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REVIEW

A mini literature review on sustainable management of poultry abattoir wastes

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Abstract
Poultry slaughtering and post-processing activities generate different kinds of highly perishable organic wastes and by-products. Poultry carcass yields are typically about 70–75% of the live bird weight, the rest is accepted as inedible waste. Depending on the efficiency of the processing methods birds' blood, feather, head, feet, offal and inedible viscera, and in some cases, treated solids make up the slaughterhouse solids in the poultry industry. The management of nutritive organic waste should aim to produce value-added by-products such as pet animal or aquaculture feed components, energy through thermochemical or biochemical processes, and agricultural fertilizer. Conventional rendering at specified temperatures and pressures are widespread processing and well-established methods to produce sellable products in the form of protein-rich meals such as poultry powder, feather powder, and fat. The utilization of raw or processed poultry by-products for animal feed is become strictly banned in both national and international scales for the poultry industry. There has been increasing stress to find alternative areas demanding nutrient-rich solid by-products. The objective of this study is to review several studies with a special focus on poultry abattoir-related activities to draw attention to proper management practices from the environmental point of view. The review shows that best management of the process, high-quality wastes need further innovative and effective processing methods to find possible feed additive either for fish or other animal meal, as well as alternative waste treatment process that provides an opportunity for energy recovery and high-quality bio-nutrient source to be used for crop production.

Keywords Poultry abattoir waste · Characterization · Sustainable management · Value-added products

Introduction

Poultry industry is producing diverse types of wastes in large volumes including excrement, mortalities, and post-processing abattoir wastes requiring regular and reliable management strategy and prompt disposal from the slaughtering facility [1]. The quantity of slaughterhouse waste has soared in recent years due to the rapid increase of the world broiler meat production. Main components of wastes from poultry abattoir include organic solid by-products and processing wastewater. Inedible parts including head, feather, feet, viscera, and trimmings approximately accounts for 28% of the live weight of a broiler chicken. For instance, a typical abattoir plant slaughtering 200,000 broilers per day with an average live weight of 2.3 kg will produce 127 MT (metric ton) of viscera and entrails [2]. Post meat processing and wastewater treatment facilities further increase the waste quantities in the waste stream of slaughterhouses. The total availability of solid by-product in Turkey generated from large slaughterhouses is estimated to be around 1 million tones/annum [3]. The diverse soft and trimmed bones are mainly processed together by rendering to yield animal fat, and meat meal for further processing into feed ingredients or renewable energy sources [4, 5]. Simultaneously, scalding, cleaning, chilling and washing facilities generate large amounts of wastewater with high content of biodegradable organic matter and suspended solids [6].

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There are 66 registered slaughterhouses in the Turkey, which are mostly producing poultry feed using slaughtering by-product after rendering. Because of legal restrictions on the use of slaughtering by products in feed ingredient and rising treatment costs, solid wastes and wastewater become as a major environmental concern to properly manage [7]. Therefore, poultry slaughterhouse waste management is one of the major daily challenges facing the sector. Considering the foregoing facts, efficient recovery of wastes in each step and processing into new product has direct positive impact on the economy and pollution prevention [8, 9].

Poultry slaughterhouse waste contains approximately 34% dry matter consist of 52% crude protein, 41% fat, and 6% ash [9]. In this regard, current methods used for the disposal of poultry slaughterhouse waste includes anaerobic treatment for methane production, thermochemical procedures for energy extraction, rendering for feed ingredients and composting for bio-nutrient sources [10]. Among them, rendering products are no longer permitted for feed preparation in European countries and Turkey due to concern on diseases transmission, meat hygiene, and ethical issues regarding cannibalism [7]. However, using as feed ingredient after proper hygienezation by rendering process has become the most profitable application for protein-rich wastes so far. Moreover, direct incineration is a microbiologically safe method against to possible disease transmission, although it is comparatively quick but expensive method [11, 12]. Accordingly, highly efficient methods for composting poultry carcasses were introduced to waste management, since thermophilic biodegradation yields a harmless humified compost that can be safely used as a soil conditioner [13].

The European regulation on animal feed sets rules on the distribution and use of feed materials, requirements for feed hygiene, rules on undesirable substances in animal feed, genetically modified food and feed, and conditions for the use of additives in animal nutrition [14], to ensure that feedstuffs do not endanger to human, animal or the environment health. As requirement, the use of poultry by-products meals for livestock feed are banned in the EU. The consequence is dramatically increased disposal difficulties for slaughterhouses and costs for poultry feed. Simultaneously, in January 2016, Turkey banned the poultry rendering product including in poultry feed [15].

