



A Review on Valorizing Poultry Wastes: Eco-Friendly and Sustainable Solutions

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ABSTRACT

The global poultry industry has experienced significant growth, leading to a noticeable increase in waste generation, including faecal excreta, feed spillage, feathers, hatchery effluent, animal mortality, and bedding material. Conventional disposal techniques such as burning, incineration, burial, and landfilling have adverse effects on the environment and human health. These disposal methods pollute the air, water, and soil by increasing greenhouse gas emissions and facilitating disease transmission, including cholera, typhoid, malaria, filaria, and dengue fever. Thus, it is imperative to use sustainable and eco-friendly waste management methods, such as composting, anaerobic digestion, pyrolysis and gasification, rendering, microbial and enzymatic treatment, and vermicomposting, which help recycle poultry wastes by converting them into useful products such as organic fertilizer, animal feed, biogas, drugs, and cosmetics. The objective of this literature review is to provide an overview of the scientific literature on sustainable and environmentally acceptable methods for valorizing poultry waste into valuable products. Valorizing poultry wastes can reduce environmental and health impacts while producing valuable products used as animal feed and industry raw material. Composting poultry waste can be used to create organic fertilizer for soil amendment. Anaerobic digestion, pyrolysis, and gasification are techniques that can generate biogas, syngas, and biochar as energy and feedstock, such as feather meal, meat and bone meal, and tallow from poultry waste. Through rendering, fats and proteins can be recovered from abattoir wastes and used in the soap, cosmetics, and pharmaceutical sectors, as well as in animal feed. Vermicomposting is another poultry-waste valorisation method that uses earthworms to decompose organic waste and produce high-quality compost. The aforementioned methods for valorizing poultry waste contribute to a circular economy by recycling waste through eco-friendly and sustainable processes, though their applications are limited by elevated capital and energy costs, scalability challenges, technical complexity, and sensitivity to waste variability. Therefore, it is recommended to promote the adoption of poultry waste valorization methods among poultry producers and enhance sustainability in the poultry sector by minimizing pollution caused by poultry waste and recycling it into valuable products.

Keywords: Circular economy, Disposal, Eco-friendly, Poultry, Valorisation

INTRODUCTION

The global poultry industry has witnessed substantial growth in recent decades due to the adoption of high-quality inputs, advanced technology, and improved management practices (Thieme and Pilling 2008). While poultry is acknowledged for its superior efficiency in converting feed into food compared to other livestock species (Mata-Alvarez et al. 2014). The poultry industry's expansion and increased production have led to the generation of substantial waste byproducts (Dalolio et al., 2017). These waste products include fecal excreta, feed

spill, feathers, hatchery effluent, animal mortality, and bedding material, all of which pose a significant threat to environmental pollution (Nebiyu et al., 2016).

The waste released from poultry farms poses a severe threat to the environment due to unpleasant odors from ammonia, amines, sulfides, methane, and disulfides, which are produced by the decomposition of the waste. These are the major components of greenhouse gases, which cause ozone depletion that could lead to global warming and climate change (Bharathy et al., 2012; Singh et al., 2018). This is supported by the U.S. Environmental

Protection Agency (EPA) and other studies, which show that poultry farming accounts for around 8.8% of total greenhouse gas emissions from manure management in the agricultural sector (Dunkley, 2011). Moreover, FOA stated that chicken produced 34% and 66% methane and nitrous oxide, respectively, from manure storage, which is equivalent to 0.1 (1.5%) total gigatonnes of CO₂ in combined. Thus, the expansion of the poultry industry worldwide has become one of the most important topics (FAO, 2013).

Besides, the waste released from these industries attracts flies, rodents, and other pests that create local nuisances and transmit infectious agents such as salmonellosis to nearby community residences and other animal farms (Szalanski et al. 2004; Faridi and Arabhosseini 2018). Similarly, Majra and Gur (2009) indicated that in India, the residences that were located in close proximity to poultry farms and hatchery industries had 83 times the average number of flies and mosquitoes, which can transmit diseases, such as cholera, typhoid, malaria, filaria, and dengue fever.

From an economic perspective, the inappropriate disposal of poultry waste poses significant challenges globally. Estimates suggest that the economic loss from improper management of poultry waste can reach up to 9 billion dollars annually. This economic loss includes costs associated with environmental damage, public health impacts, and lost opportunities for waste-to-energy conversion (Seidavi et al., 2019). Proper disposal and management of poultry waste can mitigate these losses, transforming waste into valuable resources through different innovative technologies such as vermicomposting and anaerobic digestion (Goodwin, 2023).

Traditional methods of disposing of poultry waste, including landfill, composting, and incineration, are not environmentally friendly because they contribute to greenhouse gas production (Das et al. 2002). To ensure the productivity, profitability, and sustainability of the poultry sector, it is crucial to develop innovative and cost-effective technologies and implement effective management practices to mitigate environmental impacts (Das et al., 2002; Szogi and Vanotti, 2009).

