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REVIEW ARTICLE

Slaughterhouse and poultry wastes: management practices, feedstocks for renewable energy production, and recovery of value added products

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Abstract
The slaughterhouse and poultry industry is possibly one of the fastest-growing sectors driven by the increasing demand in food availability. Subsequently, the wastes produced from the slaughterhouse and poultry industry are in huge quantities, which could be a promising resource for the recovery of value added products, and bioenergy production to minimize the dependence on fossil fuels. Furthermore, the wastes from slaughterhouses and poultry are a hub of pathogens that is capable of infecting humans and animals. This demands the emerging need for an effective and safe disposal method to reduce the spread of diseases following animal slaughtering. In light of that, the state of the production of slaughterhouse and poultry wastes was presented at first. Following this, the impact of solid waste exposure in terms of air, water, and soil pollution and the associated health challenges due to improper solid waste management practices were presented to highlight the importance of the topic. Secondly, the potency of these solid wastes and the various waste-to-energy technologies that have been employed for effective management and resource utilization of wastes generated from slaughterhouses and poultry were reviewed in detail. Finally, this review also highlights the opportunities and challenges associated with effective solid waste management, future requirements for the development of effective technologies for the recovery of value added products (like keratin, fibreboards), and biofuel production.

Keywords Solid waste · Municipal solid waste · Waste management · Slaughterhouse waste · Poultry waste · Energy/product recovery

Abbreviations

AD	Anaerobic digestion
MSW	Municipal solid waste
GHG	Greenhouse gas
C/N ratio	Carbon /nitrogen ratio
VS	Volatile solids
GI	Germination index
CMB	Chicken manure bio-char
FFA	Free fatty acid
FAME	Fatty acid methyl esters
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
CFME	Chicken fat methyl ester
SBY	Specific biogas yield
SMY	Specific methane yield
OLR	Organic loading rates
LCFA	Long-chain fatty acids
HRT	Hydraulic retention time
DNA	Deoxyribonucleic acid
gDNA	Genomic DNA
PCI method	Phenol, chloroform, and isoamyl alcohol method
RBB + C	Repeated beat beating column method
PCR	Polymerase chain reaction
SDGs	Sustainable development goal

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1 Introduction

Solid waste generation is an alarming issue worldwide due to the significant rise in population growth along with industrialization and urbanization, which retains terrific pressure on the environment and public health [1, 2]. Similarly, the management of these solid wastes is another worldwide problem because of the complexity associated with waste segregation, collection, transportation, treatment, and disposal, which greatly affect environmental sustainability. Furthermore, the improper disposal of solid wastes also creates several environmental (water, air, and soil pollution) and health issues like waterborne diseases and respiratory illness resulting from the open burning of wastes.

Global solid waste generation is estimated to be about 11.2 billion tons per year, which is projected to increase by 19 billion tons per year by 2025 [3, 4]. Out of the solid wastes, global municipal solid waste (MSW) generation was found to be about 2.01 billion tons per year resultant from the global population of 7.8 billion [5, 6]. It is estimated that the global population is projected to increase to 9.9 billion by 2050 which is approximately 26.9% increase than the present population during which the MSW generation is estimated to increase approximately by 70%, i.e., 3.4 billion tons per year. Out of the 2.01 billion tons of MSW generated annually, it was reported that about 33% is not treated properly, and thus, improper management of solid waste is quite common in many developing countries. Along with waste-handling issues, solid wastes also contribute 3% of global greenhouse gas (GHG) emissions [7]. Among these solid wastes, animal byproducts are well-recognized drivers of GHG. It was also investigated from the life cycle assessment study that meatless meals showed a 40% reduction in environmental impacts while compared to the meat-containing meals in the assessed indicators like carbon footprint, resource consumption, water use, and health impacts [8].

Generally, slaughterhouse wastes are animal byproducts that remain unutilized after slaughtering. The wastes from slaughterhouses are one of the major solid wastes that need to be accounted for. Because rising population ultimately increases the rate of meat consumption, thus abattoir waste management becomes a huge challenge, especially in urban centers. Furthermore, the amount of solid waste generation depends on the scale of the slaughtering process. Improper disposal of abattoir waste not only affects the air and water quality but also increases the threats to human health due to the presence of pathogenic microbes [9]. It is reported that about one-third to one-half of the total weight of slaughtered animal remains as unutilized or partly utilized byproducts of livestock and poultry industry [10, 11]. Similarly, the poultry industry is growing worldwide and provides huge employment opportunities, and alleviates poverty. In the poultry industry, huge quantities of wastes are being generated in terms of solid wastes (bedding material, feathers, hatchery wastes, blood, offal, shells, poultry manure/litter, etc.) and wastewater [12]. Though the poultry industries alleviate poverty, still abattoir wastes create a huge amount of environmental pollution by means of improper waste disposal or underutilization of wastes' potency. However, similar to large animal slaughterhouses, poultry wastes also have great potential for value added applications.

In many of the developing countries, like India, almost 3/4th fund allocated to urban solid waste management is utilized for waste collection and transportation [13]. This becomes a major constraint for the effective treatment of solid wastes. The main problem is the mixing of the segregated wastes like organic wastes from slaughterhouses or abattoir shops or from wholesale-centralized markets with other inorganic waste fractions. Hence, the segregation of organic wastes from centralized wholesale complexes like slaughterhouses or horticultural markets is highly essential to designing a sustainable and effective waste management system. The wastes from slaughterhouses and abattoir shops have huge potential for energy recovery or product recoveries like protein hydrolysate synthesis, enzymes, and lipids,however, they should be properly collected and treated in order to utilize their maximum potency. Hence, segregation of these bulk generators of organic wastes from Indian urban centers could prevent the inefficient use of the potency of this huge quantum of wastes [14, 15]. The suitable treatment options need to be explored to find their appropriateness based on each context. Thus, effective management of slaughterhouse and poultry wastes and their proper treatment and disposal and the value addition of slaughterhouse and poultry wastes has become one of the most significant thrust areas for the research community.

Recently, extensive researches have been focused on the development of techniques for the management of municipal solid wastes and their utilization in value-added industrial applications. So, plenty of literature and reviews exist on municipal solid waste management; however, this review article specifically intended to focus on slaughterhouse and poultry wastes, which often pose huge threats to the health and environment. Accordingly, this article reviewed several treatment alternatives suitable for the efficient utilization of slaughterhouse and poultry wastes and the process efficiencies. In addition, this review article presented in detail the quantum of waste generation and its composition, its impact on the environment, utilization potentials, and disposal options for effective utilization of the potency of these huge growing urban solid wastes. The results of this review could provide directions for the effective utilization of these bulk wastes to the stakeholders/municipal corporations to meet the urban waste management targets.

2 Global solid waste generation

Growing population along with urbanization and industrialization increases solid waste generation. Furthermore, the standards of living, disposable incomes, and consumption of goods and services increase the amount of solid waste generation. The World Bank indicated the global waste generation trend along with the projection from the year 2016–2050, which is shown in Fig. 1, which demonstrated that most of the world's waste is generated from East Asia and the Pacific region.

2.1 Municipal solid wastes generation and its composition

Municipal solid waste (MSW) is a major and critical component among the solid wastes which includes different types of waste such as household waste, commercial, construction, and demolition, institutional, retailers and shops, garden, and park waste [17]. Population increase and the associated industrialization encourage the migration of people from villages to cities for improvement in their lifestyle that generates thousands of tons of MSW daily. Globally, the composition of MSW includes 44% food and green waste, 17% paper and cardboard, 12% plastics, 5% glass, 4% metal, 2% wood, 2% rubber and leather, and 14% others. Similarly, in India, the composition of MSW include food and garden waste (40%), paper (27%), textile (6%), glass and ceramics (5%), plastic and rubber (4%), metals (3%), and inert (15%) [16]. However, the composition of MSW varies with time, and hence, the management of increasing trend of MSW generation creates significant problems in different countries, particularly in developing countries due to lack of knowledge, technical, financial, regulatory, and public participation [18]. Therefore, there is no denying that significant researches have been focused on the management and proper disposal of MSW and also effective utilization of resource-rich MSW for various applications.

2.2 Wastes of slaughterhouses and poultries

Slaughterhouse and poultry wastes are the commercial waste of MSW. The population growth increases the demand for meat products, livestock, and poultry products. It is estimated that the total world meat production is 220 million tons and is mainly contributed by buffaloes (31%), cattle (31%), sheep (5%), goats (10%), pigs (10%), and poultry (11%) [19]. Generally, slaughterhouse/abattoir operations produce a considerable amount of organic waste with relatively high levels of suspended solid, liquid, and fat [20] (Table 1). It is estimated that about 50–54% of each cow, 52% of each sheep or goat, 60–62% of each pig, 68–72% of each chicken, and 78% of each turkey is utilized for meat and the remaining is disposed of as waste [21, 22]. Furthermore, the bovine slaughterhouse generates solid waste of 27.5% of the animal weight, i.e., 275 kg/ton of total live weight killed. In the case of goat and sheep slaughterhouse, the waste generation is 2.5 kg/head that is equivalent to 17% of animal weight. Similarly, during pig slaughtering, an average waste generation is 2.3 kg/head that is equivalent to 4% of animal weight. In abattoir shops, on an average, 32.5–37.0% of poultry waste is being generated while a chicken is slaughtered, with the waste composition consisting of 57.37% of feathers and skin; 20.35% of intestines; 14.8% of legs and others (< 1%) [10, 23–25].

The slaughterhouse processes and the corresponding waste generation are schematically depicted in Fig. 2. The solid wastes from the slaughterhouses are categorized into two types namely vegetable matter (type I consisting of ruminal, stomach, and intestinal contents, dung) and animal matter (type II consisting of offals like inedible offals,

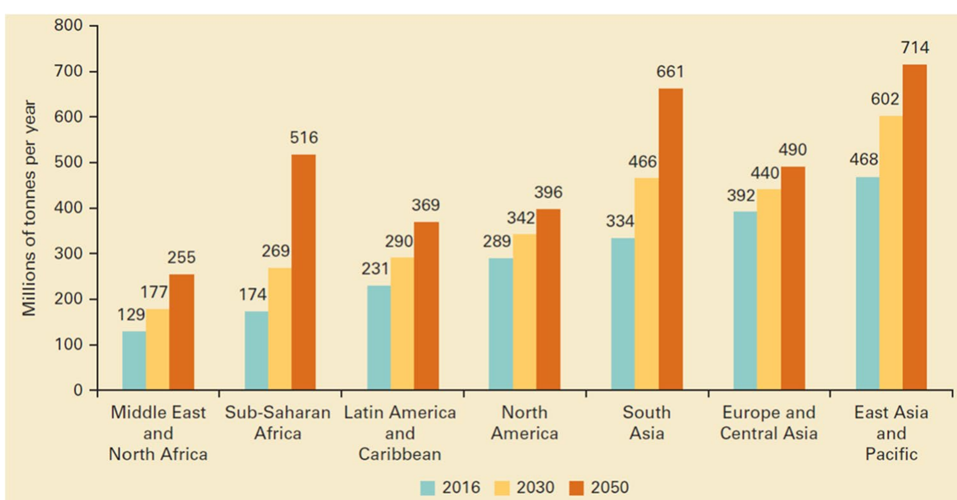


Fig. 1 Trend of the global waste generation and projection (Obtained from [16])

Table 1 Characteristics of slaughterhouse wastes

Substrate	Moisture (%)	TS (%)	VS (%TS)	Protein (%)	Lipid (%)	Carbo-hydrates (%)	C/N	References
Poultry trimmings and bones	77.6	22.4	68.0	11.4	4.9	-	-	[26]
Poultry feathers	6.1	93.9	-	85.3	2.0	-	3.5	[27, 28]
Cattle meat and fatty waste fractions	47.3	52.7	98.9	6.5	43.2	-	-	[29]
Cattle rumen content	88.3	11.7	93.0	0.8	1.8	-	-	[29]
Goat rumen content	82.9	17.1	87.7	3.0	2.6	7.6	12.6	[23]
Bovine slaughterhouse waste	46.8	53.2	98.8	3.5	46.1	-	-	[30]
Cattle manure	77.0	23.0	78.6	4.8	0.3	13.0	-	[31]
Solid cattle slaughterhouse waste	74.0	26.0	95.0	13.0	17.5	0.1	-	[32]
Poultry manure	39.7	60.3	-	-	-	-	3.8	[33]
Poultry feathers	8.8–12.3	87.7–91.2	85.5–93.5	80.0	3.0	-	3.1	[34]

– Not available

tissues, and meat trimmings) [35]. Sheep, goats, buffaloes, cattle, pigs, and poultry are the major livestock used for slaughtering. It is understood from the literature that slaughtering of cattle, pigs, and lambs generates byproducts of about 66.0, 52.0, and 68.0% of the live weight respectively. The byproducts are organs, fat or lard, skin, feet, abdominal and intestinal contents, bone, and blood. So, the slaughterhouse waste is majorly comprised of rumen (80 wt.%), dung/manure (12 wt.%), blood (5 wt.%), and others (3 wt.%). In addition, more than half the animal by-products are not suitable for consumption; however, these are potential resources for energy production and also offer benefits to the animal by-product processors.

