Review Article

TRANSFORMING OF POULTRY MANURE INTO VALUE: COMMERCIAL STRATEGIES FOR COMPOSTING, BIOENERGY AND ANIMAL NUTRITION

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ABSTRACT

Poultry manure is generated in large quantities by the rapidly expanding poultry industry and poses serious environmental management challenges when disposed of without appropriate treatment. This review critically synthesizes commercial technologies for the valorization of poultry manure into compost, bio energy and value-added agricultural inputs, with emphasis on process performance, safety and applicability under Indian conditions. Aerobic composting (windrow, in-vessel and vermin composting), anaerobic digestion and thermo chemical conversion routes are comparatively evaluated based on operating parameters, pathogen reduction efficiency, nutrient conservation and scalability. Anaerobic digestion offers dual benefits of renewable biogas generation and nutrient-rich digestate production, while composting remains the most economically feasible option for decentralized farm-level manure management. Pyrolysis-derived biochar and bio-oil provide emerging opportunities for carbon sequestration and renewable fuel production, though economic and infrastructural barriers currently limit their adoption in India. The utilization of processed poultry manure in animal feed is constrained by regulatory and biosafety considerations. This review highlights major technological gaps, economic challenges and policy needs for sustainable poultry manure valorization and proposes integrated circular-economy frameworks suitable for Indian poultry production systems.

Keywords: Poultry manure; composting; anaerobic digestion;pyrolysis; biochar; circular bioeconomy.

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INTRODUCTION

The global populationcrossed8 billion in 2022 and is projected to reach nearly 10 billion by 2050. This demographic surge is placing tremendous pressure on food systems, with forecasts suggesting that agricultural production will need to almost double to satisfy future food requirements (Manogaran *et al*., 2022). In recent years, dietary patterns in many developing nations have begun to align with those of developed countries, driven by economic growth, urban expansion, and population increases. This shift has led to a notable rise in poultry meat consumption, which in turn has brought about significant challenges in the management and disposal of poultry manure (Lee *et al*., 2017).

Chickens typically generate between 80 and 100 grams of manure per day, amounting to roughly 3–4% of their body weight (Abdeshahian *et al.*, 2016). Like other forms of livestock waste, poultry manure is rich in nutrients-particularly nitrogen, phosphorus, and potassium and is often directly applied to agricultural land as an organic fertilizer without prior treatment. This review critically synthesizes major poultry manure valorization pathways including composting, anaerobic digestion and thermo chemical conversion with emphasis on process efficiency, biosafety, economic feasibility and applicability under Indian poultry production systems.

The quantity and composition of poultry manure are influenced by several factors, including the birds' age, diet, health status, and overall farm management practices. The physico-chemical characteristics of chicken manure are critical in determining the most effective treatment method, particularly for minimizing energy use and chemical inputs while enhancing bioenergy yield from the waste material (Meky *et al*., 2021). Chicken manure is notably rich in organic matter, ammonia-nitrogen, pathogenic organisms, and microbial communities, including bacteria involved in organic degradation, as highlighted by Ibrahim *et al.* (2022). The reported total solids content is approximately 59.16 ± 0.06%, with volatile solids accounting for 48.19 ± 0.24%, yielding a volatile-to-total solids ratio of 80.15%.These properties make chicken manure a promising feedstock for bioenergy generation processes, especially anaerobic digestion for biogas production, due to its high solid content and favorable biodegradability.

In addition, the manure's nutrient profile supports diverse utilization strategies. Its elemental composition-carbon (38.91% ± 0.78), nitrogen (9.39% ± 0.21), sulfur (0.47% ±0.02), and hydrogen (5.68% ± 0.16) make it highly suitable for direct application as an organic fertilizer, thereby promoting its reuse in sustainable agricultural systems (Wang *et al.*, 2022).

Composting

Composting involves the controlled aerobic decomposition of poultry manure combined with organic additives and bulking materials to enhance microbial activity. This process promotes the generation of thermophilic conditions, which are essential for the rapid stabilization of organic matter and the production of a pathogen-free, mature compost suitable for agricultural use (Akdeniz, 2019). The composting procedure generally progresses through four distinct phases. Initially, mesophilic microorganisms, which thrive in temperatures between 20–45°C, initiate the hydrolysis of organic substrates such as proteins and carbohydrates. Their metabolic activity elevates the compost's internal temperature to around 65–68°C, creating favorable conditions for thermophilic microorganisms to dominate. At this elevated temperature, most pathogens are effectively inactivated (Tuomela *et al*., 2000).