Recently, waste valorization has become the most popular alternative to traditional disposal methods (Jagadeesan et al., 2022; Saeed et al., 2025; Talha et al., 2024). It involves reusing, recycling, or composting waste materials to create usable goods or energy sources (Tovar, 2021). Waste valorization is a fundamental concept in the circular economy, which is gaining significant policy importance in various regions, including the European

Union, China, Japan, the UK, Canada, and the business community (Korhonen et al., 2018). To maintain the sustainability of the poultry industry, it is essential to implement effective handling and management practices for poultry waste to minimize adverse environmental effects. Thus, the objective of this review paper was to provide a comprehensive overview of the existing scientific literature on innovative approaches for valorizing poultry waste into valuable resources, with a particular emphasis on environmentally friendly and sustainable practices.

MATERIALS AND METHODS

The current review employed a narrative synthesis approach, drawing on an extensive collection of 118 peer-reviewed articles on the scientific and technical aspects of eco-friendly and sustainable strategies for the valorization of poultry wastes. The bibliographic database includes Google Scholar, Scopus, PubMed, and Web of Science for scientific knowledge. Additionally, FAO documents, World Resources Institute documents, and technical documents of technical and international conferences have also been considered for policy and sustainability views. The full-text articles have all been reviewed and used combinations of keywords, including poultry waste, waste valorization, circular economy, bioenergy, composting, anaerobic digestion, rendering, and sustainable poultry waste management.

Inclusion criteria included peer-reviewed articles, review papers, book chapters, and reputable technical reports about technological, environmental, and economic aspects of poultry waste valorization methods. Exclusion criteria included non-peer-reviewed reports, non-related types of waste, Descriptive reports without data or opinions, Reports on news, or reports lacking scientific/technical rigor. No publication-year limits were applied to capture historical and recent advancements, spanning publications from 2001 to 2025. However, it was ensured that Ethiopian studies, among others, were carried out by developing countries to highlight the challenges, developments, and possibilities specific to these countries for low- and middle-income countries. Information on poultry waste types and characteristics, technologically relevant aspects of valorization methods, and performance in environmental, economic, and sustainability parameters for these processes was extracted. The extracted data were qualitatively consolidated and organized into themes intended to provide an integrated insight into sustainable poultry waste conversion processes.

Limitations include possible publication bias in the experiences documented as successes and a possible tendency to underemphasize experiences in the context of the Ethiopian scale. Since this review is a narrative review rather than a systematic review protocol for data extraction and compilation, selection bias may have been introduced in the inclusion of studies. This narrative review is based solely on the compilation and extraction of data that was documented and published.

POULTRY INDUSTRY WASTE

Poultry waste discharged from poultry farms, abattoirs, and hatcheries includes litter, feathers, dead birds, slaughter and post-processing abattoir waste, egg shells and other hatchery waste (Glatz et al., 2011; Mustafa et al., 2018; Ozdemir and Yetilmezsoy, 2019). The poultry industry generates large quantities of feather waste globally (Sinkiewicz et al. 2017). The global poultry industry has been grappling with the issue of what to do with the large volume of poultry feather waste produced annually by its companies (Tesfaye et al., 2017). Poultry litter, which consists of bedding material, feathers, manure, and spilled feed, is also a significant byproduct of poultry farming (Kaiser et al., 2009; Laca et al., 2021).

Several types of highly perishable organic waste and by-products are also generated during and after the slaughtering (post-processing stages) of poultry. Usually, the weight of the live bird is between 70 and 75 percent of the carcass output; the remaining portion is regarded as inedible waste (Ozdemir and Yetilmezsoy, 2019). Organic solid byproducts and processing wastewater (water used during poultry slaughtering and processing) make up the majority of the wastes from chicken abattoirs. A broiler chicken's inedible components, including its head, feathers, feet, viscera, and trimmings, account for about 28% of its live weight (Jayathilakan et al., 2012).

The hatcheries are another poultry industry that generates a significant volume of wastewater and solid waste. Dead chickens, infertile eggs, dead embryos, late hatchings, and empty shells are examples of solid waste. Water used to clean hatcheries, incubators, and chick-handling spaces produces wastewater in hatchery plants (Glatz et al., 2011). In both poultry hatcheries and farms, there is always mortality waste, comprising dead birds, dead embryos, and damaged organs (Rahman et al., 2022).

ECOLOGICAL AND HEALTH IMPACTS

Poultry waste disposal methods vary across the world, each with its own advantages and disadvantages (Thomas et al., 2023). Traditional methods of managing poultry waste have typically involved on-site disposal, such as land applications (Trejo et al., 2012); burial, which can contaminate the soil and groundwater (Chowdhury et al., 2019); burning at high temperatures using fuels such as wood, tires, or diesel (Singh et al., 2018); and incineration (Blake et al., 2008).