Similarly, the poultry industry is growing rapidly which generates large amounts of solid and liquid wastes. The process of poultry slaughtering and the corresponding waste

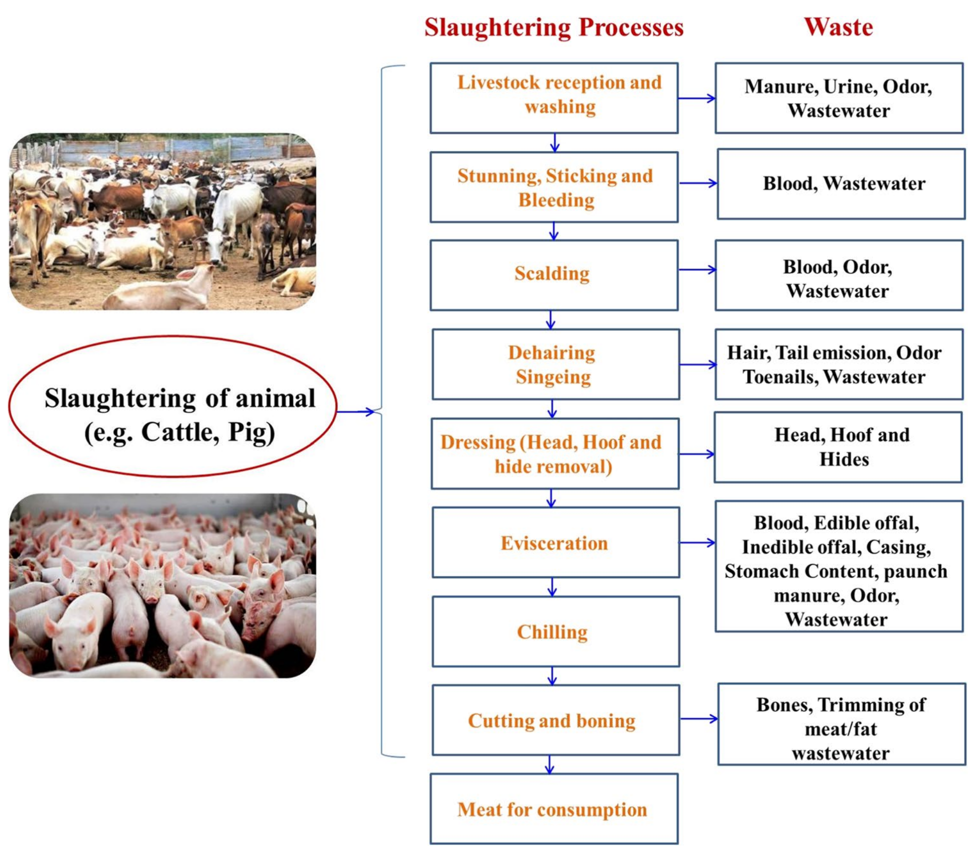


Fig. 2 Flow chart diagram of slaughtering process and the waste generation. (The cattle and pig images were obtained from [36, 37]

generation is shown in Fig. 3. It is estimated that globally, an excess of 90% of poultry waste is spread on land close to the poultry farms. These poultry solid wastes majorly comprise feathers, bedding material, excreta, feed, hatchery waste (empty shells, infertile eggs, dead embryos, and late hatchlings), dead birds, and mortality waste. Liquid waste generation includes faeces, urine, saw dust, remnants of drugs, pesticides, disinfection of chicken houses, and abattoirs. It is further estimated that approximately a chicken produces 1 kg of fresh manure with variable water content for each kilogram of feed consumed, whereas a commercial layer produces about 20 kg waste per year. These wastes comprise potential nutrients, which can be used for crop production; however, it requires crop nutrient requirement and soil testing. Moreover, poultry waste management and its potential application are mostly driven by the economic viability and environmental safety regulation of a country as well as the awareness of the public.

Animal by-products can be categorized as edible and inedible. For instance, organs like kidneys, heart, and liver are examples of edible by-products whereas horns, hooves, and hair are inedible by-products. The inedible parts of slaughtered animals vary for different categories, i.e., 49%, 47%, 44%, and 37% for cattle, sheep and lambs, pigs, and broilers respectively [25, 38]. However, parts of these wastes are being processed by the rendering industry for conversion into animal feed, pet food, poultry meal, and animal fats. Recently, slaughterhouse byproducts are being utilized in several applications such as anaerobic digestion, synthesis of a protein hydrolysate, lipids, enzymes, bioactive peptides, and synthesis of protein-based adhesive formulations [10, 39–43]. The blood from the slaughterhouses is one of the major animal byproducts that are rich in protein (about 18%) [44]. The dry protein could be used for the production of yogurt, cakes, and cheese due to its excellent gelling and emulsifying properties. The potential use of these huge quanta of slaughterhouse and poultry wastes would not only pave a way for sustainable waste management but also would increase industrial development and employment opportunities. Hence, there is an alarming need to focus on sustainable waste management technologies for the treatment and effective utilization of slaughterhouse and poultry wastes.

3 Impact of solid waste exposure

Inefficient and improper management of solid wastes creates potential risks to health and the environment. Although there is prominent development in various key sectors like socio-economic and environmental sectors, still the handling issues with effective disposal of solid wastes becomes questionable especially in most populated countries like India [45, 46]. The methane and carbon dioxide emissions from solid waste disposal dumpsites by anaerobic decomposition of wastes alleviate the global warming potential. The health impacts resulting from waste disposal may vary depending on several factors like the nature of wastes, population exposure, concentration of the pollutant, and time of exposure.

The improper disposal of solid wastes greatly imparts air quality through the burning of wastes and releases several noxious air pollutants like sulphur dioxide, oxides of nitrogen, carbon monoxide, and particulate matter [47]. These air pollutants could greatly affect human health with a wide range of diseases like cold, allergy, cardiovascular and respiratory diseases, and even cancer [48]. Similarly, improper means of solid waste disposal greatly affect surface and ground water quality by leachate, and especially the people residing nearby the dump yards who are relying on the ground water as a source of drinking and domestic applications are greatly affected. Furthermore, the illegal discharge of blood and animal faeces into streams causes oxygen depletion as well as nutrient enrichment which could

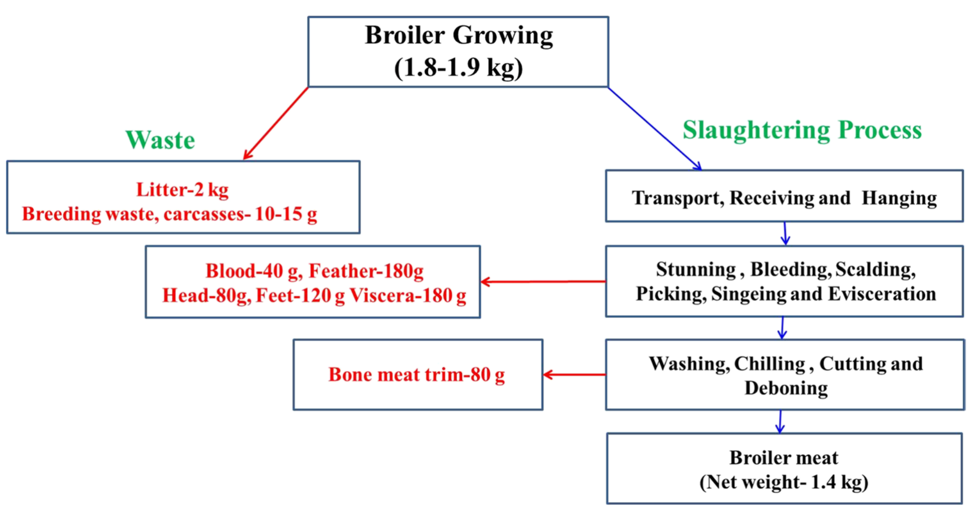


Fig. 3 Poultry waste generation during broiler farming and slaughtering process

increase the rate of toxin compounds accumulation leading to water borne and respiratory diseases [49]. The contamination of public water supplies or leaks from surrounding dumpsites could increase the potential health risk of livelihood by means of infection due to the presence of pathogens and water pollutants [50, 51]. For instance, contaminated food or water could cause gastro-intestinal diseases like typhoid fever, cholera, and hepatitis E infections [52]. The residents living close to dump yards are facing the nuisance of scavenging birds and animals that could affect their psychological health. Furthermore, diseases are being spread by different vectors such as mosquitos, birds, insects, and rodents. Similarly, mental disorders result from heavy metal poisoning [53, 54]. Furthermore, soil contamination also occurred through direct waste contact or leachate, which decreases the quality of soil and reduces the soil nutrients. Thus, these pieces of literature strongly evidenced the linkage between improper solid waste management practices and their adverse environmental and health impacts. In addition to the environmental pollution by means of affecting air, water, and soil quality, the health challenges due to poor solid waste management demand a sustainable approach for effective treatment and disposal of these solid wastes in an eco-benign way.

4 Solid wastes as renewable resources and their potential usage

Municipal solid wastes are rich in organic contents that vary from 40.2 to 51.0%, which could be a potential resource for recovery of energy and value added products [55–57]. In developing countries, out of the collected wastes, less than 12% are being treated and the rest is disposed of in dumpsites [58]. This increases the organic load to the dumpsites/landfills and also under-exploits the potential of these organic wastes as a resource [14, 15]. The consumption of broiler chicken meat production exceeds 22.85 billion chickens worldwide and the approximate waste from poultry is estimated as 32.5 to 37% [10, 23, 25, 59]. Although a huge quantum of organic solid wastes is being generated, still the recovery of value added products from these wastes would benefit society in an eco-benign way. Hassan et al. [60] experimented with the utilization of food wastes for bio-hydrogen and bio-methane recovery whereas Isarankura et al. [61] evaluated the extraction of keratin protein from waste chicken feathers. The chicken feather waste is reported to contain approximately 91% keratin proteins[62, 63]. Likewise, the waste produced from citrus processing industries exceeds 40 million tons worldwide [64]. However, these wastes are rich in carotenoids and flavonoids that provide a good source of provitamin A and antioxidants [65]. These existing studies evident the potency of organic solid wastes as a valuable resource that needs to be valorized through suitable and efficient treatment options.