As the more easily degradable compounds are exhausted, microbial activity declines, causing the compost temperature to drop. During this cooling and maturation phase, fungi become more active and degrade more complex polymers like cellulose, hemicellulose, and lignin. This transformation typically spans 3 to 6 months, culminating in the formation of stable humic substances. The resulting compost is nutrient-rich, microbiologically safe, and commonly applied as a sustainable organic fertilizer (Li *et al*., 2020).

Key environmental parameters including temperature, moisture content, porosity, aeration rate, pH, and the carbon-to-nitrogen (C/N) ratio play a crucial role in shaping microbial dynamics and metabolic activity during composting. These factors directly influence the efficiency of the decomposition process and the quality of the final compost product (Wang *et al*., 2018). Optimal composting conditions typically involve maintaining a moisture level of 50–60% on a wet basis, a C/N ratio in the range of 25 to 30, and a pH between 5.5 and 9. The ideal temperature for thermophilic microbial activity falls between 55°C and 63°C, while sustaining an oxygen concentration above 5% is essential to support aerobic microbial processes.

Windrow composting involves the periodic turning or mechanical aeration of piled organic material to sustain optimal microbial activity and environmental conditions. This method is widely regarded as cost-effective for pathogen reduction and enhancing the quality of poultry litter. Typical windrow dimensions range from 1 to 3.5 meters in height and 2.5 to 6 meters in width. Windrow composting of broiler litter between production cycles is increasingly adopted to reduce microbial contamination within poultry facilities (Macklin *et al.*, 2007).

In-vessel composting integrates multiple composting approaches within a confined, controlled reactor system. Poultry manure is often mixed with bulking agents such as sawdust and dried plant residues before being placed in the bioreactor, where it undergoes accelerated composting over 4 to 6 days under regulated temperature, moisture, and aeration conditions (Cawthon, 1998). This approach enhances process efficiency and pathogen destruction while minimizing environmental emissions.

Passive composting represents a low-maintenance approach, wherein organic materials are heaped and left to decompose naturally over an extended period. Aeration occurs passively through convection-driven air flow, commonly known as the chimney effect, where cooler air enters at the base as warm gases exit from the top, promoting aerobic microbial activity (Ogunwande and Osunade, 2011).

Vermi composting utilizes earthworms, primarily species like *Eisenia fetida*, to biologically process organic waste. These earthworms can consume organic matter at rates approaching 1 kg per kg of worm biomass daily. The resulting worm castings are rich in essential plant nutrients including nitrates, phosphorus, potassium, calcium, and magnesium, makingthem an excellent organic fertilizer. The activity of earthworms also promotes the proliferation of beneficial microbes such as actinomycetes, increasing soil microbial populations by upto six fold compared to unamended soil (Jayakumar *et al.*, 2011).

Windrow composting is economically viable for medium–large farms, whereas in-vessel composting provides rapid stabilization and superior pathogen destruction suitable for centralized compost plants. Vermi composting retains maximum nutrients and microbial diversity, making it suitable for organic input markets. Passive composting is least capital intensive but slower and less efficient.

In India, the Central Pollution Control Board (CPCB) recommends composting and anaerobic digestion as preferred poultry manure treatment methods, while the Food Safety and Standards Authority of India (FSSAI) prohibits the use of poultry excreta as an animal feed ingredient.

Regulatory constraints on manure-derived feed resources

The Association of American Feed Control Officials (AAFCO) has defined standardized terms for three types of processed poultry waste materials approved for use in animal feed, as documented by the U.S. Food and Drug Administration (FDA, 2009). These include: dried poultry waste, poultry waste with extracted non-protein nitrogen (NPN) referring to the removal of urea and/or uric acid and dried poultry litter. These classifications facilitate regulatory compliance and ensure safety in feed formulation.

Despite its potential nutritional and economic benefits, the inclusion of processed poultry waste in animal feed has raised significant ethical and safety concerns. One of the primary issues is the potential for disease transmission due to the presence of pathogens, antibiotic residues, heavy metals, and other contaminants commonly found in poultry excreta. These concerns are amplified by the possibility of bioaccumulation of harmful substances in the food chain, posing risks to both animal and human health. As a result, several countries have imposed strict regulations or outright bans on the use of poultry litter and excreta in livestock and poultry feed. For instance, the European Union prohibits the use of manure and litter in feed due to concerns about food safety and animal welfare. Similarly, India's Food Safety and Standards Authority (FSSAI) does not permit poultry excreta as a feed ingredient under current regulatory guidelines.