Land application is a traditional waste management method. It involves spreading poultry manure on agricultural fields as a fertilizer to improve soil fertility and increase crop yield. Utilizing organic waste increases nutrient availability and reduces the need for mineral fertilizers, helping farmers save money (De Bon et al., 2010). However, land application of poultry waste can lead to issues such as nutrient runoff, water pollution, soil contamination, unpleasant odors, and health risks (Bolan et al., 2010; Thanh et al., 2023).

Another conventional waste management method is burial, which involves excavating a pit, placing the waste inside, and then covering it with soil (Disposal, 2004). Burial is the chosen method of disposal for mass death due to infectious agents and natural disasters. Malone (2005) stated that the most common method of disposing of carcasses during catastrophic death events, including avian influenza outbreaks, has been on-farm burial. On-farm burial is one of the easiest and most economical ways to handle mass mortality events (Baba et al., 2017).

Commercial poultry producers use the burial method of poultry waste disposal (open pit disposal) to dispose of deceased animals because it's more economical, quicker, cleaner for the environment, and convenient (Ellis, 2001). However, this method can affect soil fertility, water quality, human health, and the ecosystem. Anaerobic decomposition of buried waste also produces methane, a greenhouse gas contributing to climate change (Chowdhury et al., 2019).

The other conventional method used to dispose of poultry waste, particularly among small-scale farmers, is burning. It involves burning mortalities at high temperatures using fuels such as wood, tires, or diesel (Singh et al., 2018). In developing countries with limited waste collection services, waste burning is a common disposal method (Arefin et al., 2024). Even after being removed to dump sites, waste is often burned openly, releasing pollutants such as greenhouse gases, reactive trace gases, and toxic compounds, which can cause chronic respiratory diseases and cardiovascular problems in humans. The emissions from waste combustors are reported in global

inventories. The emissions from open waste burning at homes (uncontrolled open burning of household waste) and dumps are more challenging to characterize and are commonly excluded from inventories such as Emissions Database for Global Atmospheric Research (EDGAR; Wiedinmyer et al., 2014).

Another common waste management approach is incineration, which eliminates the risk of disease transmission (Blake et al., 2008). The process of incinerating waste involves burning organic materials to produce ash, flue gas, and heat. Poultry waste is collected and loaded into an incinerator, where it is heated at high temperatures to achieve full combustion. Gases are released as organic molecules are oxidized, and waste is converted to ash. The gases generated during incineration are treated in a secondary combustion chamber before being released into the atmosphere. Here, high temperatures and extended residence times, typically exceeding 850-1100°C for 1-2 seconds, oxidize volatile organic compounds, dioxins, furans, and other hazardous pollutants into less hazardous substances such as carbon dioxide and water vapor (Nidoni, 2017).

Although incineration is considered biologically sound (by destroying pathogenic microorganisms), its widespread application is limited by high operating costs and the potential air-pollution hazards, which can worsen respiratory and cardiovascular diseases (Tait et al., 2020). Particularly for large-scale poultry businesses, incineration is not recommended due to potential pollution, nuisance complaints, and public health concerns (Moreki and Chiripasi, 2011). Generally, scholars indicated that the aforementioned traditional poultry waste management methods cannot effectively control environmental pollution and transmission caused by *Salmonella*, *Staphylococcus*, *Clostridium*, and fly infestation, which pose a risk to human and animal health (Grzanic et al., 2023).

ECO-FRIENDLY POULTRY WASTE VALORIZATION

Recently, valorization of waste is highly relevant to the bioeconomy, which has increased in importance and development in several countries, including China, Brazil, Germany, the United States, India, and Indonesia recently (Sheppard et al., 2011; Bugge et al., 2016; Lima, 2022; Trigo et al., 2023). It is the approach of waste management that promotes the reuse or recycling of animal by-products, which is not only economically viable but also environmentally sound. The valorization practices

listed below enable the recovery of valuable elements from waste streams (Bandaw and Herago, 2017).

Composting

Composting is a biological process that occurs in the presence of oxygen. Microorganisms decompose complex, degradable materials, producing organic by-products such as humus and inorganic by-products such as carbon dioxide (CO₂), water (H₂O), and ammonia (NH₃; Toledo et al., 2018). Composting practice offers a sustainable solution for solid waste treatment and has become increasingly popular for its ability to protect the environment and manage waste disposal. However, for composting to be widely adopted, it is crucial to establish effective operational strategies that prioritize environmental preservation and maintain product quality, such as optimized carbon-to-nitrogen ratios, regular aeration to control odors and pathogens, temperature monitoring, and moisture control (Tiquia et al., 2002).

