must be determined. However, there are no standards set specifically for chicken manure for most of its known contaminants. Even where standards exist for related products such as compost, there is a wide variation across countries and bodies mandated to set standards for the safe disposal of organic wastes. Currently, most countries do not have policies guiding the resource use on the farm, health implications, and potential tests to be carried out. Table 4 and Table 5 summarize the various concerns and risk levels associated with poultry manure for an informed approach should any country decide to use poultry manure at scale.

8 Conclusion

Poultry manure is a promising soil fertility resource with the capacity to reduce over-dependence on inorganic fertilizers. However, several risks should be handled to make it a safe and profitable farm resource. These risks include human, crop, environmental, and soil health risks. To effectively utilize and reduce risks associated with poultry manure, proper policies, and laws should be enacted to encourage the use of safe products and feeds, proper manure collection, and treatment and use. In addition, farmers should choose and apply manure within the best agronomic principles.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

Adamski JM, Danieloski R, Deuner S, Braga EJB, de Castro LAS, Peters JA. 2012. Responses to excess iron in sweet potato: impacts on growth, enzyme activities, mineral concentrations, and anatomy. Acta Physiologiae Plantarum 34:1827–1836. doi: 10.1007/s11738-012-0981-3.

Adeyemo AJ, Akingbola OO, Ojeniyi SO. 2019. Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded alfisols in southwestern Nigeria. International Journal of Recycling of Organic Waste in Agriculture 8:73–80. doi: 10.1007/s40093-019-0273-7.

Agyarko-Mintah E, Cowie A, Singh BP, Joseph S, Zwieten LV, Cowie A, Harden S, Smillie R. 2017. Biochar increases nitrogen retention and lowers greenhouse gas emissions when added to composting poultry litter. Waste Management 61:138–149. doi: 10.1016/j.wasman.2016.11.027.

Ashworth AJ, Chastain JP, Moore PA. 2020. Nutrient characteristics of poultry manure and litter. In: Animal Manure. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. p. 63–87. doi: 10.2134/asaspecpub67.c5.

Awasthi MK, Duan Y, Awasthi SK, Liu T, Zhang Z. 2020. Influence of bamboo biochar on mitigating greenhouse gas emissions and nitrogen loss during poultry manure composting. Bioresource Technology 303:122952. doi: 10.1016/j.biortech.2020.122952.

Ayoola OT, Adeniyan ON. 2006. Influence of poultry manure and NPK fertilizer on yield and yield components of crops under different cropping systems in south west Nigeria. African journal of biotechnology 5.

Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. 2021. Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. Frontiers in Pharmacology 12. doi: 10.3389/fphar.2021.643972.

Barragan-Fonseca KB, Dicke M, van Loon JJA. 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review. Journal of Insects as Food and Feed 3:105–120. doi: 10.3920/jiff2016.0055.

Bellows B. 2005. Arsenic in Poultry Litter: Organic Regulations; 1-800-346-9140. National Sustainable Agriculture Coalition 110 Maryland Avenue NE, Phone: (202) 547-5754; A Publication of ATTRA; The National Sustainable Agriculture Information Service: Washington, DC, USA.

Bennett DD, Higgins SE, Moore RW, Beltran R, Caldwell DJ, Byrd JA, Hargis BM. 2003. Effects of lime on *Salmonella enteritidis* survival *in vitro*. Journal of Applied Poultry Research 12:65–68. doi: 10.1093/japr/12.1.65.

Bicudo JR. 2009. Animal solid manure: storage, handling and disposal. Page Publishing, PA, USA.

Biratu GK, Elias E, Ntawuruhunga P, Sileshi GW. 2018. Cassava response to the integrated use of manure and NPK fertilizer in Zambia. Heliyon 4:e00759. doi: 10.1016/j.heliyon.2018.e00759.

Bolan N, Adriano D, Mahimairaja S. 2004. Distribution and bioavailability of trace elements in livestock and poultry manure byproducts. Critical Reviews in Environmental Science and Technology 34:291–338. doi: 10.1080/10643380490434128.

Bolan N, Szogi A, Chuasavathi T, Seshadri B, Rothrock M, Panneerselvam P. 2010. Uses and management of poultry litter. World's Poultry Science Journal 66:673–698. doi: 10.1017/s0043933910000656.

CEC. 1991. Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC). Offic Jour Europ Commun 135:40–52.