5 Solid waste disposal management practices and their efficiencies

The management of solid waste is the most essential process while considering the increasing trend of solid waste generation. Solid waste management majorly comprises functional elements such as generation of waste, on-site handling, storage, and processing, collection, sorting, processing and transformation, transfer and transport, processing and recovery, reuse and recycle, and disposal. However, these processes create significant challenges and are hazardous to the environment and public health. Therefore, the treatment of organic solid wastes is one among the urging research areas that have gained attention to create an alternative for the waste dump yards/landfills. There are several technologies that exist for the treatment and disposal of organic solid wastes (Fig. 4); furthermore, solid wastes are

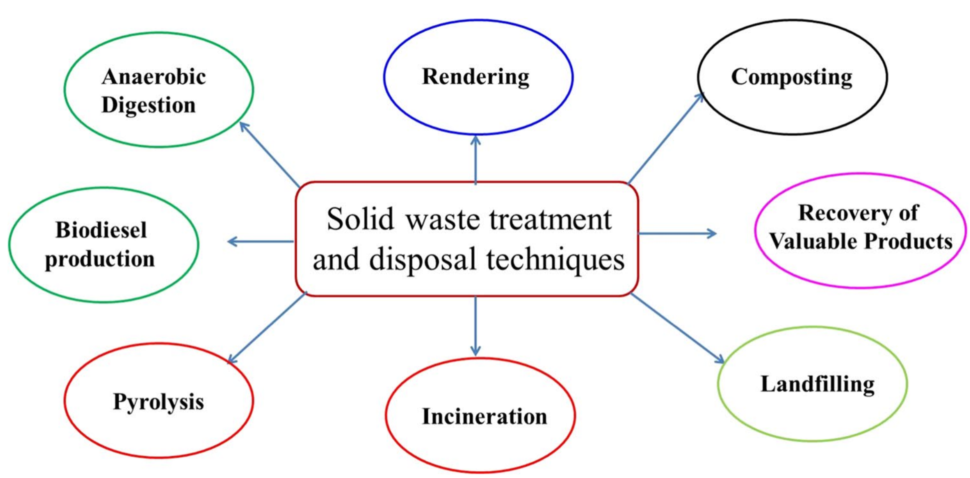


Fig. 4 Solid waste treatment and disposal techniques

potential resources for valuable products. Thus, the description of solid waste treatment techniques and details of the recovery of valuable products, especially for slaughterhouse and poultry waste are given below (Table 2).

5.1 Open dumping and landfilling

Open dumping is defined as the disposal of solid waste in an open environment or wherever the empty land is available in which the disposal does not follow the disposal guidelines, which are susceptible to burning and harmful to the environment, wildlife, and public health. Landfilling is the disposal of the solid wastes at a specific place permitted by the competent authority; however, it is susceptible to creating serious problems to the surrounding environment if the proper-engineered design is not adopted. In most developing countries, municipal solid wastes (MSW) including slaughterhouse and poultry wastes are either dumped directly in open dumpsites or in landfill sites, which underutilizes the potency of the organic wastes for energy/product generation. Both these practices cause significant environmental pollution by means of leachate contamination, fire, explosion and greenhouse gas emissions, etc. Furthermore, both these practices cause breeding of mosquitoes, cockroaches, rats, flies, and other pests, which directly influence the surrounding residential areas that affect their wellbeing by transmitting disease. In addition, the open dumping of these wastes significantly affects the surrounding water bodies' quality by means of heavy metal leaching from the dumpsite that in turn could lead to serious public health issues [78]. Also, the methane gas emission from the open dumpsites/uncontrolled landfill leads to air pollution and global warming as well. Thus, the proper solid waste management by use of poultry and slaughterhouse wastes for energy production/material recovery could reduce the global carbon footprint, which supports the economic development of the country and improve the quality of life and environment. Several technologies are available for poultry and slaughterhouse waste valorization for sustainable utilization; however, their suitability based on the waste composition needs to be explored.

5.2 Composting

Composting involves the biodegradation of organic matter present in the wastes upon the act of a mixed population of microorganisms in a moist and aerobic environment. The end product, humus/compost, is rich in nutrients that could be used as an organic fertilizer for plant growth (Fig. 5). It is the cost-effective method of waste treatment that aids in mass reduction. During composting, the carbonaceous and nitrogenous matters present in the wastes are utilized by various successive microbes and converted the same into a stable nutrient-rich end product. The rate of composting varies on the process conditions maintained and the composition of the wastes [66, 79]. The process also depends on various environmental factors like moisture, pH, aeration, temperature, particle size, C/N ratio, and nutrient availability [80].

Although composting is a simple and cost-effective method, still, pretreatment of wastes prior to this process is found to enhance the rate of hydrolysis. Pretreatment aids in the conversion of complex compounds like protein, lipid, and carbohydrates into simple compounds upon the act of microbes that releases extracellular hydrolases. Thus, pretreatment favours the rate of biodegradation that in turn reduces the process/digestion time. Furthermore, bulking agents are also added during composting for the optimal distribution of air/aeration, to adjust the porosity and also to absorb excess moisture and balance the nutrients as well [82, 83].

Poultry wastes are rich in nutrients that are useful for improving the structural stability of the soil that in turn benefits the crop yield [84]. In addition to nutrients, poultry manure contains several active enzymes produced by the digestive tract microorganisms. In addition to nutrients and energy for soil microbial activities, the use of the compost resulting from the poultry manure could also enhance the enzymatic activity of soil which in turn improves the absorption capacity, buffering capacity, and stress resistance of the soil. For a better composting of poultry and slaughterhouse wastes, the addition of carbon-rich materials like sawdust is widely suggested to provide better conditions during composting process [85]. Qasim et al. [86] carried out composting of chicken manure with an addition of carbon-rich materials and bulking agents, i.e., sawdust and wood shavings under forced aeration in a closed cylindrical composting reactor system. The results revealed the lowest ammonia and carbon dioxide emissions and high volatile solids (VS) reductions (from 81 to 61%) with GI of 84.5% during aeration of 0.25 L/min/kg VS. The rate of VS degradation is an overall indicator of the rate of composting [87]. Co-composting of cow dung with leather fleshing waste revealed complete mineralization of the compost after 49 days of composting and, the relative seed germination study showed germination index (GI) of 84%, 86%, and 94% in cucumber, bottle guard, and tomato respectively [66]. The GI of > 80% represents that the compost has attained maturity and is also free of phytotoxicity [88]. Onyuka et al. [89] carried out composting of bovine hair in thermophilic conditions at a temperature range of 40–50 °C with a pH of 7, moisture content of 55% and C/N ratio of 35, which offered reasonably stable compost with humification degree of 73% and C/N ratio of 29. Composting of poultry/slaughterhouse wastes demands the need for the addition of carbon-rich materials/bulking agents for improving the nutrient balance; however,

Table 2 Product yield from poultry and slaughterhouse wastes under different treatment technologies

Substrate	Operating conditions	Product yield	References
Mixed cow dung, waste fleshings, and leaf litter	Co-composting; hydrolysis of fleshing using Selenomonas ruminantium; square-shaped compost bioreactor (Size: 0.5 m × 0.5 m × 0.5 m); composting time: 49 days	Germination index of 84% (cucumber), 86% (bottle guard) and 94% (tomato)	[66]
Poultry wastes	Batch AD tests; 1 L glass reactor bottles; substrate to inoculum ratio—0.25; temperature: 35 °C	262 mL CH_4/g VS added	[30]
Bovine slaughterhouse wastes	Batch AD tests; 1 L glass reactor bottles; substrate to inoculum ratio—0.25; temperature: 35 °C	572 mL CH_4/g VS added	[30]
Mixed cattle manure and food wastes	Batch AD tests; 1 L glass reactor bottles; temperature: 35 °C; mixed food wastes (1 proportion) with cattle manure (2 proportion)	388 mL CH_4/g VS added	[67]
Mixed slaughterhouse and food wastes	Semi-continuous AD tests; 5 L lab scale reactor; temperature: 35 °C; helix type mechanical stirrer: 70 rpm; Retention time: 30 days	630 mL CH_4/g VS added	[68]
Commercial feather meal	Biodiesel production; transesterification process; temperature: 70 °C; process time: 1 h	7–11% biodiesel (on dry matter basis)	[69]
Poultry waste feathers	Keratin extraction; feather with reducing agent (1:20); reaction time: 6 h; temperature: 40 °C	Keratin yield of 88% (with sodium sulphide) and 66% (with L-cysteine)	[70]
Chestnut Burrs (CB), Cow Manure (CM), Bovine Bone (BM)	Co-composting; waste shredding using mechanical shredder; 50 L compost bins; composting period: 38 days	Best compost yield with 15% BM; 55% CM to CB, Rich in macro and micronutrients; Relative seed germination (98.36%); Germination Index (104.21%); pH-6.02; C/N-18.32	[71]
Cattle manure with sewage sludge	Incineration; pilot-scale rotary kiln incinerator; Temperature: 750–850 °C and air ratio (0.9–1.4)	N_2O Emission factor = 1.9–6.0% g-N_2O-N/g-N; CH_4 Emission factor = 0.0046–0.26 g-CH_4/g of burning object	[72]
Poultry litter	Fast pyrolysis; temperature: 530 °C; lab scale bubbling fluidized bed reactor; bedding material: Aluminium oxide	Bio-oil yield: 27%; Heating value: 32 MJ/kg	[73]
Meat and bone meal	Protein meal; plasticizer added: glycerol; bioplastic sheets synthesis; composition of meal: 4–7% moisture, 50% protein, 8–12% fat, and 35% ash	Bioplastic sheets; Tensile strength of sheet: 0.8 ± 0.1 MPa	[74]
Poultry waste feathers	Protein extraction; plasticizer added: glycerol; bioplastic sheets synthesis; 60 ml of keratin solution with varying glycerol concentration of (2, 5, 10 wt %)	Bioplastic sheets; SEM revealed good morphologies without cavity, holes and edge; Keratin with 2% of glycerol showed best thermal and mechanical properties	[75]
Slaughterhouse wastes	Protein extraction; operation conditions: pH: 9; reaction time: 1 h; temperature: 20–40 °C	Protein yield of 75% (pork lungs); 64% (beef lungs); 83% (chicken meat)	[76]
Poultry waste feathers	Keratin extraction; dissolving of feathers (50 g feather + 2 L of sodium sulphide solution (0.5 M)); protein precipitation (feather filtrate solution and ammonium sulfate solution (1:1)) and protein extraction	Keratin yield of 53% (sodium sulphide as reducing agent)	[77]

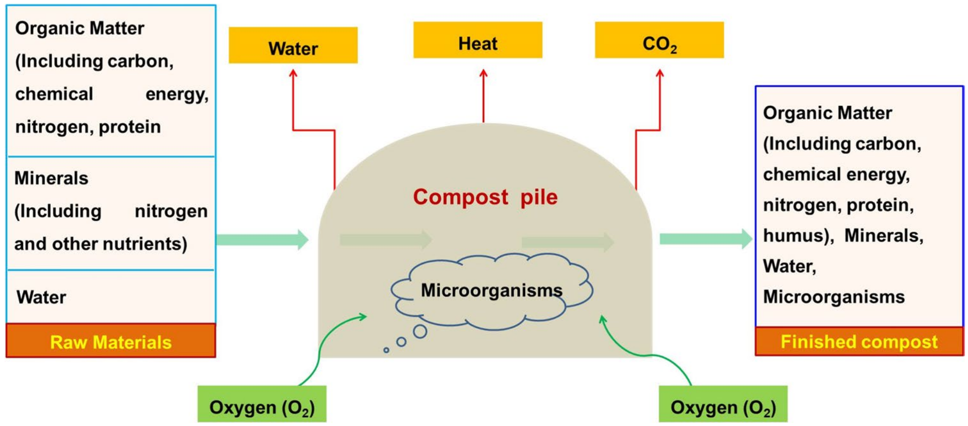


Fig. 5 The composting process (Obtained from [81])

it is a simple and effective option for the treatment and disposal of solid wastes. The resulting compost would be an alternative source of organic fertilizer to enhance the soil properties and plant growth.