The use of poultry by-product meal for livestock feeding was banned in 2002 in the European Union [16]. On the contrary, Commission Regulation [14] has been allowed the use of non-ruminant terrestrial animal by-products meals for the preparation of pet food, fur animals and aquaculture feeds. The use non-edible by-product of poultry industry for the production of animal feeds can increases the commercial value of these by-products for sustainable economy [17]. The wastes, which are not suitable for preparing the food or feed ingredients, alternative methods, such as thermochemical treatments or thermophilic composting can be considered for renewable fuel production or processing for utilization as bio-nutrient sources [8].

There is a need for both recovery the feed materials that is negatively affecting the supply of feed ingredients as well as sustainable management for poultry slaughterhouse waste in lower costs. Therefore, the main objectives of the present study are adding contribution to local and international management practices and attracting the vitality and urgency of process-related issues.

Characterization of poultry abattoir wastes and by-product

Waste generation in poultry abattoir

Various kind of organic by-products and associated solid wastes are generated depending on different processing lines of the broiler meat industry. Figure 1 shows the main phases of broiler slaughtering processes and arising solid waste or by-products from each phase of poultry industry. Solid waste accumulation starts from the reception step to the slaughterhouse with poultry excrements and mortalities, blood from the bleeding stage, feathers from the depilation process, the offal and intestinal residues of the evisceration process, and

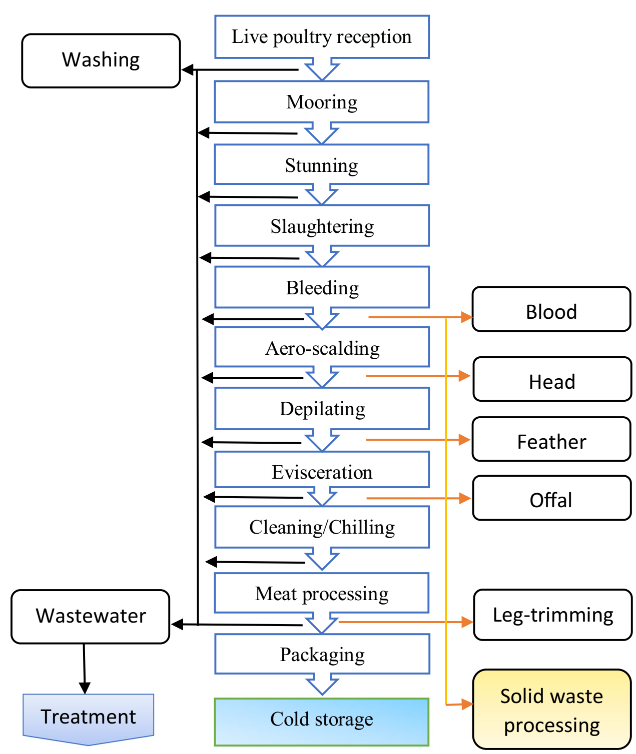

Fig. 1 Slaughtering and poultry meat processing phases (adapted from [1, 8])

bone and inedible meat residues at trimming and deboning step [8]. The amount of inedible meat by-product calculated based on live weight after sellable carcass removed has been accounted for 30% of the live poultry weight [18]. Based on the waste characteristics, poultry abattoir wastes can be broadly classified into soft wastes (i.e. offal, intestines, and bones), feather, blood, and wastewater generated from washing and cleaning steps depicted in Fig. 1.

Soft wastes

Poultry abattoir soft waste category includes mainly viscera, intestines, heads, feet, bones, poultry skin, meat, and fat trimmings that are not ready or directly suitable for human consumption [1]. Detailed characterization of poultry meat by-product and solid organic wastes are presented in Table 1. It is reported in the previous studies that, 22–23% of broiler chicken waste is considered as soft waste containing head, feet, offal and intestine, but a considerable variation exists [10]. These category of by-products and wastes are mainly composed of chicken proteins and fats (Table 2). After slaughtering process, meat tissues lose their antioxidant defense and lipid, myoglobin, and protein oxidation in mishandled by-products may deteriorate the raw material [19]. To process value-added new product, proper management practices based on regulations are vital for poultry solid wastes. Improper management could lead to serious environmental consequences due to excessive organic matter and nutrients, source of pathogen transmission, odor emissions, and water, soil and health hazards [20].

Feather

Feather is another significant and protein-rich waste, constitutes up to 7–8% of total chicken weight, reaching more than 50 g per chicken of waste material generated by the poultry industry. Feathers has been frequently converted into feather meal, fertilizers for agricultural usage, as bedding material, and for decorative purpose [26]. Feathers are principally made up of non-digestible keratin protein with the rate of 74–91% [27]. To solubilize keratin into a readily digestible protein, physical, chemical or biological pretreatments are usually practiced according to the utilization purpose [2]. The most commonly used method is rendering with high-pressure autoclaving at more than 133 °C in the availability of amino acids. Providing convenience to large-scale industry, feather meal is generally produced following drying and grinding of the hydrolyzed feathers by rendering process. Biological treatment using feather degrading bacterium (*Bacillus licheniformis*) or keratin degradation enzymes [28] is another common method to convert feathers to a digestible protein source.

