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Review

A Review of Poultry Waste-to-Wealth: Technological Progress, Modeling and Simulation Studies, and Economic-Environmental and Social Sustainability

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Abstract: The poultry industry has met more than one-third of the human demand for meat and all the demand for eggs during the past several decades, and it has also been recognized as a very efficient sector in the livestock industry. However, increasing poultry production has also led to the massive generation of various poultry wastes, which are a great threat to climate change, environmental safety, and human health. Traditionally, landfilling and burning are the most frequently used techniques for treating poultry waste. With rich contents of organic matter, nutrients, and keratin, poultry waste can be applied to produce value-added products that can be used in many sectors by using a variety of emerging technological processes. Considering the massive generation, profound environmental pollution, and wide range of applications of poultry waste, this paper categorizes poultry waste as litter and manure waste, feather waste, mortality waste, abattoir waste, and hatchery waste. This paper also reviews modeling and simulation studies on poultry waste-to-wealth, and six current or emerging technological processes for poultry waste-to-wealth are described: anaerobic digestion, pyrolysis, gasification, hydrolysis, enzymatic treatment, and microbial conversion. Finally, the economic, environmental, and social impacts of the sector of poultry waste-to-wealth are discussed. For further research, we suggest a focus on the poultry waste-to-wealth projects in different regions, the behavior strategy of different stakeholders, and policymaking for the commercialized application of poultry waste-to-wealth technologies.

Keywords: poultry waste-to-wealth; technological progress; poultry waste treatment processes; economic- environmental and social sustainability

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Citation: Zhang, L.; Ren, J.; Bai, W. A Review of Poultry Waste-to-Wealth: Technological Progress, Modeling and Simulation Studies, and Economic- Environmental and Social Sustainability. *Sustainability* **2023**, *15*, 5620. https://doi.org/10.3390/su15075620

Academic Editor: Elena Cristina Rada

Received: 2 March 2023
Revised: 21 March 2023
Accepted: 21 March 2023
Published: 23 March 2023

1. Introduction

As an important source of human food supply, the poultry industry has provided adequate meat and eggs for humanity. Poultry product consumption around the world has been increasing dramatically during the past several decades, as indicated in Figure 1. According to Our World in Data, poultry meat has outplaced pork as the greatest meat production type since the late 2010s and accounted for more than 36% of global total meat production, as shown in Figure 2. In addition, global egg consumption has also increased from 61.7 million tons to 76.8 million tons between 2008 and 2018 [1]. The fast growth of the poultry industry has greatly promoted agricultural economic growth and made a significant contribution to social employment and the living conditions of residents [2].

The increasing production of the poultry industry has also brought some tricky problems, and a typical one is the treatment and management of the massive generation of poultry waste [3]. Poultry production is a major sector in the livestock industry and has also been considered a significant contributor to environmental problems if the poultry waste failed to be properly treated [4]. Poultry production can discharge a great number of wastes, including hatchery waste, litter and manure waste, feather waste, mortality waste, and abattoir waste [5–7], and generates plenty of greenhouse gases, ammonia, aerosol, and other gases to the air, which may lead to climate change and environmental pollution [8,9]. In addition, it may bring risks to human health due to the spread of bacteria and diseases [7]. In fact, with the advancement of industrial technologies, these poultry wastes can also be recycled and reused as resources to produce value-added products or they can be used as raw materials in wood adhesives, biomaterial development, biomedical applications, environmental remediation, textiles, leather processing, the production of flame retardants and biocomposites, and even as an organic fertilizer and animal feed in agriculture, or as an energy source in biodiesel production [10]. From a life cycle perspective, the recycling and valorization of wastes can not only save materials and minerals but also achieve great benefits in the reduction of GHG emissions and pollutant generation [11,12].