Chastain JP, Camberato JJ, Skewes P, Manure NCOP. ???? Poultry Manure Production and Nutrient Content. https://www.clemson.edu/extension/camm/manuals/poultry/pch3b_00.pdf.

Chatterjee C, Gopal R, Dube BK. 2006. Impact of iron stress on biomass, yield, metabolism and quality of potato (*Solanum tuberosum* L.). Scientia Horticulturae 108:1–6. doi: 10.1016/j.scienta.2006.01.004.

Chen M, Zhang S, Liu L, Wu L, Ding X. 2021. Combined organic amendments and mineral fertilizer application increase rice yield by improving soil structure, p availability and root growth in saline-alkaline soil. Soil and Tillage Research 212:105060. doi: 10.1016/j.still.2021.105060.

Chen Z, Jiang X. 2014. Microbiological safety of chicken litter or chicken litter-based organic fertilizers: A review. Agriculture 4:1–29. doi: 10.3390/agriculture4010001.

Cook DF, Dadour IR, Keals NJ. 1999. Stable fly, house fly (Diptera: Muscidae), and other nuisance fly development in poultry litter associated with horticultural crop production. Journal of Economic Entomology 92:1352–1357. doi: 10.1093/jee/92.6.1352.

Cook KL, Rothrock MJ, Eiteman MA, Lovanh N, Sistani K. 2011. Evaluation of nitrogen retention and microbial populations in poultry litter treated with chemical, biological or adsorbent amendments. Journal of Environmental Management 92:1760–1766. doi: 10.1016/j.jenvman.2011.02.005.

Dikinya O, Mufwanzala N. 2010. Chicken manure-enhanced soil fertility and productivity: Effects of application rates. Journal of soil science and environmental management 1:46–54.

Dorgham MM. 2014. Effects of eutrophication. In: Eutrophication: Causes, Consequences and

Control. Springer Netherlands. p. 29–44. doi: 10.1007/978-94-007-7814-6_3.

Enujeke EC. 2013. Response of watermelon to five different rates of poultry manure in Asaba Area of Delta State, Nigeria. IOSR Journal of Agriculture and Veterinary Science 5:45–50. doi: 10.9790/2380-0524550.

Erickson MC, Islam M, Sheppard C, Liao J, Doyle MP. 2004. Reduction of *Escherichia coli* O157:H7 and *Salmonella enterica Serovar Enteritidis* in chicken manure by larvae of the black soldier fly. Journal of Food Protection 67:685–690. doi: 10.4315/0362-028x-67.4.685.

Feng G, Tewolde H, Zhang B, Buehring N, Adeli A. 2021. Soil physical and hydrological properties as affected by a five-year history of poultry litter applied to a cotton–corn–soybean rotation system. Soil Science Society of America Journal 85:800–813. doi: 10.1002/saj2.20224.

Gopal R, Sharma YK, Shukla AK. 2015. Effect of molybdenum stress on growth, yield and seed quality in black gram. Journal of Plant Nutrition 39:463–469. doi: 10.1080/01904167.2015.1016176.

Guo Z, Zhang J, Fan J, Yang X, Yi Y, Han X, Wang D, Zhu P, Peng X. 2019. Does animal manure application improve soil aggregation? insights from nine long-term fertilization experiments. Science of The Total Environment 660:1029–1037. doi: 10.1016/j.scitotenv.2019.01.051.

Ikeh AO, Ndaeyo NU, Uduak IG, Iwo GA, Ugbe LA, Udoh EI, Effiong GS. 2012. Growth and yield responses of pepper (*Capsicum frutescens* L.) to varied poultry manure rates in Uyo, Southeastern Nigeria. ARPN Journal of Agricultural and Biological Science 7:735–742.

Inckel M, de Smet P, Tersmette T, Veldkamp T. 2005. The Preparation and Use of Compost. Wageningen: Agrodok 8 Agromisa Foundation.

Karmous I, Bellani LM, Chaoui A, Ferjani EE, Muccifora S. 2015. Effects of copper on reserve mobilization in embryo of *Phaseolus vulgaris* L. Environmental Science and Pollution Research 22:10159–10165. doi: 10.1007/s11356-015-4208-1.

KEBS. 2018. Organic fertilizer specification. Kenya Bureau of Standards. https://webstore.kebs.org/index.php?route=product/category&path=3.