Due to the unique physicochemical structure, such as low density, high slenderness ratio good pliability, moderate

Table 1 Poultry industry by-products and their potential uses (adapted from [2])

Type of by-product	% of live weight	Uses
Feathers	7–8	Poultry bedding material, bio-nutrient source, feather meal, decorative purpose, yarn, and textile applications
Heads	2.5–3.0	Poultry meal
Blood	3.2–3.7	Blood meal
Gizzard and proventriculus	3.5–4.2	Edible, source of chitinolytic enzyme
Feet	3.5–4.0	Soup, technical fat/poultry grease
Intestines and glands	8.5–9.0	Meat meal, poultry grease, and active principles (hormones and enzymes)

Table 2 Organic matter content and basic composition of poultry slaughterhouse wastes

Material sample	Volatile matter (%)	Crude fat (%)	Crude protein (%)	Ash (%)	TN	Reference and region
Poultry meal	78.4	16.0	65.0	12.9	11.6	[5], Turkey
Mix slaughterhouse waste	84.5–90.9	18.0–27.9	50.7–62.7	9.14–15.5	–	[9], Iran
Poultry offal	95.0	54.0	32.0	–	5.3	[18], Finland
Mix slaughterhouse waste	–	28.21	43.69	15.78	–	[21], Iran
Mix slaughterhouse waste	88.1	52.03	–	11.9	–	[22], Poland
Mix slaughterhouse waste	83	–	–	–	–	[23], Iran
Soft tissue wastes	96.6	36.1	34.0	–	5.1	[24], Ireland
Viscera	95.3	43.4	39.3	–	–	[25], USA

TN total nitrogen

strength, spinnability, fineness and length, durability properties, microstructure and thermal stability make the feather suitable for yarn fabrication and technical textile applications [29]. Adding value to keratin based waste using in the manufacture of yarn and technical textile products offers an economically and environmentally integration of beneficiation.

Blood

Approximately 2% of the live broiler poultry weight is consist of blood [18]. When the average live weight of 2340 g broiler is slaughtered, about 45 g of blood is produced at the bleeding stage (obtained from the authors' personal communication). Dry poultry blood contains about 95% protein with high nutritional and functional quality, good balance of amino acids, and significant amount of micronutrients (i.e. iron, when processed to produce blood meal) [30]. Blood is actually sterile in a healthy non-medicated animal. During slaughtering, blood is usually collected separately from the other solid wastes and handled on taking proper sanitation precautions to process high-grade blood meal. Yet, in some small slaughter plants, blood is disposed together with feather, and intestinal content of through the wastewater treatment. High-grade blood meal can be used in feed formulation for different animal species as well as nutrient sources for commercial crops.

Wastewater

Due to the extensive amount of water usage from different slaughtering and poultry meat processing phases (e.g. reception and preprocessing of birds, stunning, slaughtering, scalding, feathering, evisceration, and further meat trimming and processing), a substantial amount of high-strength wastewater [with a high organic matter content, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total organic carbon (TOC), nutrients such as total nitrogen (TN), phosphorus (TP), cleaning detergents, and different species of microorganism] is generated and needs an appropriate treatment. Characterization of wastewater reported in the previous literature is summarized in Table 3. The wastewater is composed of cleaning water of processing steps containing excrements, blood, fat, feather, and undigested feed substances from the digestive system [31, 32]. After a preliminary treatment to eliminate settled solid materials, floating materials, the wastewater proceed to the coagulation-floatation unit to remove grease and finally activated sludge system for the final treatment [6]. The degree of treatment required is determined by the specified discharge limitations as defined by the industrial wastewater treatment regulation [33]. Wastewater sludge is generally dewatered in three steps (i.e. decanter, separator, and drying, respectively) to obtain sludge with a moisture content less than 40%. Finally, dried sludge is received by a contracted waste processing company to prepare RDF (refuse derived fuel) for the incineration in cement clinker.

Poultry abattoir with the slaughtering capacity of 100,000 bird day^{-1} uses 1050 m^3 day^{-1} process water and generates 2.2 mg day^{-1} sludge cake discharged from the wastewater treatment plant [8]. Moreover, the poultry abattoir sludge is generally rich in plant nutrients [34], and it was reported as 22.4 kg of nitrogen was obtainable per 1000 heads of poultry waste [8] which could be a bio-nitrogen source in the plant nutrition.