Composting enhances land application, stabilizes soil nutrients, and eliminates diseases and weed seeds (Iraji et al., 2025). The compost bin is made from concrete or wooden blocks with holes in them to promote aerobic decomposition. Microorganisms convert raw materials into compost and release carbon dioxide, heat, and water vapor (Cambardella et al., 2003). Composted poultry litter is an organic fertilizer with a low moisture content and unscented texture. This product is designed to be simple to operate and verified to contain no harmful microorganisms (Kelleher et al., 2002).

When composting poultry manure, the use of additions such as zeolite, straw, peat, wood chips, paper trash, and elemental sulfur helps minimize nitrogen losses. The most effective approach to minimizing nitrogen loss is to use cereal straw for aerobic composting, as it contains easily decomposable carbon (Preusch et al., 2002). Poultry manure can be composted with phosphate rock and elemental sulfur to produce nutrient-rich, environmentally friendly compost. This is a useful source of nutrients, particularly for organic farming methods (Agbede, 2025). A tiny amount of elemental sulfur (typically 0.5% of the compost's dry weight) added to the compost lowers its pH, which in turn lowers ammonia volatilization losses. Additionally, this elemental sulfur improves the breakdown of rock phosphate and adds phosphorus- and sulfur-based nutrients to the compost (Roig et al., 2004; Bolan et al., 2010). Positive outcomes have been seen when alum and zeolite are used to decrease ammonia volatilization and phosphorus solubility in poultry litter (Guo and Song, 2009). The application of such

supplements not only addresses environmental issues but also improves living conditions for workers and birds by reducing ammonia emissions, thereby minimizing unpleasant odors and respiratory irritation, while simultaneously raising the manure's nitrogen-to-phosphorus ratio to improve crop utilization. Therefore, it presents an economically feasible waste-disposal option for poultry producers, though it requires land, financial investment, labor, and management (Rahman et al., 2022; Hemavarshini et al., 2025).

Anaerobic digestion

One method of producing biogas from organic matter is anaerobic digestion, a methanogenic process. Animal waste, industrial sludge, municipal sludge, and wastewater are all treated using anaerobic digestion. It provides environmental benefits, such as greenhouse gas emissions reduction and control of odor and disease transmission, such as cholera, typhoid, malaria, filaria, and dengue fever, sludge reduction, conservation of nutrients, and energy production (Wilkie, 2005). It involves microbial breakdown and stabilization of organic substances in anaerobic environments to produce biogas. The primary components of biogas are methane (CH₄) and carbon dioxide (CO₂), along with trace amounts of other gases, such as hydrogen sulfide (H₂S) and ammonia (NH₃). Organic matter combines with water under anaerobic conditions, where anaerobic microorganisms break it down to produce methane (CH₄), carbon dioxide (CO₂), new microbial biomass, ammonia (NH₃), hydrogen sulfide (H₂S), and heat (Gerardi, 2003).

The biogas produced from poultry waste can be directly used as a renewable energy source for heating, cooking, and electricity generation. When biogas is purified, the methane component can be upgraded to biomethane, which can be used as a substitute for natural gas in pipelines or compressed for use as a vehicle fuel (Kelleher et al., 2002). Replacing fossil fuels with methane as a bioenergy source can reduce carbon dioxide emissions. Anaerobic digestion can handle pasty and moist poultry wastes, minimize pathogens and odors, and treat them with minimal land area. Furthermore, the process may be effectively regulated to minimize any discharges into the air, water, or land. The majority of nutrients remain in the byproducts after anaerobic digestion and can be extracted for use in animal feedstock or agriculture, such as digestate for soil amendment, biogas for energy, and nutrient-rich liquids and fertilizers (Singh et al., 2010).

Pyrolysis and gasification

Pyrolysis is the process of using heat to break down biomass in the absence of oxygen. Syngas, mostly biogas, biocharcoal, and biocrude oil, is produced via pyrolysis (Demirbas and Arin, 2002). Pyrolysis of poultry manure can produce valuable chemicals, liquid fuels, and solid char that can be used as a fertilizer. In agriculture, the solid char generated can enhance soil quality (Zikhali et al., 2023). Sikder and Joardar (2019) examined the effectiveness of poultry litter and its char as fertilizers for *Gima Kalmi* plants. They found that applying either fertilizer significantly increased plant growth or biomass output. Notably, poultry char utilization enhances growth more.

After pyrolysis, gasification is a step that further breaks down partly degraded biomass or organic material into a mixture of flammable gases by raising the temperature and regulating the oxygen content (Dupont et al., 2007). The gas, tar, and char produced by pyrolysis continue to react during the gasification phase. Gasification is a fundamental method in the manufacture of chemicals and clean electricity. It involves converting biomass into fuel gas, typically containing CH₄ and some N₂, or syngas, which mostly consists of H₂ and CO. Several reactions, such as methanation and tar cracking, occur during the gasification process (Goktepe, 2015). In gasification, volatile hydrocarbons and char are converted to syngas in the presence of steam. The resulting syngas can be used for electricity generation, as a fuel for internal combustion engines, or as a chemical feedstock for producing hydrogen, methanol, and other valuable chemicals (Chhiti and Kemiha, 2013).