5.3 Incineration

Incineration is one of the potential thermal treatment technologies for waste volume reduction [90]. It involves thermal waste decomposition in the temperature range of 850–1200 °C in an oxidizing environment to ensure complete combustion [91]. The heat produced from the process could be used for energy recovery and the resulting ash from the process could be used for material recovery or could be solidified as a binder in construction applications based on the ash composition [92]. Poultry and slaughterhouse wastes contain pathogens like *Escherichia coli* and *Salmonella s*p., *E.coli* normally exists in the lower intestinal part of animals, some of which are harmful that are prone to cause food poisoning and health illness [93]. Similarly, Salmonella is widely found in an animal slurry that is prone to cause typhoid, food poisoning, and paratyphoid fever [94]. However, heat treatment of 70 °C is sufficient for the inactivation of both i.e. *Escherichia coli* and *Salmonella* sp. [95, 96]. Therefore, incineration of wastes could be potentially effective in destroying the infectious agents thereby can eliminate the spreading of diseases that ensure safe disposal of pathogenic wastes. Furthermore, the resulting ash from the meat incineration is also found to contain a lot of macronutrients and micronutrients like calcium, copper, iron, magnesium, manganese, phosphorus, potassium, and zinc. Thus, it could be a potential additive for a high value added fertilizer. However, the air emissions should be properly controlled by adopting effective air pollution control treatment technologies [97].

Incineration of mixed slaughterhouse wastes (waste feather, poultry litter, meat, and bone meal) was carried out in a high scale rotary kiln incinerator in a temperature range of 600 to 900 °C in a residence time of 20 to 25 min [27]. The moisture content of the wastes was found to be 4.2%, 54.6%, and 13.4% for meat and bone meal, feathers, and poultry litter respectively. The nutrient profile analysis at varying process conditions revealed the nutrient richness of the resultant incinerated ash, i.e., calcium (17–30%), phosphorus (4–17%), and potassium (0.6–3.6%). Oshita et al. [72] carried out incineration of cattle manure and sewage sludge in a pilot-scale rotary kiln with a screw feeder at varying process temperature (750–850 °C) and air ratio (0.9–1.4). Prior to the incineration process, the wastes were sun-dried to 34 °C. The N_2O emissions were reported to increase with the increasing temperature whereas they decreased with low air ratios while CH_4 emissions were found to be higher above a process temperature of 800 °C at a low air ratio. The emission factors of N_2O and CH_4 were obtained as 1.9–6.0% g-N_2O-N/g-N and 0.0046–0.26 g-CH_4/g of the burning object respectively. Incineration of solid wastes is reported to show a higher volume reduction of greater than 90% [23, 98, 99]. Furthermore, a twofold benefit could be observed as a result of incineration of mixed slaughterhouse wastes i.e. pasteurization of pathogenic wastes and value added byproduct formation as an additive to organic fertilizer. The existing incineration studies, although found to be effective in waste valorization, still necessitate pre-drying of wastes prior to incineration to remove the high moisture content in order to reduce the energy demand of the process and to achieve high waste volume reduction. The pre-drying of wastes could also increase the nutrient content of ash since it is primarily influenced by the mass fraction of the input components.

5.4 Renewable energy production

A large part of the research is focused on eco-friendly and sustainable energy from waste biomass to replace conventional fossil fuels [100]. The slaughterhouse and poultry wastes are growing renewable energy resources and the resultant enhanced share in total energy supply would reduce carbon dioxide emissions. Furthermore, both these wastes are rich in protein content and hence could be an ideal substrate for biofuel production. Biofuels are applied in all three states of matter, i.e., solid, liquid, and gas. In solid form, they normally exist as charcoal, wood and chips, pellets, etc., whereas in liquid form, biodiesel and bioethanol stand out. In gaseous form, biofuel exists as biogas, produced predominantly by anaerobic fermentation, or by gasification during partial oxidation of wastes at high temperatures [101]. Due to the energetic and biological characteristics of poultry and slaughterhouse wastes, their sustainable use as bioenergy can be produced through biochemical or thermochemical routes, i.e., anaerobic digestion, pyrolysis and transesterification of poultry tallow. Most of the existing research on slaughterhouse and poultry wastes focused on biodiesel, biogas, and bio-oil production as renewable biofuels and the potential of each technology in producing electricity, bio-oil, bio-diesel, etc. are comprehensively reviewed in this section.

5.4.1 Anaerobic digestion

Anaerobic digestion (AD) of organic wastes involves the biological decomposition of organics in an anaerobic environment by the anaerobic bacteria through a sequence of reactions such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The process provides dual output as bio-fuel (biogas) and nutrient-rich digestate that could be converted as organic fertilizer (Fig. 6).

In hydrolysis, the breakdown of complex compounds into simple compounds will take place and the hydrolysis of cellulose could be found in Eq. 1 as follows.

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 + nH_2 \quad (1)$$

This process eases the microbial accessibility to the biomass that is fed into the AD system. For example, protein is hydrolyzed to amino acids, lipids into fatty acids, and carbohydrates into simple sugars. In acidogenesis, the hydrolyzed products from the hydrolysis are acted upon by the acidogenic bacteria and converted into volatile fatty acids like acetate, butyrate, propionate, alcohols, carbon dioxide, and hydrogen (Eqs. 2 and 3). Subsequently, these products are utilized by acetogenic bacteria in acetogenesis and forms acetate and hydrogen (Eqs. 4 and 5).

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (2)$$

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (3)$$

$$CH_3CH_2OH + 2H_2O \rightarrow CH_3COO^- + H^+ + 3H_2 \quad (4)$$

$$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+ + HCO^- + 3H_2 \quad (5)$$

The last step in AD process is methanogenesis where the methanogens convert acetic acid and hydrogen into methane and carbon dioxide as shown in Eqs. 6 and 7.

$$2CH_3CH_2OH + CO_2 \rightarrow CH4 + 2CH_3COOH \quad (6)$$

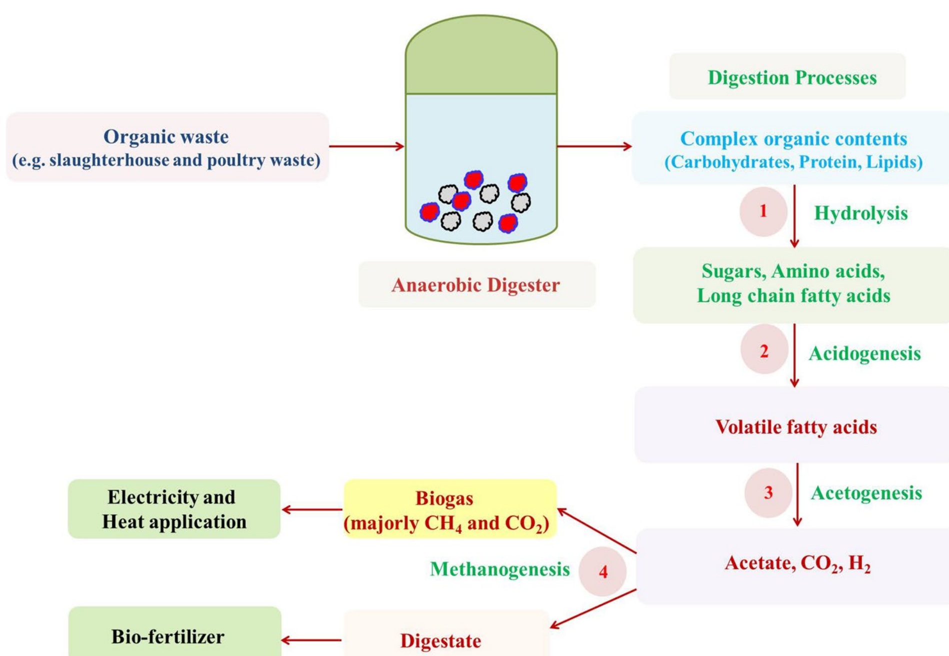


Fig. 6 Schematic diagram of anaerobic digestion of solid waste

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (7)$$

Biogas can be produced from any feedstock that contains substrates like proteins, fats, carbohydrates, and cellulose. In this aspect, organic fractions of municipal solid wastes are a potential resource for energy recovery through the AD process due to its richness in moisture content and organic matter. However, there are several factors that influence the process namely composition of wastes, loading rates, carbon–nitrogen balance, ammonia, volatile fatty acids, and sulphide concentrations. An excess/lower concentration of all these factors could cause AD process inhibitions that need to be balanced by incorporating the easiest and least expensive method of feedstock optimization.

Anaerobic co-digestion of poultry and slaughterhouse wastes Specifically, while reviewing the AD of poultry and slaughterhouse wastes, it could be observed that both of these wastes have poor carbon/nitrogen balance due to the higher nitrogen contents in the wastes. The high nitrogen compounds during the AD process successively result in the formation of excess ammonia levels that can alter the intracellular pH and cause inactivation of the key enzymes by penetration into the microbial cell walls thereby affecting bio-chemical reactions during AD of protein-rich substrates [102]. Also, the high lipid content of slaughterhouse wastes is vulnerable to the accumulation of long-chain fatty acids (LCFA) during the AD process. The high LCFA levels are inhibitory to acetotrophic and hydrogenotrophic methanogens thereby resulting in operational issues within the anaerobic digester and leading to reactor instability based on their concentrations [103]. The C/N ratio of slaughterhouse and poultry wastes is found to vary between 7 and 10, which is inhibitory for a stable AD process for which the optimal C/N ratio is 25–30 [68, 104, 105]. Although the high organic and nutrient content of the slaughterhouse and poultry wastes makes it an ideal substrate for bioenergy recovery, however, anaerobic mono-digestion of these wastes often fails due to improper nutrient balance leading to excessive long-chain fatty acid levels, ammonia inhibitions, etc. Hence, it demands the need for co-substrate addition during the AD process for an effective and stable means of the utilization of these wastes.

The co-digestion with a carbon-rich substrate that is low in protein/fat content could add a proper nutrition balance to overcome these inhibitory problems. For instance, Pagés-Díaz et al. [106] found a 31% enhancement in the methane yield during AD of equal proportions of mixed cattle abattoir wastes, manure, various crops, and MSW in batch AD reactors at a thermophilic temperature of 55 °C for 70 days. Anaerobic co-digestion of rendering plant and slaughterhouse wastes were carried out in a semi-continuous reactor for 178 days at a mesophilic temperature of 35 °C at an organic loading rate (OLR) of 1.5 g VS/L/day in a hydraulic retention time (HRT) of 50 days showed methane yield of 720 mL/g VS. However, in thermophilic conditions, at an OLR of 1.5 g VS/L/day, the reactor showed instability with excessive ammonia and LCFA concentrations during AD of slaughterhouse wastes [30]. Zhang et al. [67] found a 41.1% increase (with methane yield of 388 mL/g VS) in the methane yield during AD of mixed food wastes (1 proportion) with cattle manure (2 proportion). Furthermore, in the same study, the results of semi-continuous AD tests showed enhancement in the methane yield by 55.2% during co-digestion and also found improvement in the buffering capacity of the reactor. Similarly, Borowski et al. [68] found a maximum methane yield of 630 mL/g VS during AD of mixed food and slaughterhouse wastes in a 3 L (working volume) lab-scale semi-continuous reactor in a solid retention time of 30 days. AD of slaughterhouse/poultry wastes with a carbon-rich substrate is a promising option to utilize the potency of these wastes for enhanced energy recovery through improved substrate management alternatives thereby providing an alternative source of clean green energy production from organic wastes.