Conventional poultry abattoir waste processing and products

The solid waste generated from the slaughtering and meat process is a slaughterhouse responsibility on the frame of ongoing national regulations. Until the restriction by regulation [11] organic by-products from poultry abattoir, such as blood, offal, viscera and entrails, trimming, bones and, feather have mainly been processed to produce animal feed through the rendering process within the integrated industrial facility. Considering the need for substantial amount of animal feed, hygienic disposal alternative method, guarantee environmental safety, public and animal health, it is

Table 3 Characterization of industrial poultry slaughterhouse wastewater

Material	TSS (mg/L)	TOC (mg/L)	COD (mg/L)	BOD (mg/L)	Oil/Grease (mg/L)	TN (mg/L)	TP (mg/L)	Reference and region
Sample 1	1904	–	3020	–	716.2	–	–	[1], Brazil
Sample 2	2450	3–9	3102	1780	375	186	76	[4], Brazil
Sample 3	–	–	2380	–	–	182	–	[6], Turkey
Sample 4	2800	–	6888	–	–	675	8.95	[31], Turkey
Sample 5	–	3–9	2171	1113	143.1	–	9,65	[32], Turkey

TSS total suspended solids, *TOC* total organic carbon, *COD* chemical oxygen demand, *BOD* biological oxygen demand, *TN* total nitrogen, *TP* total phosphorus expected that conventional rendering will continue as the industry search for new ways to increase high-grade feed for aquaculture, pet food or other value-added new product.

Rendering

Poultry slaughterhouse wastes (e.g. offal, trimmings, and off-cuts) are rapidly perishable waste and may deteriorate if they are left ambient temperature for extended period and mishandled before preliminary processing. Due to the high content of biodegradable organic matter in poultry abattoir waste, the availability of resource-based products, and current status of applicable technologies, rendering is the most promising method to obtain and preserve the nutritional quality of end product, and quickly transforming the animal by-products into high-grade hygienic new products [21]. Autoclaving at high temperature and pressure break down whole undecomposed poultry by-products including soft wastes, bones, feathers, and other specific portions of the carcass separately or in a mixture [9]. Conventional rendering processes convert the organic poultry processing wastes into marketable products, such as poultry meal, edible, and inedible fats for feed ingredient and industrial use such as fuel blending agents. Each of rendering product is an excellent source of specific use and generally provides a cost-effective source of animal protein [35]. The derived products are environmentally acceptable, because high temperature and pressure at legislative standards totally sterilize the waste product [17]. As previously stated, the rendering products has great amounts of lipids and proteins that make it a convenient source of animal feed, feedstock for biogas plants, in chemical industry products, or alternatively renewable biofuel [5, 21, 36]. Rendering process implemented for poultry slaughterhouse wastes and the corresponding rendering products are illustrated in Fig. 2.

There is an increasing demand for protein rich meals world-wide for the use in feed ingredient particularly in the pig and aquaculture industries. For instance, it is reported that Finland uses an annual 370 million kg of feed for fur animal, mainly prepared from the meat and fish industry by-products [18].

Poultry meal

Soft solid waste and by-products produced in broiler slaughtering such as feet, head, bone, trimmings, and intestinal organs, are combined together to produce poultry meal. These by-products are rich in protein and lipid which make them highly perishable due to chemical and enzymatic processes. For further processing of these waste materials into high-grade new products, those solid parts are quickly processed by rendering to produce product of protein-rich poultry meal and fat. Raw solid organic materials consist of 32% protein and 54% lipid and have high digestibility potential [18].

Cooked poultry meal provides an excellent source of balanced amino acids and also mineral nutrients such as phosphorus [37]. Poultry meal has high volatile matter, protein, fat content, and metabolic energy (Table 4). Due to its high protein and fat, and relatively lower ash content, poultry