Biogas production

Anaerobic digestion (AD) is a biological process that utilizes multiple microbial consortia to degrade organic substrates in the absence of oxygen. This process occurs under strictly anaerobic conditions, typically characterized by an oxidation reduction potential (ORP) below

−200mV, and results in the production of biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2).AD proceeds through four key biochemical stages: hydrolysis, where complex organic matter is broken down into simpler soluble compounds; acidogenesis, which converts these products into volatile fatty acids and other intermediates; acetogenesis, where acids are further converted into acetic acid, hydrogen, and carbon dioxide; and finally, methanogenesis, in which methanogenic archaea produce methane from acetic acid or hydrogen and carbon dioxide.

AD provides both energy and fertilizer benefits and is the most sustainable technology for clustered poultry belts.In anaerobic digestion, hydrolysis is the initial phase where complex organic compounds such as proteins, lipids, carbohydrates, and nucleic acids are broken down into solublemonomers by extracellular enzymes (e.g., cellulase, xylanase, lipase) secreted by hydrolytic bacteria. These monomers are then processed during acidogenesis by facultative and obligate anaerobes, producing short-chain fatty acids, alcohols, hydrogen, carbondioxide and volatile fatty acids (VFAs) (Bharathiraja *et al.*, 2018). The concentration of hydrogen generated in this stage significantly influences the metabolic pathways and end-products formed.

During acetogenesis, there intermediates are further converted primarily into acetic acid by homoacetogenic bacteria, which utilize H_2 and Co_2 in a symbiotic relationship with methanogens (Kremp *et al.*, 2018; Mutungwazi *et al.*, 2021). This step is critical as acetate serves as a direct substrate for methanogenesis, the final stage, methane is produced either by acetoclastic methanogens, which convert acetate to CH_4 adn CO_2 (Szuhaj *et al.*, 2016), or by hydrogenotrophic methanogens, which reduce CO_2 using H_2 (Bharathiraja *et al.*, 2018).

Thermo chemical conversion and pyrolysis products

Pyrolysis refers to the thermo chemical decomposition of biomass under an oxygen-free environment, leading to the formation of three main products: bio-oil, solid biochar, and non- condensable gases. This process involves a complex network of concurrent and sequential reactions that occur when organic material is subjected to elevated temperatures in an inert atmosphere (Kan *et al*., 2016). Depending on operational parameters such as heating rate, temperature, and residence time, pyrolysis is generally classified into three distinct types: slow pyrolysis, fast pyrolysis, and flash pyrolysis. Slow pyrolysis operates at low temperatures and heating rates, with extended vapor residence times ranging from 5 to 30 minutes. This prolonged interaction among vapor-phase compounds promotes higher char yields, though it compromises bio-oil quality due to secondary cracking reactions. The extended duration and low heat transfer efficiency also demand greater energy input (Selvarajoo, 2021).

Fast pyrolysis, in contrast, involves rapid heating of biomass in the absence of oxygen, with carefully controlled reaction temperatures and short vapor residence times. This setup favors bio-oil production, offering high energy efficiency and low capital cost—especially for small-scale applications. The produced bio-oil is easily stored and transported, making the process attractive for generating liquid fuels and specialty chemicals (Selvarajoo, 2021).

Flash pyrolysis is characterized by extremely high heating rates and very short gas residence times (less than 1 second) at temperatures between 450–1000°C. It can yield up to 75% bio-oil, making it suitable for fuel generation. However, it presents challenges such as poor thermal stability, oil corrosiveness, high viscosity, and contamination with solids and pyrolytic water due to char-related reactions (Patel *et al.*, 2020; Gupta *et al.*, 2021).

Biochar is a carbon-rich, porous solid with a high energy density, well-developed surface area, and robust structural stability, including resistance to decomposition and aromatization. In the context of animal manure pyrolysis, the most defining feature is it selevated ash content,with biochar being the primary output under conditions of low temperature, slow heating rates, and extended residence times (Chen *et al.*, 2021). Manure-derived biocharis widely employed as a soil amendment owing to its porous architecture and high nutrient content, which collectively enhance soil fertility. Beyond agriculture, biochar finds applications as an adsorbent for environmental contaminants, a medium for carbon sequestration, a catalyst in pyrolysis reactions, and a material in energy storage systems, such as super capacitors. Additionally, during the pyrolysis process, heavy metals present in manure become immobilized within the biochar matrix, effectively reducing their environmental mobility and preventing soil and water contamination (Yu *et al.*, 2020).