The study by De Priall et al. (2022) stated that converting waste biomass resources through downdraft gasification can produce gas for a combined heat and power unit. With appropriate conversion methods in place, switching from fossil fuels to downdraft gasification could save thousands of pounds a year, improve environmental performance, and ensure energy security. In recent years, there has been interest in the gasification of poultry litter. Small-scale (less than 250 kW) gasification units can provide on-site heat and power for poultry farms (De Priall et al., 2021). Generally, pyrolysis and gasification provide a significant contribution to waste recycling, which is known to be a circular-economy model for handling poultry litter waste, although they require high energy inputs and elevated temperatures.

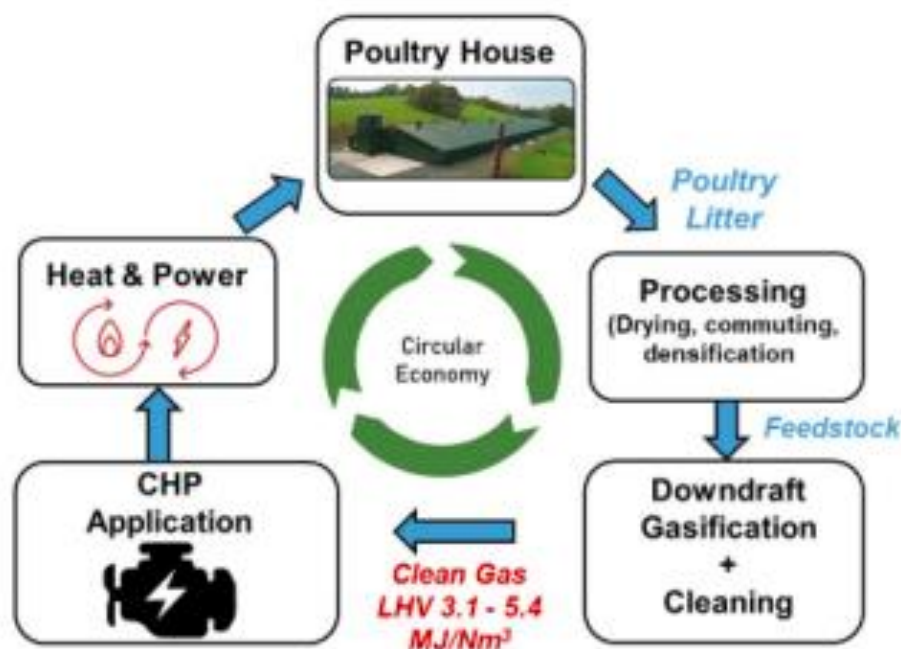


Figure 1. Circular economy model to handle poultry litter waste. Source: De Priall et al. (2022)

Rendering

Rendering is a technique that has proven to be effective in preserving the nutritional quality of animal by-products and converting them into new, high-quality, and safe products (Farmanesh et al., 2019). This method continues to hold substantial importance on a global scale, as it is currently the most regulated approach for handling the disposal of animal by-products and mortalities (Leiva et al., 2018). It is an effective way to lessen environmental contamination (Sindt and Engineer, 2006). The process of waste recycling through rendering is commonly employed in slaughterhouses, livestock, poultry, and fish farms by utilizing a combination of mechanical, thermal, and sometimes chemical processes (Hicks and Verbeek, 2016).

It is crucial to subject the poultry by-products to a minimum temperature of 133°C for at least 20 minutes under a pressure of 3 bars to ensure safety (inactivate harmful microorganisms; Muduli et al., 2019). Whole, undecomposed poultry by-products, such as soft wastes, bones, feathers, and other specific portions of the carcass, can be broken down by autoclaving at high temperatures and pressure either separately or in combination. This makes the by-products useful for animal feed, biogas plant feedstock, chemical industry products, or renewable biofuel (Kantarli et al., 2016). By eliminating moisture and destroying microbes, heat treatment also lengthens the shelf life of the finished goods (Disposal, 2004). It yields animal feedstock, such as meat and bone meal (MBM) and

tallow (fats and oils), or pelleted soil additions. The tallow can be used in the soap, cosmetics, and pharmaceutical sectors, as well as in animal feed and other applications. Meat and bone meal is used as a non-ruminant stock feed or fertilizer (Bandaw and Herago, 2017).

Microbial and enzymatic treatment

Microbial bioconversion is a technique that has garnered a lot of attention and is increasingly used to address the drawbacks and environmental problems associated with conventional poultry waste processing. Microbial bioconversion processes biowaste into useful biofuels and chemicals by using a variety of microorganisms, such as bacteria, yeasts, fungi, and microalgae (Brandelli et al., 2015; Paula et al., 2019). This approach leverages the ability of certain microorganisms, particularly proteolytic bacteria and fungi, to degrade and hydrolyze the recalcitrant keratin present in feather waste, thereby releasing amino acids and peptides (Karuppanan et al., 2021; Sahoo et al., 2023). It has been demonstrated that a variety of microbial enzymes, including lipases, proteases, and combination enzyme preparations, are advantageous in the bioconversion of poultry wastes (Brandelli et al., 2015).