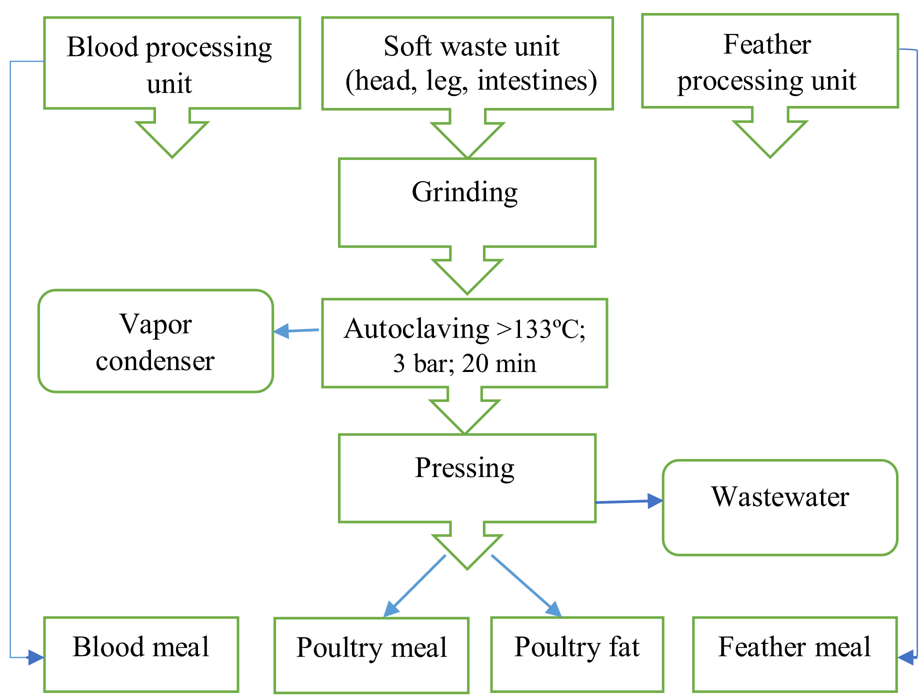

Fig. 2 Rendering process applied for poultry slaughterhouse wastes and rendering products (adapted from [10])

Table 4 Composition of poultry meal mixture

Material sample	Volatile matter (%)	Crude protein (%)	Crude fat (%)	Ash (%)	Gross energy (kJ g^{-1})	Reference and region
Sample 1	78.4	65.0	16.0	12.9	24.7	[5], Turkey
Sample 2	92.9	71.6	13.1	9.1	–	[17], Costa Rica
Sample 3	92.5	55.6	13.8	16.6	–	[35], Turkey
Sample 4	95.3	67.4	15.9	12.4	23.2	[37], China
Sample 5	–	69.8	12.6	13.7	21.7	[40], Australia
Sample 6	–	64.0	14.0	13.0	20.5	[41], Turkey

meal has higher energy value which make it suitable for various poultry derived food, feed, and intermediated energy products. For instance, with a more than 10% lipid content, poultry meal is more favorable feedstock for biodiesel production [5], but its nitrogen content might raise questions about the emission quality of biofuel.

Feather meal

Considering nitrogen- and protein-rich content, poultry feather has a great potential for various utilizations. However, keratin is an insoluble structural protein with high mechanical stability and resistant to degradation by common proteolytic enzymes [38]. To solubilize keratin into a readily digestible protein, physical, chemical or biological pre-treatment are generally combined in practice, according to the final utilization alternative. The most commonly used method is rendering with high-pressure autoclaving at more than 133 °C, 3 bar pressure to form an edible gel for feed blend. Providing convenience to large-scale industry, feather meal is generally produced following to drying and grinding of the hydrolyzed feathers by rendering process. However, the digestibility rate of feather meal is reduced in steam hydrolyzed feather [17]. Biological treatment using feather degrading bacterium, *Bacillus species* or keratin degradation enzymes [28] another common methods to convert feathers to feather lysate, an amino acid-rich digestible protein source for feeding [27]. A keratinase enzyme, synthetized by different microorganism, is purified and characterized. Types of keratinase secreted by a different bacterium that hydrolyzes feather keratin have been expressed by different experimental studies, without losing significant alteration in amino acid profile and digestibility [26]. The composition of feather meal reported in different studies is summarized in Table 5.

Currently in Turkey, feathers are processed in rendering at high-pressure and temperature over 133 °C to obtain feather meal and used for animal feed component. Thermo-hydrolyzed feather meal is a rich-protein source including 74 to 91% crude protein [9], sufficient in cystine, but relatively deficient in lysine and methionine amino acids [21]. The unsatisfactory level of lysine and methionine may cause nutritive imbalance in feeding diet which needs specific feed formulations for different animal species. The digestibility rate of the feather meal nutrients can vary depending on the applied autoclaving conditions and used animal species [27]. Conversion of keratinous feather waste into slow release organic fertilizers is also meaningful for nitrogen recovery and recycling.