Pre-treatment and Anaerobic digestion/co-digestion of pre-treated poultry and slaughterhouse wastes Due to the major shares of fat and protein in poultry and slaughterhouse wastes, pre-treatment of wastes is necessary to reduce these insoluble contents in order to increase their solubility. In order to aid physical mass transfer, Ware and Power [107] carried out pre-blending of cattle soft offal consisting of intestinal residues, fat, meat trimmings to a particle size of less than 8 mm to aid biodegradation. The results of AD tests in a 900 mL batch AD reactor showed methane yield of 650.9 L/kg VS. Porselvam et al. [108] carried out pre-treatment (using KOH and NaOH) of intestinal waste prior to the AD process and carried out anaerobic co-digestion with food wastes that resulted in the increase in the methane yield from 119.7–238.1 to 331.5 L/kg VS. In our previous study, extrusion pre-treatment of cattle ruminal contents and blood followed by anaerobic co-digestion with vegetable market wastes, showed an increase in methane production from 273 to 304 L/kg VS. Furthermore, AD of ozone pre-treated animal dung followed by anaerobic co-digestion with agro-wastes showed enhancement in the methane yield from 205.3 to 300 L/kg VS [109].

Furthermore, several authors experimented with pasteurization as a pre-treatment of slaughterhouse wastes for the inactivation of pathogens in slaughterhouse wastes. For instance, AD of pasteurized slaughterhouse wastes (70 °C for 1 h) in a batch 900 mL AD reactor at 36–39 °C in a retention time of 30 days showed enhancement in the methane yield from 515.5 to 569.15 L/kg VS [110]. Similarly, Luste and Luostarinen [111] carried out semi-continuous

AD of pasteurized animal by-products (70 °C for 1 h) in co-digestion with sewage sludge in a 4 L anaerobic reactor at 300 rpm with a HRT of 14–25 days at an OLR of 1.8–4.0 g VS/L/d and found enhancement in the methane yield from 400 to 430 L/kg VS. Also, AD of pasteurized slaughterhouse wastes at a temperature of 70 °C for 1 h showed a four-fold increase in the biogas yield of 1.14 L/kg VS of wastes Edström et al. [112]. Thus, pasteurization as a pretreatment prior to AD of slaughterhouse wastes has improved the efficiency of the AD process. Further benefits of thermal pre-treatment include a high level of sludge solubilization and pathogen reduction [113].

Factors affecting AD of poultry and slaughterhouse wastes There are several factors that impart AD of poultry and slaughterhouse wastes. Especially, due to the delay in the hydrolysis of poultry and slaughterhouse wastes, the retention time greatly affects the rate of biogas production. The increase in the retention time further increases the reactor volume, which would increase the cost of the reactor. This can be resolved by increasing the mass transfer within the AD system through pre-treatment of wastes prior to the AD process to aid the structural breakdown of complex compounds [114]. Another major parameter that affects the AD of these wastes is the poor C/N ratio resulting from the high nitrogen content of poultry and slaughterhouse wastes. However, as stated above, a carbon-rich substrate needs to be co-digested to balance the nutrient distribution within the AD system to resolve the process inhibitions [115, 116].

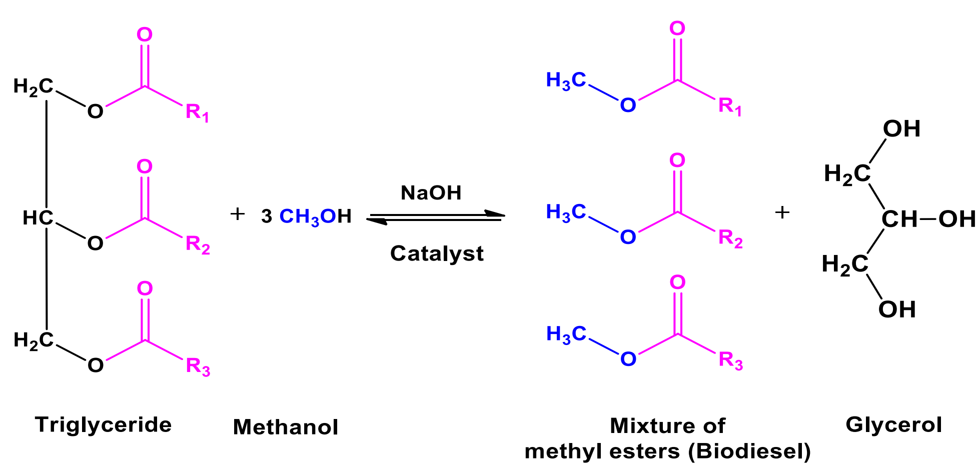
5.4.2 Biodiesel production

Biodiesel is the mono-alkyl esters (ethyl or methyl) of long-chain fatty acids produced by trans-esterification of triglycerides in reaction with alcohols (methanol or ethanol) in presence of acid/alkali catalyst (usually NaOH/KOH) (Fig. 7). The oil/tallow produced from renewable energy feedstocks would be trans-esterified for the production of biodiesel. The resultant biodiesel could be blended with diesel based on the product properties. In addition to the potential extraction of valuable products (lipid) from the wastes during this process; furthermore, the use of biodiesel could reduce the hydrocarbon, suspended particulate matter, oxides of sulphur and carbon monoxide emissions [117, 118]. Glycerol is a by-product of the trans-esterification process,however, it will be in crude form since it is contaminated by the formation of soap, unreacted fats, water, potassium hydroxide, etc. Nevertheless, it could be used as a potential raw material for the synthesis of various chemicals, biodegradable polymers, energy production, etc. [119].

Animal wastes are potential sources of biodiesel production due to their lipid richness and also a low-cost alternative feedstock compared to vegetable oil. The major processes involved in biodiesel production from animal waste are shown in Fig. 8. The process yield varies with several parameters such as process time, temperature, catalyst used, alcohol molar ratio, and free fatty acid contents [120]. The main problem with the use of extracted animal fat from wastes for biodiesel production is the high free fatty acid concentration (FFA) that will end up in low conversion rates [121]. However, in such cases, the product yield can be improved by employing a two-stage biodiesel conversion process, increasing alcohol molar ratio and catalyst addition, and the use of recyclable nano-catalysts [122]. The use of catalysts enhances the reaction rate and temperature that in turn increases the miscibility of fat with alcohol [123].

Alptekin and Canakci [125] evaluated biodiesel production from chicken fat under varying process temperatures, reaction time, and alkaline catalysts. Initially, it was subjected to heating (110 °C for 1 h) for the removal of moisture followed by filtration to remove insoluble materials like meat and bone components. Subsequently, pretreatment of chicken fat (by esterification process) was carried out to reduce the FFA level to 0.67% that is sufficient for the trans-esterification process. After trans-esterification, the chicken fat methyl ester was characterized and the results revealed

Fig. 7 Transesterification reaction of animal fats or vegetable oil to biodiesel



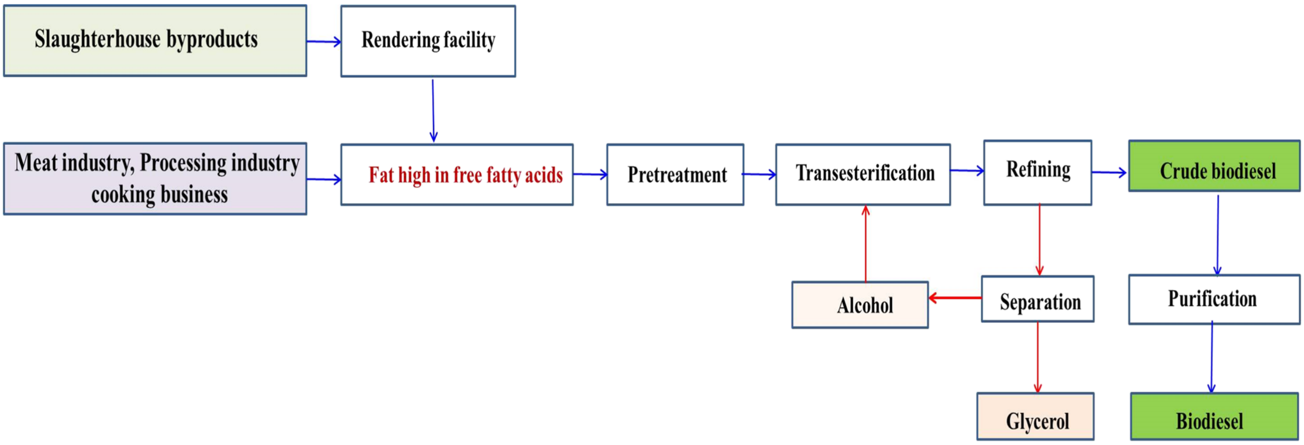


Fig. 8 Flow chart of steps involved in the biodiesel production from animal fat waste (obtained from [124])

that the produced biodiesel met both ASTM D6751 and EN 14,214 standards while using KOH and NaOH at 60 °C for 4 h. Kondamudi et al. [69] performed biodiesel production from commercial feather meal that is the waste product of the poultry industry. Initially, the fat from the feather meal was extracted and subsequently, trans-esterification of the extracted fat into biodiesel was carried out by reaction with KOH and methanol as catalyst (70 °C for 1 h). The product yield was found to be 7–11% (on a dry matter basis) and the purified biodiesel was subjected to fatty acid methyl esters (FAME) characterization. The results confirmed that the biodiesel produced is of good quality (with good cetane number and high oxidation stability) in comparison with other biodiesel produced from common feedstocks. Similarly, Mata et al. [126] carried out the quality evaluation of biodiesel production from tallow, lard, and poultry fat. The product yield was found to be 90.8%, 91.4%, and 76.8% for tallow methyl esters, lard methyl esters, and poultry fat methyl esters respectively. The results of FAME characterization revealed that B100 blends are not possible in any of the above-produced biodiesel since all the evaluated parameters do not comply with EN 14,214 standards. However, B20 blends (20% biodiesel + 80% conventional diesel) fulfill the requirements of EN 14,214 standards thereby revealing as a good alternative or blend for the conventional diesel to meet the rising energy demands in a sustainable way. Similarly, Barik and Vijayaraghavan [127] evaluated the FAME properties of chicken fat methyl ester (CFME) produced from chicken fat while blending with conventional diesel in different blends. The results revealed optimal blend as 30% of CFME with 70% of diesel, which in turn lowers the carbon monoxide, hydrocarbons, and smoke emissions by 24.4%, 22.9%, and 14.4% respectively. Su and Chou [128] carried out biodiesel production from slaughterhouse sludge cake through acid methanolysis. The sludge cake was transesterified with methanol, *n*-hexane, and acids (using H_2SO_4 or HCl) at varying concentrations (2%, 4%, and 8%, v/v) in different time periods (4, 8, 16, and 24 h). The highest accumulated FAME yield of 2.51 ± 0.08% and 2.27 ± 0.09% was obtained at 8% of H_2SO_4 or HCl in a reaction time of 4 h. It is mentioned that the methyl esters of palmitic acid, palmitoleic acid, stearic acid, and oleic acid were the major components of FAME produced from the slaughterhouse sludge cake through acid methanolysis. Mahyari et al. [118] performed the biodiesel production ability of chicken fat waste generated from broiler chicken slaughterhouse and performed the survey with respect to waste generated in Iran. It is estimated that 736 kilotons of poultry slaughter waste is generated annually, which could be utilized to produce 112 million liters of biodiesel by trans-esterification process (with methanol as alcohol and KOH as catalyst) with the production cost of around 14,277 rial/liter. Thus, 30% of diesel in the transportation field could be replaced with B2, i.e., 98% diesel with 2% biodiesel or even B20. The cost of production can still be lessened if the socio-economic benefits of pollution reduction and employment generation are taken into account.