One class of proteolytic enzymes, called keratinases, breaks down keratin found in hair, feathers, nails, and collagen. A variety of keratinolytic bacteria produce keratinases, peptidases that break down keratin in feathers

(Jeevana et al., 2013). According to Mazotto et al. (2011), certain *Bacillus* species, *actinomycetes*, and fungi are among the keratinolytic microorganisms that can produce these keratinases and peptidases. Compared with other similar proteases, keratinases are efficient on dense substrates, such as keratin-rich waste (Brandelli, 2008). Because of their many uses in the hydrolysis of keratinous substrates, especially the leftovers from agro-industrial processes, these enzymes are becoming increasingly important (Anitha and Palanivelu, 2013).

By converting the keratin present in feather debris, keratinases can produce protein hydrolysates that can be added to animal feed as supplements or used to make nitrogen fertilizers. The development of microorganism-derived enzymes has generally created opportunities to improve energy-efficient technologies, such as anaerobic digestion and enzymatic hydrolysis, that can bioconvert poultry waste into lucrative end products (Brandelli et al., 2015). It is now possible to isolate bacteria that degrade feathers from chicken waste. Three strains of *Bacillus subtilis*, *Bacillus pumilus*, and *Bacillus cereus* are among the isolates capable of degrading feathers, producing keratinolytic activity of 142, 96, and 109 units/mL, respectively (one unit is defined as the amount of enzyme causing a 0.01 increase in absorbance at 280 nm from TCA-soluble peptides released from feather keratin under assay conditions; Muduli et al., 2019).

Vermicomposting

The process of vermicomposting involves the utilization of earthworms, specifically *Eisenia andrei* and *foetida*, to break down organic material into nutrient-rich compost. Earthworms are primarily used, even if other microorganisms are also included (Khan, 2006). In vermicomposting, one kilogram of earthworms consumes one kilogram of residue per day. The worm excrement is rich in nutrients that improve soil fertility. In addition, vermicompost can also increase the multiplication of other microorganisms in the soil by up to sixfold, which accelerates decomposition and nutrient release (Jayakumar et al., 2011).

Perionyx ceylanensis can vermicompost organic substrates, such as turkey litter mixed with cow dung (1:1), producing a nutrient-rich vermicompost (1). Vermicompost has a higher microbial population and greater soil nutrient levels, making it a useful fertilizer (Jayakumar et al., 2011). However, the process of vermicomposting poultry litter is not without challenges. The high ammonia content and potential presence of heavy metals in poultry litter can be detrimental to

earthworms and may inhibit their activity and reproduction (Hamilton et al., 2008). To mitigate these issues, it is often recommended to pre-compost the poultry litter for a short period to lower the ammonia levels and to mix it with other organic materials to dilute potential toxins (Sharma, 2003).

POULTRY WASTE-DERIVED PRODUCTS

In order to face the problems that come with poultry industrialization and respond to population growth, it is necessary to focus on recycling natural resources (Thore et al., 2021). Thus, poultry waste can be converted into useful products through various methods, such as composting, anaerobic digestion, pyrolysis and gasification, rendering, microbial and enzymatic treatment, and vermicomposting (Zhang, 2023). Among such products, feather meal can be mentioned, which can be obtained through chemical and physical treatments of poultry feathers or by using keratinolytic bacteria. Feather meal can be used as feed and supplements for livestock and poultry, as organic fertilizer, and in biodiesel production (Syed et al., 2009; Tiwary, 2012). Another product produced from chicken feathers is nonwoven textile material (lightweight, insulating, and biodegradable fabrics used for applications such as thermal insulation, filtration, cushioning, and sound absorption; Chinta, 2013). Concurrently, the recoveries of chicken feather keratin serve as a primary raw material for many sectors, such as animal feed, chemicals, medicine, biotechnology, and beauty care (Ma et al., 2016; Muduli et al., 2019).

On the other hand, poultry litter is a useful by-product used as an organic fertilizer to increase soil fertility and hence yields. It has nitrogen, phosphorus, and potassium, which make it an appropriate soil fertilizer, and it also regulates the water-holding capacity of the soil (Olumayowa and Abiodun, 2011). However, the conventional uses of poultry litter have a number of drawbacks, including water pollution through eutrophication, pathogen transmission, and production of noxious compounds, air pollution, and greenhouse gas emissions. To address these issues, composting and pelletizing methods have been employed. These methods dispose of nutrients slowly and allow them to be taken up gradually, thus causing the least harm to the environment (Shakya and Agarwal, 2017).