Fat

Poultry rendering plants produce less expensive edible or inedible fat and grease, which are potential to use in non-livestock animal feed, chemical industry products, and fuel blending agents. In the rendering process, poultry by-products consisting soft solid waste (e.g. heads, feet, trimming, bone, and intestines) either ground and cooked separately or rendered with feathers [21]. Rendering operation at high temperatures heat up the raw materials and separates

Table 5 Composition of feather meal

Material sample	Dry matter (%)	Crude protein (%)	Crude fat (%)	Ash (%)	Gross energy (kJ g^{-1})	Reference and region
Sample 1	98.2	90.8	3.6	–	–	[25], USA
Sample 2	94.8	84.2	10.4	3.0	23.4	[27], Portugal
Sample 3	90.5	78.6	5.4	2.9	–	[35], Turkey
Sample 4	92.0	83.0	11.7	2.9	22.8	[37], China
Sample 5	86.2	81.2	9.8	4.8	–	[39], Venezuella

fat from raw material by boiling in water. Following the dewatering process, much of the melted fat is removed from batch by draining, and the residue is passed through a screw press to remove some of the remaining fat and moisture from the rendered product. The amount of extractable fat from the poultry wastes varies from 2 to 30%, depending on raw material and applied rendering conditions [2]. Rendered fat is generally lower in cost than vegetable oils, therefore it is used substantially in feed ingredient [40]. The inclusion of fat into aquafeed increase metabolizable energy, and thus higher energy diets stimulate the growth and improve feed conversion ratio.

Alternative ways of the utilize the slaughterhouse products

Aquaculture feed

After restriction of using the rendered poultry by-product meals in farmed livestock feed ingredients, the demands from commercial aquacultures have been prospectively increased for protein sources in aquafeeds ingredients, and numerous studies have evaluated its potential across a range of aquaculture fish species [27, 41]. The aquaculture species especially fishes have been feeding with high protein and energy containing feeds. Rendering products have included high proportion protein so as to this can be used an important source for it [42]. However, nutritional quality, digestibility and amino acid profile show variability depending on the applied rendering process and composition and quality of raw materials used to produce the meal [40]. The most important factor determining nutritional quality is poultry raw material freshness and rendering conditions (e.g. temperature), that cause protein oxidation, amino acid racemization, peroxidation of fats, and formation of biogenic amines [19].

It is estimated that about 230 thousand tons of farmed fish and crustaceans is dependent upon the supply of external nutrient inputs in Turkey. As aquaculture increase, aqua feed production is also increasing. Thus, poultry by-products meal could be a very suitable option to support aquaculture sector relying heavily on high-grade fish meal and to maintain an environmentally benign sustainable. Poultry meal has the well balanced amino acid profile and can be incorporated animal feed with a mean use of 5–10%. Protein digestibility is reported higher than 80% for poultry by-product meal in fish production [43]. Dietary supplementation of poultry meal or feather meal at 5 to 25% has been reported as positive contribution on growth performance and feed utilization ratio of fish species when certain amounts replaced with fish meal [40]. In contrary, the opposite example of feed conversion ratios were also reported by several researcher depending on fish species, rate of poultry meal substitution, nutrient composition of feed, processing method used for meal, and developmental stage of the fish [41], which point out to adjust most appropriate substitution ratio for a specific situation.

Fly larvae production

Detritivore insect larvae rearing is an emerging technology in organic waste processing because they have an ability to convert wasted entropic energy back into valuable food substances for variable uses. Nutrient-rich poultry abattoir wastewater sludge could be a feasible substrate for full-scale insect larvae rearing, and larvae can be used as a feed alternative as well as waste residue as a bio-fertilizer. A pictorial representation of the steps of the larvae meal production by poultry abattoir wastes is depicted in Fig. 3. Proximate analysis of fly larvae meal on the dry weight basis contained in the range of 41.1–43.6% crude protein, 15.0–34.8% ether extract, 7.0% crude fiber, 14.6–28.4% ash, and 5278.49 kcal kg^{-1} gross energy [44]. For instance, research on house fly larvae (*Musca domestica*) produced in poultry waste indicated high protein (63.1%) and fat (15.5%) contents which were a well-balanced amino acids profile than soybean meal and could be substituted to produce better quality chicken feed ingredient [45]. Similarly, black soldier fly (*Hermetia illucens*) has a capacity to convert different kind of organic waste into insect meal [46]. Dried maggots and pupae contain 56.9–60.7% crude protein and 19.2–20.9% crude fat, respectively. Their protein and amino acid compositions similar to fish meal, and digestibility rate is very high (98%). These compositions can replace 7% of the fish meal in broiler chicken feed [47]. It is estimated that a 1200 m^2 poultry shed produces about 113 tons of manure per year, and the rearing of fly to convert that amount of

Fig. 3 Steps of the larvae meal production by poultry abattoir wastes (adapted from [10])

waste would result in about 65 tons of bio-fertilizer and about 47 tons of insect larvae for the protein production [46].