Overall, the fat extracted from poultry and slaughterhouse wastes can evident to be a potential feedstock for producing a high-quality biodiesel subject to the availability of huge quantity and cost-effectiveness. Mostly sulphuric acid, KOH, and NaOH are used as catalysts during the trans-esterification process. Due to the presence of high free fatty acid content, a two-step trans-esterification process is usually applied. The FAME properties reveal that the biodiesel produced from poultry and slaughterhouse wastes does not fully comply with international standards however blending with commercial diesel is possible that in turn exhibit acceptable fuel characteristics which would enhance environmental sustainability and economy.

5.4.3 Pyrolysis

Pyrolysis, a thermal waste valorization technology, involves the thermo chemical decomposition of organic material in the absence of oxygen in a controlled environment. The end product would be solid (bio-char), liquid (bio-oil), and gaseous products (Fig. 9). The yield of products varies with operating conditions like heating and gas flow rate, temperature, particle size, and residence time [23, 129]. Recently Zhao et al., [130] utilized the pyrolysis (slow and fast) technology for valorization of poultry waste into sustainable bioenergy which could be applied in various demandable places. Slow pyrolysis possesses low heating rates and long residence time and takes place at low temperatures (300–450 °C). Fast pyrolysis possesses high heating rates and occurs at high temperatures (450–600 °C). Slow pyrolysis yields bio-char, bio-oil, and syngas as the major products whereas fast pyrolysis yields bio-oil as the major product with biochar as a byproduct. The syngas combustion offers energy for the pyrolysis technology. Similarly, the bio-oil can be upgraded into liquid fuels (gasoline and diesel) through hydroprocessing upgrading technology, which could be used for transportation and heating application. For instance, Kluska et al. [131] observed enrichment in the heating value of the gaseous products (2.0 to 9.5 MJ/Nm^3) during pyrolysis of leather wastes while increasing the process temperature from 300 to 500 °C. The yield of bio-char is positively correlated with the fixed carbon contents of samples to be pyrolyzed [132]. The loss of volatile solids during the process mainly relies on the quantitative share of carbohydrates, protein, and lipid content of the wastes and its thermal stability differences [133]. The bio-oil product could be further processed for alternative energy production whereas the bio-char could be used for activated carbon synthesis or soil amendment applications [134]. Also, the bio-char is resistant to microbial degradation, lighter and moisture resistant,thereby, it is easy to transport and also could be stored for a longer time that in turn lessens the environmental pollution resulting from the direct dumping of raw wastes [135]. In addition, depending upon the temperature of the pyrolysis process, various value added products were identified in the pyrolysis oil, like alcohols, phenols, aromatics, aldehydes, furfural, toluene, and 1-methoyx-2-propyl acetate [131, 136–138].

Cuixia et al. [139] carried out the pyrolysis of chicken manure at varying process temperatures from 200 to 800 °C and evaluated the use of chicken manure bio-char (CMB) for the removal of lead. The adsorption capacity of lead ions is positively correlated with process temperature and the maximum adsorption capacity of 242.57 mg/g was obtained using CMB prepared during pyrolysis of chicken manure at 800 °C. Kantarli et al. [140] performed the catalytic fast pyrolysis of poultry meal and poultry litter, and the calorific value of the obtained organic bio-oil was calculated as 41.9 and 41.8 MJ/kg respectively. The use of catalysts was found to reduce the oxygen content of the organic phase of the bio-oil as well as undesirable compounds. Upgrading the bio-oils through hydrothermal treatment could further reduce the oxygen and nitrogen contents that in turn could be used as a potential biofuel or for the synthesis of renewable chemicals. Hassen-Trabelsi et al. [141] carried out the pyrolysis of animal fatty wastes (swine, poultry, lamb) at a temperature of 500 °C with a heating rate of 5 °C/min, which showed higher bio-oil yields in the range of 58–77.9%. The analysis of produced bio-oil showed the presence of several organic compounds like hydrocarbons, carboxylic acids, aldehydes, and ketones. The fuel properties of the bio-oil further showed its suitability for use as an engine fuel or could be used for the synthesis of chemicals. Pyrolysis of slaughterhouse wastes could also help to recover phosphorus (P) especially from bone char. Because fertilizer production

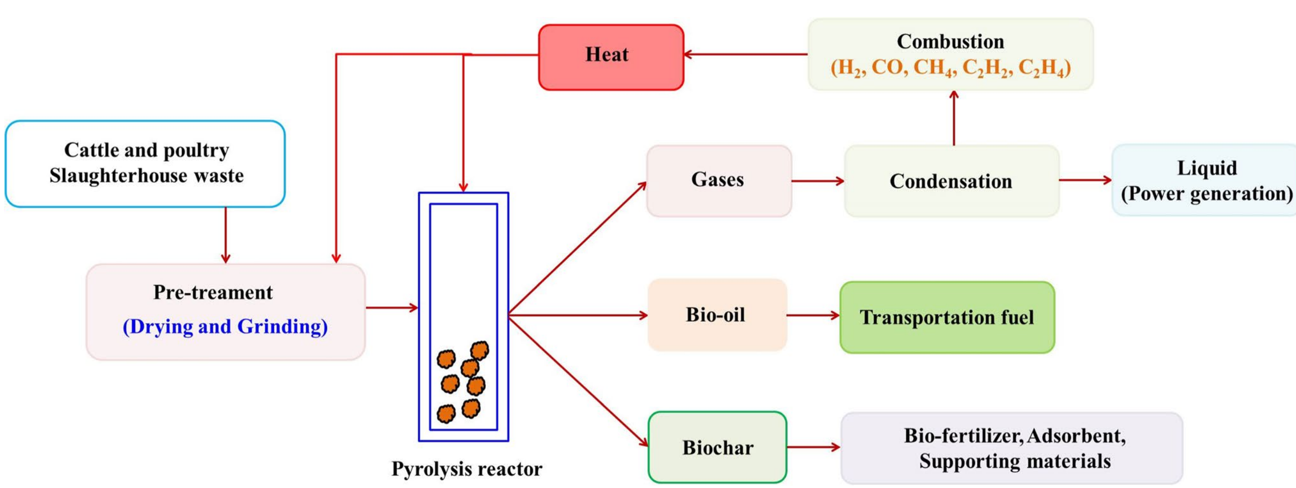


Fig. 9 Schematic diagram of pyrolysis process of cattle and poultry slaughterhouse waste

consumes more than 80% of rock phosphate, which is being mined annually and excessive use of the same could also leads to environmental pollution. So, the production of P-rich fertilizer from organic wastes could lead to a sustainable phosphorus cycle. The concentration of formic-P in pyrolyzed bone char was reported to be 147 g/kg by Zwetsloot et al. [142] which were found to be five times higher than the Idaho rock phosphate and it was only 24% less than formic-P in Triple superphosphate (TSP, 194 g/kg). Also, Pandey et al. [73] performed the fast pyrolysis of poultry litter at 530 °C in a lab-scale bubbling fluidized bed reactor with aluminium oxide as bedding material and nitrogen as fluidizing medium (34 L/min flow rate). The yield of bio-oil was found to be 27% with a higher heating value of about 32 MJ/kg. The phosphorus and potassium recovery was above 75% thereby indicating its potency as an effective organic soil amendment. Baniasadi et al. [143] performed the slow hydrolysis of poultry litter waste in the laboratory-scale fixed bed reactor in the temperature range of 400–800 °C yielded gaseous, two liquid condensates and char as main products. The results demonstrated that 550 °C is the optimum for higher product yields. The gaseous products are mainly comprised of CO_2, CO, and CH_4. The higher heating value (HHV) of carbon monoxide and methane is 12.63 MJ/Nm^3 and 39.82 MJ/Nm^3, respectively. The liquid condensates are comprised of 33 compounds which mainly comprise phenols, fatty acids, sterols, and N-containing compounds and they could be upgraded and used as biofuel. Furthermore, the N-containing compounds could be possible feedstocks for the synthesis of value added products in the pharmaceutical, chemical, and food industries. The char products have high energy content; nevertheless, it contains sulphur in major concentration which could be processed for further application. Although pyrolysis of poultry and slaughterhouse wastes have greater potential, still the wastes need to be dried before introducing into the pyrolysis chamber. Since the moisture content of these wastes is usually greater than 70%, it would otherwise consume more energy for pre-heating the wastes itself for eliminating the moisture content up to a reasonable level.

5.4.4 Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical treatment process where waste biomass is heated under low-temperature with high moisture content and autogenous pressure to produce a value added carbon-rich hydrochar material. The usage of low temperature and energy input for treatment of high moisture content has potential advantages than the other thermal treatment technologies (pyrolysis and combustion). The carbon-rich hydrochar solid materials have high heating value, thermal stability, and the hydrophobic material structure makes them potential solid fuels similar to that of lignite coal. In addition, the hydrochar materials could be utilized for environmental remediation and solid amendment applications [144]. Oh and Yoon [145] calculated the total energy recovery from biochar and hydrolysate that is obtained from hydrothermal carbonization of poultry slaughterhouse sludge cake. The hydrothermal carbonization of sludge cake was carried out at different temperatures (170, 180, 190, 200, and 220 °C). It is demonstrated that the yield of biochar decreased with an increase in the carbonization temperature whereas the calorific values and energy densification were increased from 29.6 to 31.3 MJ/kg and 1.07 to 1.13 respectively. The energy potential of raw feedstock was 4.541 MJ/kg and the total gross energy recovery of the biochar was decreased (81.2 to 75.6%) with an increase in the temperature whereas the total gross energy recovery of 4.318 MJ/kg was obtained at 180 °C which maximized gross energy recovery efficiency by 95.1%. Lee et al. [146] performed the HTC of cattle and pig slaughterhouse waste in a batch scale type laboratory reactor at different temperatures (150, 200, 250, and 300 °C). It is known that the carbon content is closely associated with the energy capacity of combustible material and it is observed that the carbon content of hydrochar is increased with an increase in the hydrothermal carbonization temperature. Similarly, the fuel ratio of cattle and pig slaughterhouse-derived hydrochar is increased with an increase in the carbonization temperature. Higher the fuel ratios better the produced solid fuel. Furthermore, the hydrochars having enhanced HHVs, the HHVs of pig slaughterhouse-derived hydrochar are increased from 4674 to 8804 kcal/kg, whereas the HHVs of the cattle slaughterhouse-derived hydrochar are increased only by ~ 1600 kcal/kg. It is further demonstrated that both the waste-derived hydrochar possess higher energy-related properties. However, the cattle slaughterhouse-derived hydrochar showed little lower energy retention due to the lipid-rich characteristics of raw cattle slaughterhouse waste. Therefore, the slaughterhouse and poultry waste could be a potential resource for the hydrothermal carbonization technology to create value added solid fuel.

6 Recovery of value added products

In addition to management practices and renewable energy production, the slaughterhouse and poultry byproducts and the wastes are potential resources for the generation of value added products (e.g., protein, protein hydrolysate) which could be valuable alternatives to commercial counterparts. The utilization of slaughterhouse and poultry by-products and wastes for recovery and fabrication of value added products are described in the following section [147].