Poultry litter can be incorporated into the diets of dairy calves, sheep, and beef calves. Nonetheless, the ash level should be kept as low as possible, and the litter should be well processed to minimize the risk of

pathogens such as *Salmonella*, *Clostridium*, and *Enterobacter spp.* (Kawata et al., 2006; Bolan et al., 2010). Heating is needed to destroy mycotoxins produced by fungi in the manure or litter. Despite the application of processing of poultry litter for use as animal feed, such as drying, heat treatment, composting, fermentation, or pelleting, which aims to reduce pathogens and improve

safety, feeding the animals with litter has had limited usage in animal farming since it has some bad public perception of coprophagia (Bolan et al., 2010). Additionally, it has the potential to cause copper toxicity, especially in sheep, which requires careful management (Sharma et al., 2005).

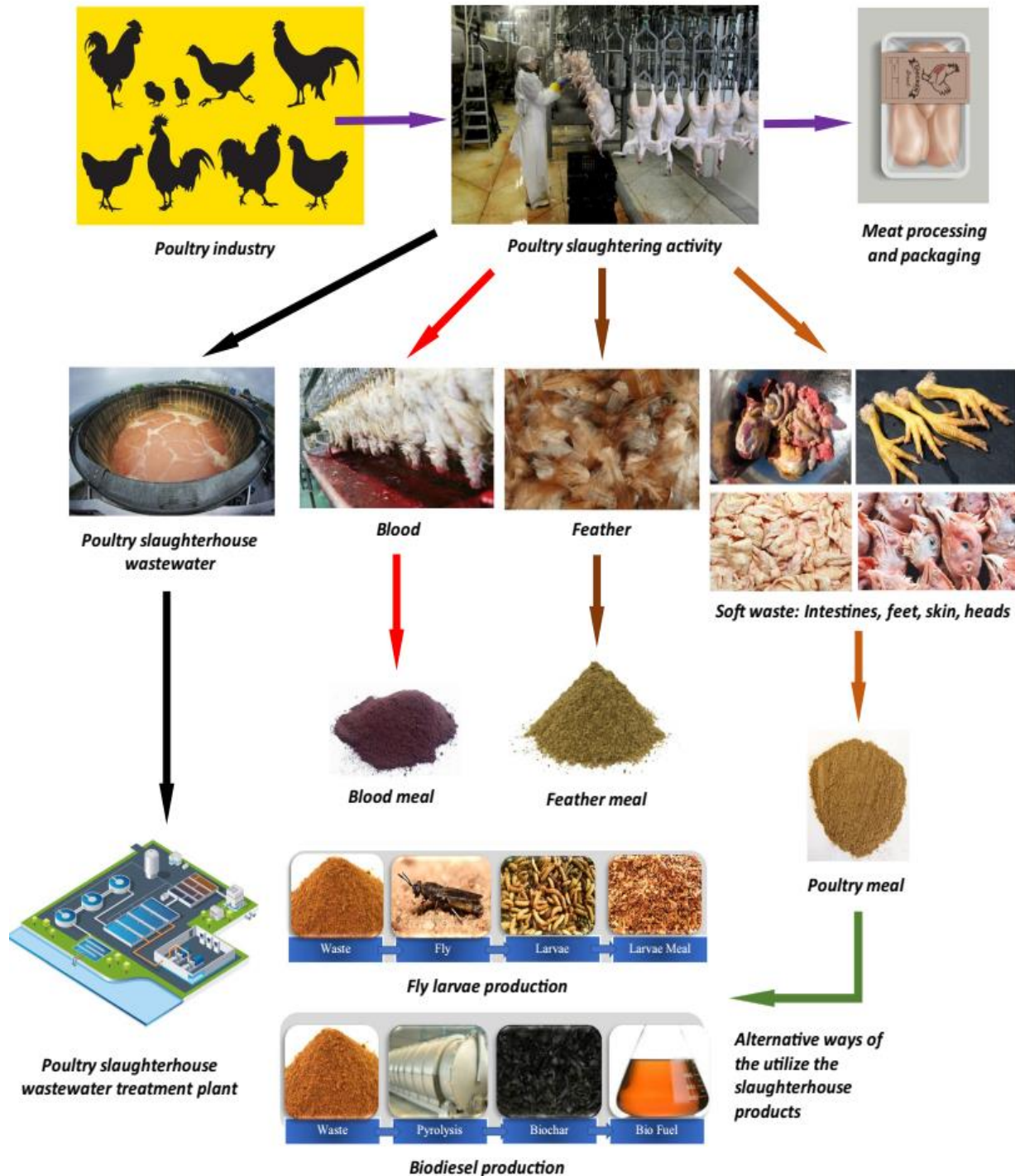


Figure 1. The poultry slaughtering and post-processing activities. Source: Ozdemir and Yetilmezsoy (2019)

Waste generated from poultry abattoirs, such as blood, offal, and other by-products, represents an important resource for recovery and is commonly converted into poultry meal and fat through rendering, a process that involves heating the material to separate and distill fats from proteins (Salminen and Rintala, 2002). Rendered fats from animal sources are commonly used in animal feed because they are cheaper than vegetable oils (Lewis et al., 2019). Blood meal is another animal-origin feed ingredient produced from fresh blood, dried, and ground into a meal. It is used in animal feeds, especially in aquafeed and pet food. Additionally, blood meal can be used as a fertilizer (Pearl, 2004).