Bio-oil is considered the most valuable output of the pyrolysis process, offering significant promise as a renewable substitute for fossil fuels in both transportation and industrial sectors. It also serves as a sustainable feedstock for producing various chemicals and materials. Unlike intermittent energy sources such as wind, solar, tidal, and geothermal power, bio-oil can be easily stored and transported, making it a reliable energy carrier that enhances energy security. Optimal bio-oil production requires high temperatures, rapid heating rates, and brief vapor residence times. (Erdogdu *et al.*, 2019).

In conventional pyrolysis of manure, biogas is generated as a secondary product, constituting approximately 40 wt% of the output. However, its lower heating value (LHV) remains moderate due to the inherently low hydrogen-to-carbon (H/C) ratio in manure. Elevated temperatures and extended residence times favor increased biogas production, yet pyrolysis conditions are typically optimized to maximize biochar or bio-oil yields, which limits biogas generation (Huang *et al.*, 2022). The primary constituents of manure-derived biogas include hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ethylene (C_2H_4), propylene (C_3H_6), along with trace amounts of light hydrocarbons.

Biogas produced is often utilized as a heat source during pyrolysis or pretreatment steps to improve overall process energy efficiency.

Economic Feasibility

Among the available poultry manure valorization pathways, composting remains the most economically viable option for decentralized farm-level adoption due to its low capital investment, simple infrastructure requirements and stable market demand for organic fertilizers. Anaerobic digestion involves moderate initial costs but offers long-term economic benefits through renewable energy generation, savings on electricity and cooking fuel, and production of nutrient-rich digestate. Thermo chemical conversion through pyrolysis is comparatively capital intensive and currently feasible mainly for centralized facilities, limiting its adoption in small and medium poultry farms. Overall, economic sustainability of poultry manure valorization in India depends largely on scale of operation, availability of incentives, energy tariffs and access to organized manure-based product markets.

Despite extensive research on poultry manure management, most studies remain laboratory-based and lack region-specific techno-economic evaluations under commercial Indian farming conditions. Standardized quality benchmarks for manure-derived compost, digestate and biochar suitable for Indian soils are inadequately defined, and long-term environmental impact data are limited. Moreover, integration of poultry manure valorization into national circular bioeconomy policies, incentive frameworks and carbon-credit mechanisms remains insufficiently explored, highlighting the need for applied, field-scale research to enable sustainable large-scale adoption. The review is limited by the availability of region-specific techno-economic data and long-term field performance studies in India.

CONCLUSION

Poultry manure valorization offers a viable pathway for integrating waste management with renewable energy and sustainable agriculture. Composting remains the most feasible decentralized solution in India, while anaerobic digestion provides superior environmental and energy benefits for clustered poultry regions. Pyrolysis-derived biochar represents a promising but capital-intensive emerging option. Future research must focus on Indian techno-economic optimization, digestate quality standardization, and carbon-credit-linked incentive frameworks to enable large-scale adoption.

Table.1. Comparative performance of poultry manure composting technologies

Parameter	Windrow	In-vessel	Passive	Vermi composting
Process duration	30–60 days	4–10 days	3–6 months	45–60 days
Pathogen reduction	High	Very high	Moderate	High
Capital cost	Low	High	Very low	Low
Labour requirement	Moderate	Low	Very low	Moderate
Nutrient retention	Moderate	High	Low	Very high
Suitability	Medium & large farms	Commercial centralized units	Backyard & small farms	Organic farming units

Table 2. Anaerobic Digestion Performance and Energy Potential

Parameter	Typical range
Methane content	55–65 %
Biogas yield	0.25–0.35 m^3/kg VS
Pathogen reduction	>99 %
Digestate value	Rich NPK bio fertilizer

Table 3. Pyrolysis, Biochar and Bio-oil Synthesis

Product	Value
Biochar yield	30–45 %
Bio-oil yield	35–55 %
Carbon sequestration	High
Heavy metal immobilization	Effective

Limitation: High capital cost and lack of Indian demonstration plants restrict adoption.

Table 4. Safety and Pathogen Reduction

Technology	Salmonella	E. coli	Helminths
Windrow	✓	✓	✓
In-vessel	✓ ✓	✓ ✓	✓ ✓
AD	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Passive	✓	✓	✗

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