Under the optimum environmental conditions, the life span of black soldier fly is 2–4 weeks depending on the availability of food sources and practically suit to produce nutrient rich, amino acids balanced feed for aquaculture. The remaining organic residues has potential to be used as bio-fertilizer [48]. The emerging technology has potential to convert organic wastes into a valuable new feed material either for poultry or fish farming. However, to establish the commercial scale, there is a need further research on well optimized, and standardized insect rearing technologies that use well-defined substrates, producing insects or insect meals that attend the quality standards as stated by the legislation [46]. According to EU regulations nonpathogenic terrestrial invertebrates must be processed in accordance with the animal by-products to become processed animal protein before they can be fed to farmed animals other than fur animals [16].

Waste to energy systems

Poultry slaughtering waste has been shown to be an excellent renewable biomass fuel source [49]. Anaerobic digestion and direct combustion are frequently used technologies to convert poultry waste material to energy [50]. Following technological advances and diversification of methodology in the last decades, energy generation from waste materials has become one of the first alternative for the sustainable waste management option [25]. Waste to energy technologies has also coincided with reducing carbon emissions, unstable costs, as well as environmental and health concerns (e.g. less odors, disease transmission, and vector attractions) on poultry wastes [7].

Proteins and lipids rich poultry abattoir wastes and their meal has great potential to produce high methane yields at different concentrations of volatile solids [51, 52]. The biochemical methane reaction chains of slaughterhouse wastes need more time, thus longer retention time such as 50 days [23], probably due to long chain fatty acid inhibition on methanogens reactions. The length of time depends on the source and various concentrations of inoculum and incubation temperature. Feather showed lower methane yield of 0.21 m^3 kg^{-1} when volatile solids were added (50 m^3 ton^{-1} wet weight) [53]. Combined thermal (120 °C, 5 min) and enzymatic (commercial alkaline endopeptidase, 2–10 g L^{-1}) pre-treatments resulted in increased methane yield by 37 to 51%, which confirm the suitability of the poultry slaughter wastes for anaerobic digestion and high methane yield [24]. Similarly, pretreatments improve the bio-methane production of feather [53]. The estimated energy recovery from the poultry slaughterhouse was 35.4 N m^3 1000 $head^{-1}$ as CH_4. Typically, the total recovered CH_4 from evisceration to wastewater treatment stage occupied 88.1% and 7.2% of amount of methane, respectively [8].

Thermochemical conversion process is a novel technology that can be adapted for management of abattoir wastes and by-products with high bio-oil and biochar yields [54–56]. The flash pyrolysis is one of the emerging technologies, operates in the absence of air, and produce a solid, liquid and gaseous fuel, which are suitable for storage and transport. Main advantage of this technology is energy provision from a waste resources in the milder operating conditions, typically around 250–500 °C while compared with 800 to 900 °C for gasification, and short treatment duration for anaerobic digestion. The steps of the bio-fuel production from poultry abattoir wastes is illustrated in Fig. 4.

Slaughterhouse wastes like feathers, blood, and viscera contain up to 12% inedible fat. Environmentally friendly processes are developed for the production of biodiesel from wastes with high oil-grease content. In biodiesel production, primarily fat is obtained from poultry slaughterhouse wastes in boiling water (70 °C) and subsequently trans-esterified into biodiesel using potassium, nitrogen and methane, and 7–11% biodiesel can be produced in this process [57]. Physico-chemical and energetic analysis confirmed that biodiesel obtained from poultry waste showed excellent fuel properties when compared to biodiesel produced from other common crop-based feedstocks. Finally, a pictorial diagram is demonstrated in Fig. 5 for a visual understanding of the above-noted processing methods (e.g. poultry slaughtering, meat processing, rendering, and alternative implementations) reported in this study.

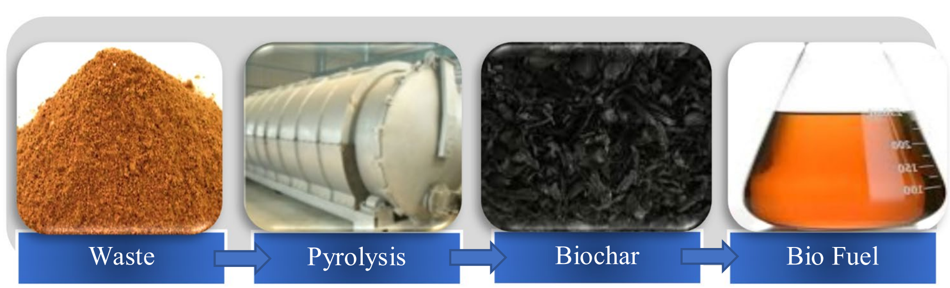

Fig. 4 Bio-fuel production from poultry abattoir wastes (adapted from [10])