Furthermore, poultry waste can be used to feed fly larvae such as the house fly (*Musca domestica*) and the black soldier fly (*Hermetia illucens*). Such flies transform the waste into high-protein biomass that is used to feed fish farms and other livestock (Kenis et al., 2018; Khan, 2018). This method will not only help eliminate waste but also align with the principles of the circular economy by converting low-value waste into a high-value feed product (Hwangbo et al., 2009). The production of biogas is another possible application for poultry abattoir waste. Organic waste materials are broken down via anaerobic digestion to produce biogas, which is mostly methane and can be used as a source of energy (Sahlström, 2003).

Amongst all the components of hatchery wastes, eggshells hold a lot of potential for the recovery of resources and the creation of new products. Because of the high content of calcium, it can be added advantageously to animal feed supplements. In aquaculture, powdered eggshells are useful in feeding the fish and fertilizing algae, thus helping in creating a symbiotic system of farming (Amarnath et al., 2020). Furthermore, eggshells can be utilized as supplements to calcium-fortified foods such as cakes, yogurts, sausages, biscuits, and calcium-enriched coffee (Aditya et al., 2021).

Another potential application of eggshells is in the co-composting mixtures for the improvement of the soil. It can improve soil fertility and structure by balancing acidity with calcium (Soares et al., 2015). Eggshells can also be used in the production of biodiesel by acting as an excellent catalyst (Khemthong et al., 2012). However, eggshells must be heat-treated to remove any microbial contamination before they can be used in the above-mentioned applications. It is an important aspect to ensure that all the final products are safe to be used in agricultural and industrial practices, as well as to observe hygiene,

most importantly to control communicable diseases (Yoo et al., 2009).

Another valuable hatchery waste is eggshell membrane, which is rich in collagen that could be retrieved. Collagens obtained from eggshells can be used in the production of foods, drugs, and cosmetics due to the valuable properties inherent in this biomaterial. In the food industry, it can help improve the texture, color, and nutritional content of many food products (Kulshreshtha et al., 2022). In pharmaceuticals, it is valued for its curative and restorative properties, particularly as a remedy for diseases of the joints and connective tissues (Ruff et al., 2012). In cosmetics, it is highly valued for properties that enhance skin elasticity and skin moisture content (Marimuthu et al., 2020).

CONCLUSION

Poultry waste generation increases substantially in conjunction with sectoral advancements. Conventional methods for poultry waste disposal, such as landfilling, burning, burial, and incineration, are inadequate for effectively managing and utilizing this waste. Furthermore, these methods do not effectively address environmental pollution and disease transmission, leading to issues such as nutrient runoff, water pollution, soil contamination, unpleasant odors, and health risks. Conversely, the valorization of poultry waste through composting, anaerobic digestion, pyrolysis, gasification, rendering, vermicomposting, and microbial enzymatic treatment presents a superior and environmentally friendly solution for both the disposal and utilization of poultry waste by converting it into useful products such as organic fertilizer, animal feed, biogas, drugs, and cosmetics. Therefore, based on the above conclusion, it is recommended that education and training programs be introduced to poultry farmers and other industry operators to facilitate the adoption of environmentally friendly poultry waste valorization practices; a community-based approach to managing poultry waste with active participation of local stakeholders should be encouraged. Furthermore, tight collaboration among academia, industry, and government agencies is needed to expand knowledge sharing and ensure efficient technology transfer in poultry waste management. Future research should focus on the development and optimization of innovative poultry waste valorization technologies to evaluate the long-term environmental and economic implications for local production systems.

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Authors' contributions

The idea, literature review, and draft manuscript were conceptualized by Mohammed Beriso Godana. Ewonetu Kebede Senbeta conducted the scientific aspects of the manuscript and reviewed it for editing and finalization. The authors reviewed and approved the final version of the manuscript.

Availability of data and materials

As a review, the present study has no original experimental results. However, any supporting materials or information can be provided upon request from the corresponding author.

Ethical considerations

The present article does not involve any animal or human experiments. The authors carefully observed and addressed ethical concerns, including plagiarism, misconduct, data integrity, and duplicate publication. The authors confirm that AI (Grammarly) was only used to correct some limited grammar errors in this study.

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Competing interests

The authors declared no conflicts of interest regarding the publication of the present study.

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