6.1 Extraction of keratin/protein

Keratin, an abundant polymer, is a fibrous protein found mainly in hair, nails, feathers, wool, and horns of mammals, birds, and reptiles. It has several applications in pharmaceutical, biomedical, food, and cosmetic industries. The major constituent of feathers (> 90%) is keratin, and hence, poultry feather wastes have great potency to be utilized in various applications [148] (Fig. 10). Pourjavaheri et al. [70] extracted the keratin from waste chicken feathers with the mass ratio of feathers to the reducing agent (sodium sulphide and L-cysteine) as 1:20 with a reaction time of 6 h at a temperature of 40 °C. The result revealed keratin yield of 88% and 66% while using sodium sulphide and L-cysteine respectively. Similarly, Gupta et al. [77] carried out keratin extraction from chicken feathers and found high product yield (53%) while using sodium sulphide as a reducing agent as compared to thioglycolic acid and potassium cyanide. Though the use of sodium sulphide provides a higher yield in both the studies, still the use of L-cysteine is an eco-friendly alternative.

Like poultry feathers, the inedible tissues/parts of animals slaughtered from slaughterhouses are also becoming a waste, which contains a high amount of protein that could be extracted for potential applications. The processes involved in handling and recovery of protein from inedible parts of slaughterhouse waste are shown in Fig. 11. Selmane et al. [76] carried out protein extraction from slaughterhouse wastes. At an operating condition of pH of 9, temperature of 20–40 °C with a reaction time of 60 min, the product yields were found to be 75%, 64%, and 83% for pork lungs, beef lungs, and chicken meat respectively. Furthermore, the study showed the possible use of these extracted proteins in meat products instead of ingredients from milk or soy. Similarly, Robatjazi et al. [149] extracted protein from poultry slaughterhouse waste powder. An enzymatic hydrolysis method was applied for the protein extraction by the use of alcalase enzyme and the maximum protein yield of 295.92 mg/g powder was obtained with an incubation period of 24 h with sodium hydroxide (0.1 M) at a reaction temperature of 70 °C.

6.2 Production of fibreboard

Recently research is being carried out for the fabrication of natural insulation composite fibreboard samples from mixed waste poultry feathers and wood residues [150]. Fibreboard samples were prepared by mixing feathers with wood shavings (coarse structure) or mixed wood residues (finer and denser structure) in different proportions. The proportions are blend structure F (mixed wood residue 70%/ feather 20%/adhesive 10%); fine sandwich structure SF (feather 70%/ mixed wood residue 20%/ adhesive 10%); fine sandwich structure SF (feather 20%/ mixed wood residue 70% / adhesive 10%); coarse sandwich structures SC (feather 70%/ wood shaving 20%/ adhesive 10%); and coarse sandwich structures SC (feather 20%/ wood shaving 70%/ adhesive 10%), respectively (Fig. 12). The properties of the produced fibreboard showed the highest bending strength with the mixed combinations (with 20% feather; 70% waste wood; 10% adhesives) (Fig. 13). Also, the thermal insulation properties and biodegradation were improved while increasing the share of feathers in the fibreboards. Furthermore, this research shows the possibility of utilization of two organic waste materials, i.e., poultry feathers and wood residues.

Similarly, Bessa et al. [151] studied the use of chicken feather fibres in the strengthening of polymeric matrices and the experimental results revealed the suitability in terms of

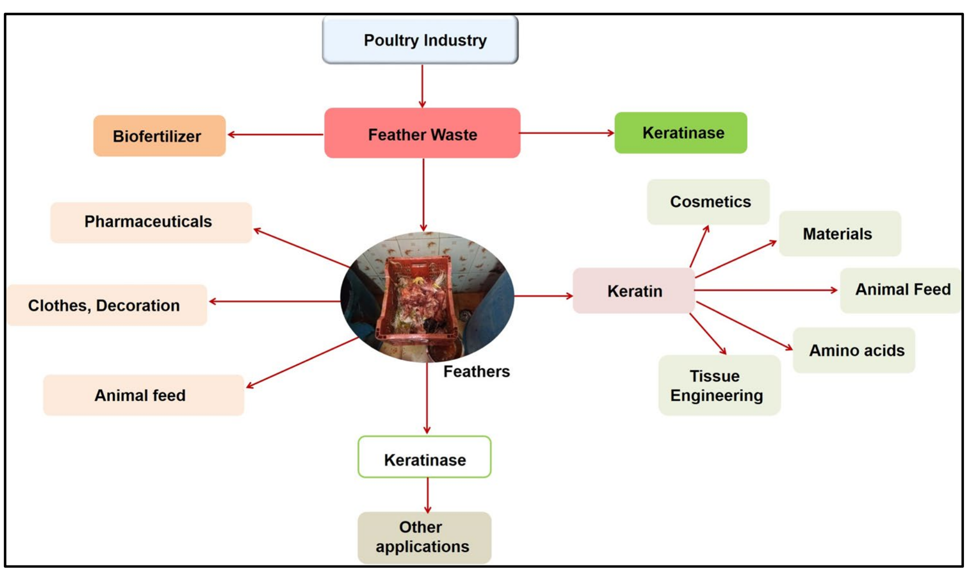


Fig. 10 Applications of feathers (obtained from [148])

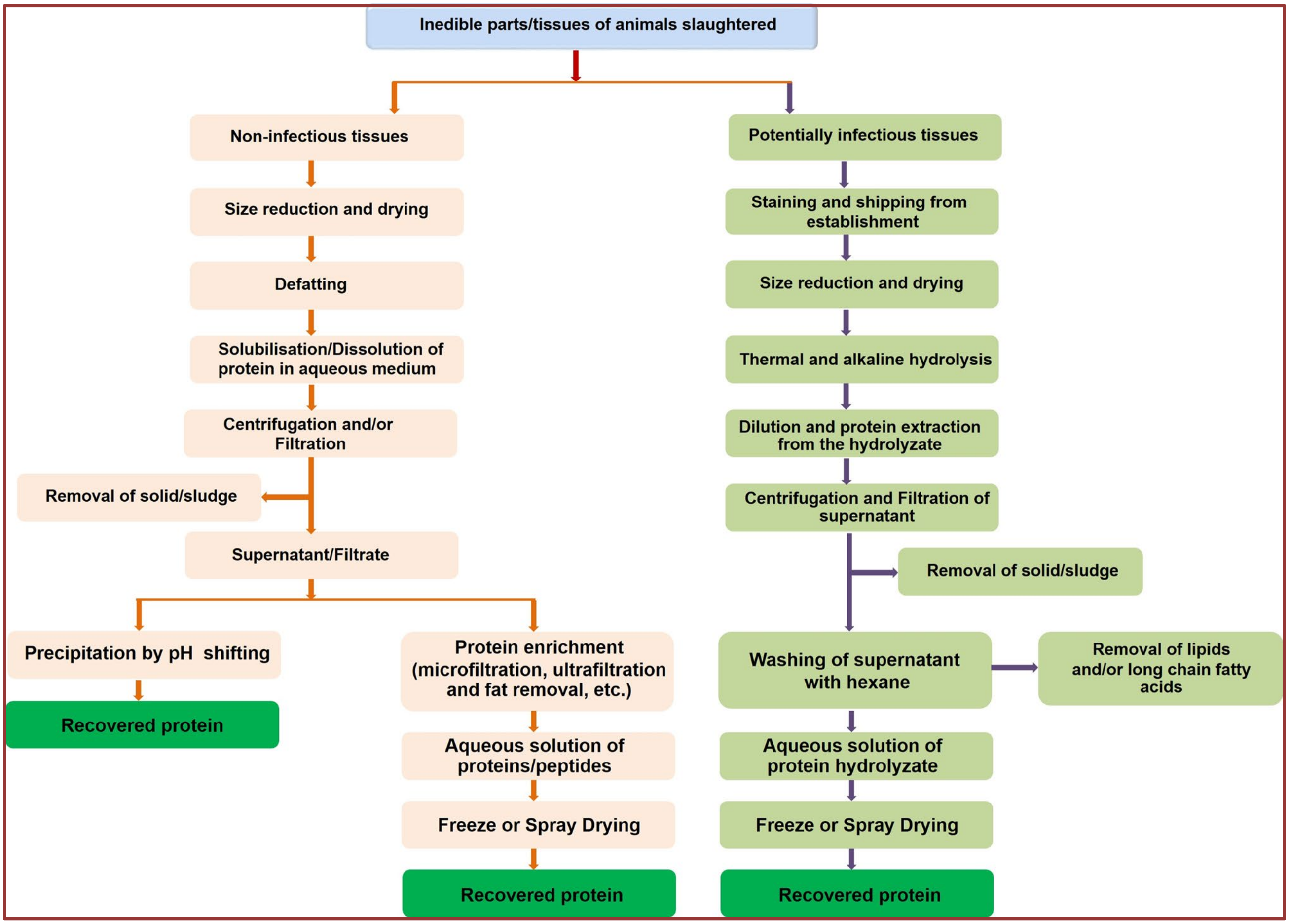


Fig. 11 Process flow diagram of protein/hydrolyzed protein extraction from inedible parts/tissues of slaughterhouse waste (Obtained from [10]

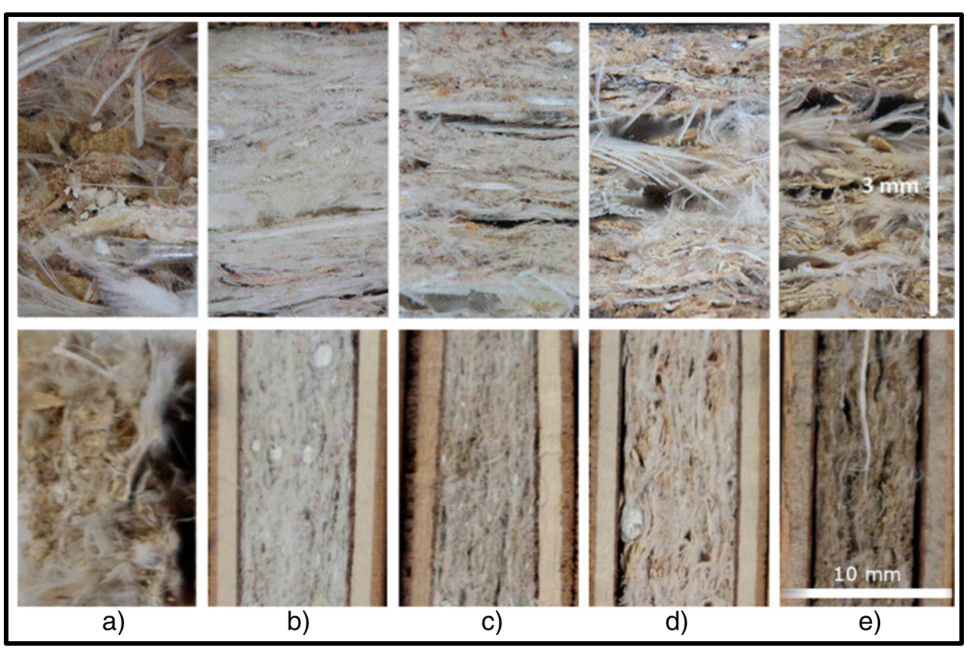


Fig. 12 Horizontal close look and cross-sections of fibre-board samples with different proportions. **a** blend structure F (70/20); **b** fine sandwich structure SF(70/20); **c** fine sandwich structure SF(20/70), **d** coarse sandwich structures SC(70/20); and **e** coarse sandwich structures SC(20/70) (obtained from [150]

good acoustic and thermal insulation. The thermal resistance showed a value of 0.175 $m^2 K W^{-1}$ while using 80:20 proportion of chicken feather fibre and epoxy resin. Furthermore, the resistance is higher than coir fibre reinforcing polypropylene with a thermal resistance of 0.114 $m^2 K W^{-1}$. This concept of natural/waste material utilization would pay a way to attain sustainability in the building materials by means of fabricating thermal and acoustic insulating materials using waste materials.