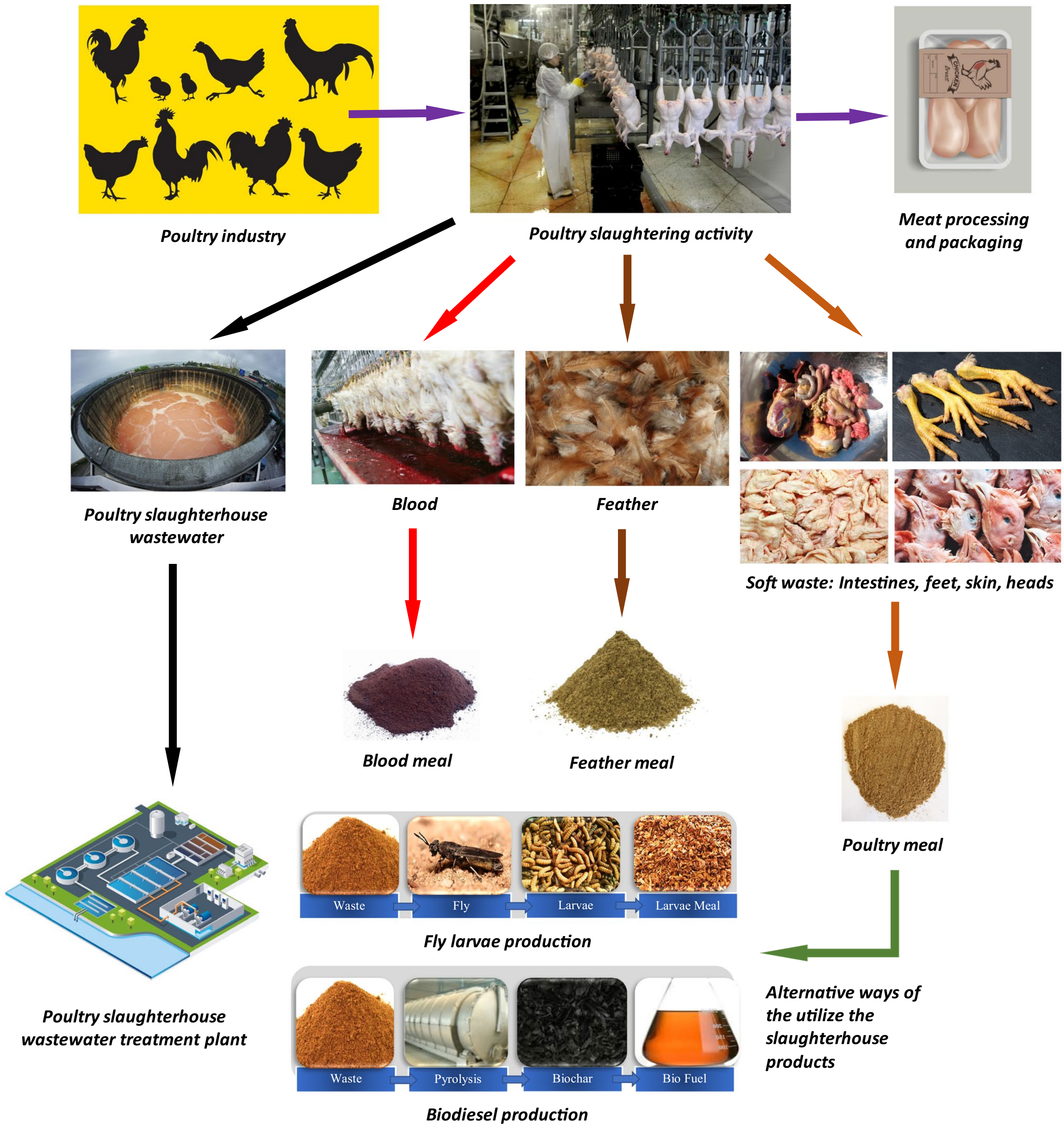

Fig. 5 A visual representation of the poultry slaughtering and post-processing activities

Conclusions

Poultry slaughterhouses generate a high amount of waste that needs to be an urgent solution in the short term. The highly deteriorating nature of those organic wastes poses major environmental and health risks, as well as creating economic value loss, if not properly managed. Before regulatory restrictions, solid poultry slaughterhouse wastes were treated by conventional rendering, the process provides valuable derived product and hygienic feed ingredients to the poultry itself and ruminants. Protein- and fat-rich poultry by-product and solid wastes have distinctive nutritive value, which can be converted to different commercial material, but demand to the feed and food for non-livestock still stands out with respect to the additional source of income. There are several accepted methods like biological conversion, thermal conversion, and thermophilic anaerobic digestion for the final disposal of poultry solid wastes. Rendering is still the most desired process for poultry wastes to satisfy regulation limits, to reduce the health and environmental effects, and to produce a range of value-added and microbiologically safe products like aquaculture feed, pet food, insect meal, renewable energy sources, and bio-nutrients.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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