Khan S, Cao Q, Zheng YM, Huang YZ, Zhu YG. 2008. Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environmental Pollution 152:686–692. doi: 10.1016/j.envpol.2007.06.056.

Kim CH, Ryu J, Lee J, Ko K, yeon Lee J, Park KY, Chung H. 2021. Use of black soldier fly larvae for food waste treatment and energy production in Asian countries: A review. Processes 9:161. doi: 10.3390/pr9010161.

Kingery WL, Wood CW, Delaney DP, Williams JC, Mullins GL. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. Journal of Environmental Quality 23:139–147. doi: 10.2134/jeq1994.00472425002300010022x.

Kleiber T, Grajek M, et al. 2015. Tomato reaction on excessive manganese nutrition. Bulgarian Journal of Agricultural Science 21:118–125.

Knockaert C. 2021. Possible consequences of eutrophication. http://www.coastalwiki.org/wiki/Possible_consequences_of_eutrophication, Accessed on 11 December 2022.

Kulesza S. 2020. Guidelines for the Commercial Application of Poultry Litter. https://content.ces.ncsu.edu/guidelines-for-commercial-application-of-poultry-litter.

Kyakuwaire, Olupot, Amoding, Nkedi-Kizza, Basamba. 2019. How safe is chicken litter for land application as an organic fertilizer? a review. International Journal of Environmental Research and Public Health 16:3521. doi: 10.3390/ijerph16193521.

Lalander C, Diener S, Zurbrügg C, Vinnerås B. 2019. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). Journal of Cleaner Production 208:211–219. doi: 10.1016/j.jclepro.2018.10.017.

Li X, Payne JB, Santos FB, Levine JF, Anderson KE, Sheldon BW. 2007. Salmonella populations and prevalence in layer feces from commercial high-rise houses and characterization of the *Salmonella Isolates* by serotyping, antibiotic resistance analysis, and pulsed field gel electrophoresis. Poultry Science 86:591–597. doi: 10.1093/ps/86.3.591.

Li X, Yang Y, Jia L, Chen H, Wei X. 2013. Zinc-induced oxidative damage, antioxidant enzyme response and proline metabolism in roots and leaves of wheat plants. Ecotoxicology and Environmental Safety 89:150–157. doi: 10.1016/j.ecoenv.2012.11.025.

Lin C, Sheu DS, Lin TC, Kao CM, Grasso D. 2012. Thermophilic biodegradation of diesel oil in food waste composting processes without bioaugmentation. Environmental Engineering Science 29:117–123. doi: 10.1089/ees.2010.0212.

Locatelli A, Hiett KL, Caudill AC, Rothrock MJ. 2017. Do fecal and litter microbiomes vary within the major areas of a commercial poultry house, and does this affect sampling strategies for whole-house microbiomic studies? Journal of Applied Poultry Research 26:325–336. doi: 10.3382/japr/pfw076.

Miller AO, Buckwalter SP, Henry MW, Wu F, Maloney KF, Abraham BK, Hartman BJ, Brause BD, Whittier S, Walsh TJ, Schuetz AN. 2017. Globicatella sanguinis osteomyelitis and bacteremia: Review of an emerging human pathogen with an expanding spectrum of disease. Open Forum Infectious Diseases 4. doi: 10.1093/ofid/ofw277.

Miller ER, Lei X, Ullrey DE. 1991. Trace elements in animal nutrition. Micronutrients in agriculture 4:593–662. doi: https://doi.org/10.2136/sssabookser4.2ed.c16.

Millner PD. 2009. Bioaerosols associated with animal production operations. Bioresource Technology 100:5379–5385. doi: 10.1016/j.biortech.2009.03.026.

Moore PA, Daniel TC, Edwards DR. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. Journal of Environmental Quality 29:37–49. doi: 10.2134/jeq2000.00472425002900010006x.

Moore PA, Daniel TC, Sharpley AN, Wood CW. 1995. Poultry manure management: Environmentally sound options. Journal of soil and water conservation 50:321–327.

Muhammad J, Khan S, Lei M, Khan MA, Nawab J, Rashid A, Ullah S, Khisro SB. 2020. Application of poultry manure in agriculture fields leads to food plant contamination with potentially toxic elements and causes health risk. Environmental Technology & Innovation 19:100909. doi: 10.1016/j.eti.2020.100909.