6.3 Extraction of deoxyribonucleic acid

Deoxyribonucleic acid (DNA) is the complex molecule that is essential for life's inception, which contains all the necessary information for the building up and maintenance of an organism within the living cells. Although commercial kits, depending on the sample type, are available for molecular biology studies, few novel studies have evidenced the isolation of genomic DNA from bovine blood samples. Genomic DNA (gDNA) is an essential component for performing molecular studies and blood clots [152]. Goud et al. [153] carried out genomic DNA isolation from bovine blood using conventional phenol, chloroform, and isoamyl alcohol (PCI) and detergent method. The product yield was found to be 329.1 and 406.6 µg/5 mL of blood while using PCI and detergent methods respectively. Yu and Morrison [154] carried out an extraction of PCR quality community DNA from rumen digesta sample. The repeated beat beating column (RBB + C) method yielded the product recovery of 82.5 µg of community DNA per gram of sample. It was found that 85% of the DNA recovered is found to be greater than 1.5 kb (length of the gene from densitometry measurements), thereby making it suitable for the use of PCR-based analyses of microbiomes.

6.4 Fabrication of bioplastic sheets

Nowadays, synthetic plastics are gradually being replaced by bioplastic materials to tackle sustainability and environmental challenges. Slaughterhouse/poultry wastes are one of the renewable sources of protein for the fabrication of bioplastic films. Lukubira and Ogale [74] evaluated the effect of chemical modification (using calcium hydroxide) of plasticized meat and bone meal (with a composition of 4–7% moisture, 50% protein, 8–12% fat, and 35% ash) on bioplastic sheets fabrication for potential geo-structural uses. In this meal, glycerol was added as a plasticizer in different ratios along with this meal. The sheets fabricated with 30% glycerol and meat and bone meal showed a tensile strength of 0.8 ± 0.1 MPa; however, it is comparatively lower than the tensile strength of synthetic polymers (linear low-density polyethylene with a tensile strength of 30 MPa). The

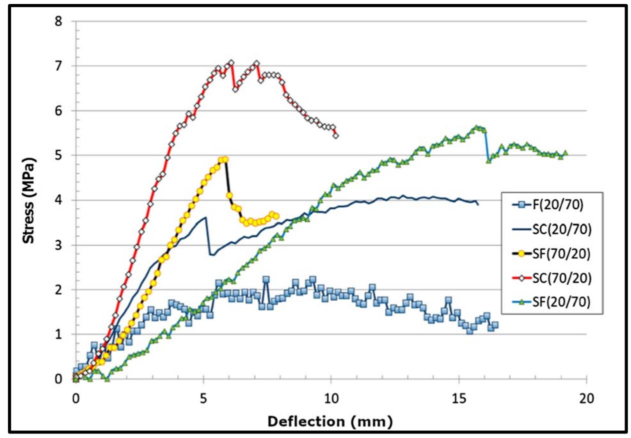


Fig. 13 Stress–deflection graphs as the results of the three-point bending testing of fibreboard samples (obtained from [150]

thermoplastic processing of meat and protein meal for sheet fabrication is found to depend primarily on the particle size, plasticizer addition, and environmental humidity. Bier et al. [155] produced a thermoplastic from bloodmeal which is a denatured protein by-product of the meat processing industry and plasticized with triethylene glycol that improved the thermal and mechanical properties of the waste-derived bio-plastics. In addition, the effect of varying triethylene glycol amount and addition of other additives with constant triethylene glycol amount (20 pph_{BM}) on the mechanical and thermal properties of bio-plastics were studied. Riedel et al. [156] produced biodegradable and biocompatible polyhydroxyalkanoates polyesters using waste animal fats as carbon feedstocks with *Ralstonia eutropha* as biocatalyst. The polyhydroxyalkanoates polyesters are considered suitable alternatives to petroleum-based plastics. Furthermore, Verbeek et al. [157] decolored the bovine bloodmeal waste using peracetic acid subjected to extrusion treatment and then followed by injection moulding for bioplastics preparation with high mechanical stability. In addition, the additives such as triethylene glycol and sodium dodecyl sulfate are reported to have a significant influence on the processability and mechanical stability of the bioplastics. Similarly, Ramakrishnan et al. [75] performed the protein extraction from poultry waste feathers for the fabrication of bioplastic sheets. Glycerol was added as a plasticizer for sheet formation. The bioplastics made with 2% glycerol addition showed good thermal and mechanical properties. Further, the biodegradability tests (by incubating in protease enzyme solution prepared using phosphate buffer solution) revealed that all the bioplastics are completely biodegradable (Fig. 14), which shows the potential use of this film to replace plastics, which are harmful to the environment.

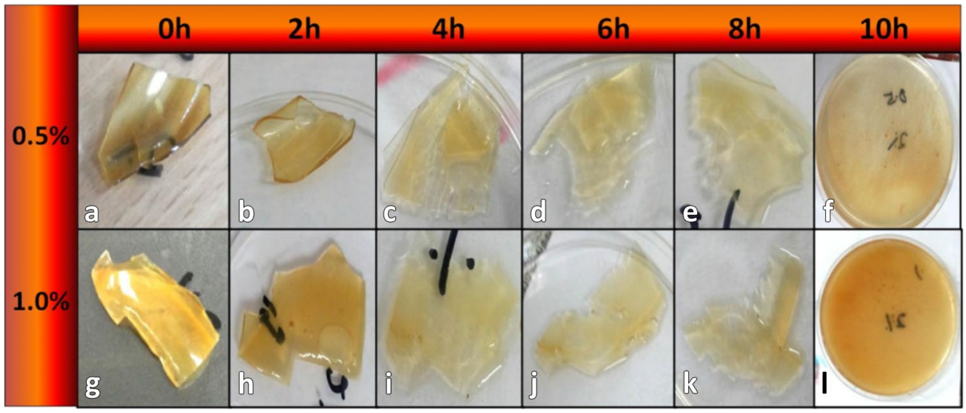


Fig. 14 Biodegradability study of 2% glycerol bioplastic film in 0.5% (**a**–**f**) and 1% (**g**–**l**) of stock solution (stock solution: protease enzyme solution) (obtained from [75])

7 Barriers, opportunities, and challenges associated with solid waste management

The large volume of solid waste generation could not be avoided with the rising population and the associated industrialization and urbanization. So, sustainable solid waste management is emerging as one of the significant alarms in front of us because it depends upon the quantity and composition of waste generated. Furthermore, solid waste comprises numerous valuable products which could be used as an alternative for commercially available products. Therefore, solid waste management requires effective waste management practices/technologies and policies related to the environment and public health.

As discussed above, several technologies exist for the management of solid wastes and for effective product/energy recovery; nevertheless, in majority of the developing countries, the wastes are disposed of in landfills/dumpsites. This not only increases the load to the dumpsites and decreases the empty land and also underutilizes the potency of these renewable resources. Furthermore, the managemental obstacles prevail such as space limitations, burning, and illegal dumping, lack of waste collecting points, irregularity of waste collection, and improper waste segregation at source. However, in order to attain a sustainable solid waste treatment, making sufficient facilities for waste collection and segregation at source should be made mandatory and regulated by the government by applying necessary guidelines, which would reduce the treatment cost, load to the dumpsites and also increase the process efficiencies.

Apart from proper waste collection and segregation facility, insufficient funding is another barrier for setting up effective treatment technologies for treating large volumes of waste. However, nowadays, government incentives could be used for tackling this issue. Furthermore, the lack of communication and participation, and poor communication between the municipality and residents in waste management practices are the other major barriers. The technological barriers associated with various treatment methods could be managed by the use of integrated treatment systems. The existing research on value added products recovery from slaughterhouse and poultry wastes reveals that the wastes could be initially treated for product recovery followed by energy recovery and fertilizer recovery from the leftover treatment residue to carry out an integrated treatment system for effective and sustainable waste management. The selection of treatment systems for slaughterhouses also relies on waste availability, which determines the nature of the treatment to be adopted that adds economic value. For smaller waste quantities, composting with or without prior product recovery would be a good option whereas for large waste quantities, extraction, energy recovery, and composting would be possible. Extraction of value added products like keratin and protein hydrolysate could yield a high economic value. Following this, the leftover fractions could be used for biofuel recovery like biogas/biodiesel through thermochemical and biological conversion methods. The leftover residue after these treatments could be composted to produce an organic fertilizer that in turn adds value further to bring out a circular economy approach. This type of integrated treatment approach will overcome the process inefficiencies associated with mono-treatments therein reducing the carbon footprint of slaughterhouses and improving the return of investment from the wastes in a sustainable way.

8 Conclusion and future prospective

With the rising population along with an increase in urbanization and industrialization, huge volume of wastes is being generated creating threats to the environment and human health. Furthermore, the rising population increases the consumption rate that in turn enhances the slaughterhouses and poultry production which subsequently intensify the solid waste generation. Improper waste management would also greatly affect the balance of ecosystems by means of water, air, and soil pollution. However, solid wastes are potential resources for recovery of various value added products and renewable energy. To tackle these rising environmental issues and best use of the potency of these solid wastes (slaughterhouses and poultry), conventional and several alternative treatment technologies are available which have been detailed in this review article. In addition, the efficacy of technology as well as the need for improving their treatment efficiency is also reviewed in this article. However, in order to improve the environmental quality, to protect public health and to provide support to India's goal (Swachh Bharat and Smart Cities Mission) and international missions (sustainable development goals of united nations, SDGs), it is highly essential to identify the effective integrated sustainable waste treatment system for these wastes that must be completely applied in collaboration with the public, local authorities, and private sectors. This would help to guarantee a healthy environment while promoting sustainable economic growth. However, the integration of technologies to add revenue to meet the treatment cost and to increase the process efficiencies still needs further research for attaining zero solid waste discharge to bring out a circular economy approach. Furthermore, the recovery of value added products from slaughterhouses and poultry wastes could pave a way for a country to become self-reliant (e.g., India's Mission Aatmanirbhar Bharat (self-reliant India)), which will be highly helpful for the country's growth and economic development during any pandemic situation. The details of value added products recovered from slaughterhouse and poultry wastes and also the processes involved for recovery have been reviewed here; nevertheless, profound research focus still requires improvement in the quality of the recovered products so that it could completely replace the commercially available products.

In addition, in most of the developing countries, the amount of solid waste generation is low in urban areas when compared with industrialized countries; however, the availability of solid waste management techniques is inadequate and highly challengeable. Especially, the management system for slaughterhouse and poultry waste is very poor, and specific action needs to be involved for effective management of these wastes. Therefore, the necessity of waste management has to be encouraged by effective waste management practices as mandatory at all levels of public, communities, and businesses including meat industries which create awareness to minimize the waste generation and enable them to reuse the renewable waste resources and decreases the depletion of natural resources for bringing out a circular economy concept for managing the wastes from slaughterhouses. Specifically, community participation is the key in solid waste management. Thus, essential efforts need to be made to educate the community for understanding the waste segregation at generation points for effective solid waste management. In addition, efforts are needed to cut down the expenditures by employing the use of low-cost new sustainable processing methods for slaughterhouse and poultry waste treatment, where waste effluents would be successfully treated and the value added products from waste could be recovered and upgraded for various commercial applications.

Credit author statement VM: Conceptualization, methodology, writing-original draft preparation, review and editing, project administration.

TSN: Conceptualization, methodology, writing-original draft preparation, review and editing, project administration.

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Declarations

Conflict of interest The authors declare no competing interests.

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