Muhieldeen OA, Ahmed EA, Shalih AM. 2014. Effect of sugar cane bagasse, cattle manure and sand addition on some physical and chemical properties of the clay soils and sunflower production in central of Sudan. International Journal of Scientific & Technology Research 3:47–52.

Nautiyal N, Singh S, Chatterjee C. 2005. Seed reserves of chickpea in relation to molybdenum supply. Journal of the Science of Food and Agriculture 85:860–864. doi: 10.1002/jsfa.1929.

Ndambi OA, Pelster DE, Owino JO, de Buisonjé F, Vellinga T. 2019. Manure management practices and policies in sub-saharan africa: Implications on manure quality as a fertilizer. Frontiers in Sustainable Food Systems 3. doi: 10.3389/fsufs.2019.00029.

Nevels M, Tauber B, Spruss T, Wolf H, Dobner T. 2001. 'hit-and-run' transformation by adenovirus oncogenes. Journal of Virology 75:3089–3094. doi: 10.1128/jvi.75.7.3089-3094.2001.

Ngogang MP, Ernest T, Kariuki J, Mouiche MMM, Ngogang J, Wade A, van der Sande MAB. 2020. Microbial contamination of chicken litter manure and antimicrobial resistance threat in an urban area setting in Cameroon. Antibiotics 10:20. doi: 10.3390/antibiotics10010020.

Otieno HMO. 2019. Growth and yield response of maize (*Zea mays* L.) to a wide range of nutrients on ferralsols of western Kenya. World Scientific News :96–106.

Otieno HMO. 2021. A review of the current state of soil infertility and management options in Kenya: The case of maize growing regions. International Journal of Innovative Approaches in Agricultural Research 5:241–256. doi: 10.29329/ijiaar.2021.358.9.

Otieno HMO, Chemining'wa GN, Zingore S. 2018. Effect of farmyard manure, lime and inorganic fertilizer applications on soil pH, nutrients uptake, growth and nodulation of soybean in acid soils of Western Kenya. Journal of Agricultural Science 10:199. doi: 10.5539/jas.v10n4p199.

Ouma JP, Lelei JJ. 2017. Effect of integrated chicken manure and inorganic fertilizers on growth and yield of hybrid maize (*Zea mays* L.) in Malawi. International Journal of Sciences: Basic and Applied Research 36:262–175.

Rauber LP, Andrade AP, Friederichs A, Mafra ÁL, Baretta D, da Rosa MG, Mafra MSH, Correa JC. 2018. Soil physical indicators of management systems in traditional agricultural areas under manure application. Scientia Agricola 75:354–359. doi: 10.1590/1678-992x-2016-0453.

Reeves RD. 2000. Metal-accumulating Plants: Phytoremediation of toxic metals: using plants to clean up the environment. Wiley & Sons, New York, USA.

Renwick SA, Irwin RJ, Clarke RC, McNab WB, Poppe C, McEwen SA. 1992. Epidemiological associations between characteristics of registered broiler chicken flocks in canada and the salmonella culture status of floor litter and drinking water. The Canadian Veterinary Journal 33:449.

Ritz CW, Vendrell PF. 2014. Poultry litter sampling. https://secure.caes.uga.edu/extension/publications/files/pdf/B%201270_2.PDF.

Rothrock MJ, Cook KL, Warren JG, Eiteman MA, Sistani K. 2010. Microbial mineralization of organic nitrogen forms in poultry litters. Journal of Environmental Quality 39:1848–1857. doi: 10.2134/jeq2010.0024.

Rothrock MJ, Cook KL, Warren JG, Sistani K. 2008. The effect of alum addition on microbial communities in poultry litter. Poultry Science 87:1493–1503. doi: 10.3382/ps.2007-00491.

Sarkar S, Pal S, Chanda S. 2016. Optimization of a vegetable waste composting process with a significant thermophilic phase. Procedia Environmental Sciences 35:435–440. doi: 10.1016/j.proenv.2016.07.026.

Sathya V, Maheswari M. 2017. Nutrient mineralization during the application of poultry manure. Nature Environment and Pollution Technology 16:905.

Scantling M, Waldroup A, Mary J, Moore P. 1995. Microbiological effects of treating poultry litter with aluminum sulfate. Poultry Science Abstracts 74:216.

Schiffman SS, Williams CM. 2005. Science of odor as a potential health issue. Journal of environmental quality 34:129–138.

Scott JG, Warren WC, Beukeboom LW, Bopp D, et al. 2014. Genome of the house fly, *Musca domestica* L., a global vector of diseases with adaptations to a septic environment. Genome Biology 15:1–17. doi: 10.1186/s13059-014-0466-3.

Serna MD, Pomares F. 1991. Comparison of biological and chemical methods to predict nitrogen mineralization in animal wastes. Biology and Fertility of Soils 12:89–94. doi: 10.1007/bf00341481.

Sharma RK, Agrawal M, Marshall F. 2007. Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India. Ecotoxicology and Environmental Safety 66:258–266. doi: 10.1016/j.ecoenv.2005.11.007.

Singh J, Kalamdhad AS. 2011. Effects of heavy metals on soil, plants, human health and aquatic life. Int J Res Chem Environ 1:15–21.

Sistani KR, Simmons JR, Jn-Baptiste M, Novak JM. 2019. Poultry litter, biochar, and fertilizer effect on corn yield, nutrient uptake, N_2O and CO_2 emissions. Environments 6:55. doi: 10.3390/environments6050055.

Sprynskyy M, Kosobucki P, Kowalkowski T, Buszewski B. 2007. Influence of clinoptilolite rock on chemical speciation of selected heavy metals in sewage sludge. Journal of Hazardous Materials 149:310–316. doi: 10.1016/j.jhazmat.2007.04.001.

Stern N, Robach M. 2003. Enumeration of campylobacter spp. in broiler feces and in corresponding processed carcasses. Journal of Food Protection 66:1557–1563. doi: 10.4315/0362-028x-66.9.1557.

Stringfellow K, Caldwell D, Lee J, Byrd A, Carey J, Kessler K, McReynolds J, Bell A, Stipanovic R, Farnell M. 2010. Pasteurization of chicken litter with steam and quicklime to reduce *Salmonella typhimurium*. Journal of Applied Poultry Research 19:380–386. doi: 10.3382/japr.2009-00097.

Tian W, Wang L, Li Y, Zhuang K, Li G, Zhang J, Xiao X, Xi Y. 2015. Responses of microbial activity, abundance, and community in wheat soil after three years of heavy fertilization with manure-based compost and inorganic nitrogen. Agriculture, Ecosystems & Environment 213:219–227. doi: 10.1016/j.agee.2015.08.009.

Tomlinson PJ, Savin MC, Moore PA. 2014. Long-term applications of untreated and alum-treated poultry litter drive soil nitrogen concentrations and associated microbial community dynamics. Biology and Fertility of Soils 51:43–55. doi: 10.1007/s00374-014-0949-0.

Udom GM, Bello HM. 2009. Effect of poultry litter on the yield of two maize varieties in the Northern Guinea Savanna. Agro-Science 8. doi: 10.4314/as.v8i1.44114.

US EPA. 2022. Composting at Home. https://www.epa.gov/recycle/composting-home, Accessed on 20 December 2022.

Van Horn HH. 1998. Factors affecting manure quantity, quality, and use. In: Proceedings of the mid-south ruminant nutrition conference, Dallas-Ft. Worth, pp. 9–20.

Walker JT, Aneja VP, Dickey DA. 2000. Atmospheric transport and wet deposition of ammonium in North Carolina. Atmospheric Environment 34:3407–3418. doi: 10.1016/s1352-2310(99)00499-9.

Watson DW, Rutz DA, Keshavarz K, Waldron JK. 1998. House fly (*Musca domestica* L.) survival after mechanical incorporation of poultry manure into field soil. Journal of Applied Poultry Research 7:302–308. doi: 10.1093/japr/7.3.302.

Watts DB, Torbert HA, Feng Y, Prior SA. 2010. Soil microbial community dynamics as influenced by composted dairy manure, soil properties, and landscape position. Soil Science 175:474–486. doi: 10.1097/ss.0b013e3181f7964f.

Williams RE. 2009. Veterinary entomology: livestock and companion animals. CRC Press.

Yeng SB, Agyarko K, Dapaah HK, Adomako WJ, Asare E, et al. 2012. Growth and yield of sweet potato (*Ipomoea batatas* L.) as influenced by integrated application of chicken manure and inorganic fertilizer. African Journal of Agricultural Research 7:5387–5395.

Yongabi K, Harris P, Lewis D. 2009. Poultry faeces management with a simple low cost plastic digester .

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