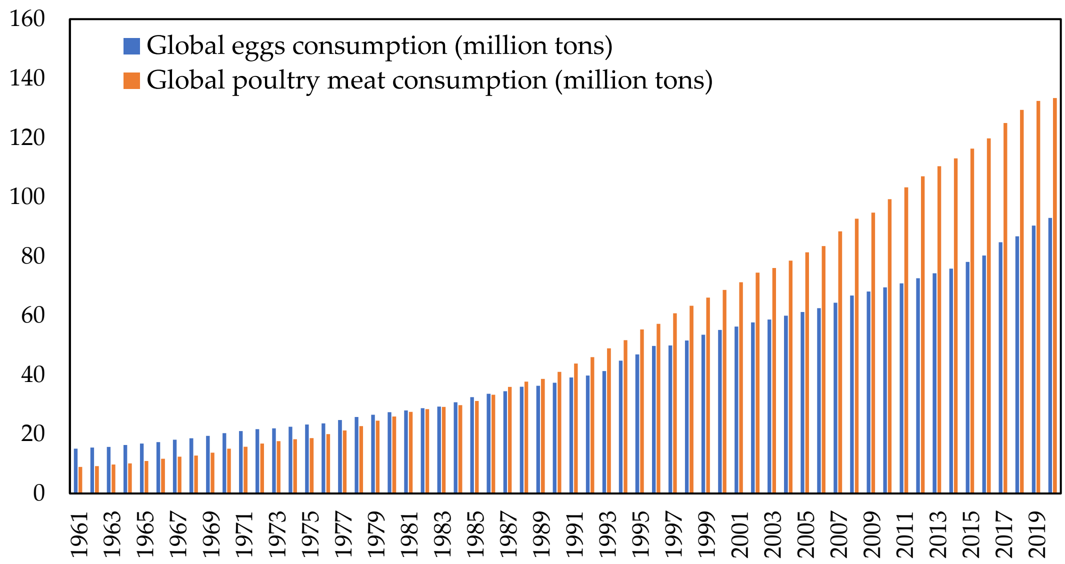

Figure 1. Global eggs and poultry meat consumption, 1961–2020. Data source: Our World in Data [13].

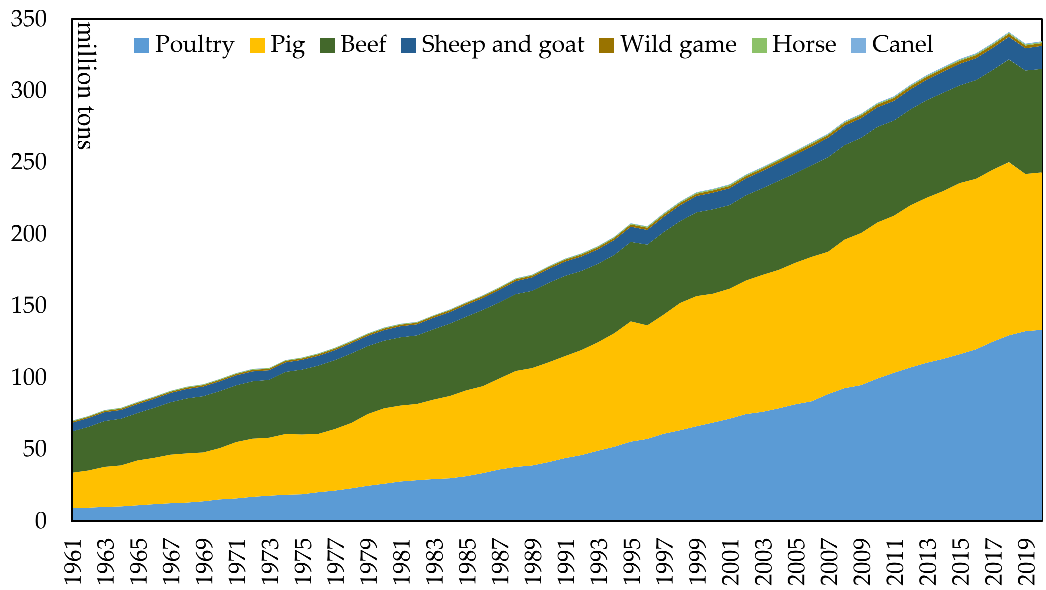

Figure 2. World meat production by livestock type, 1961–2020. Data source: Our World in Data [14].

Considering the massive generation of waste, profound environmental pollution, and wide range of applications of poultry waste, this paper tries to review poultry waste generation, modeling and simulation studies, technological applications, and the economic, environmental, and social impacts in the sector of poultry waste-to-wealth. The rest of this paper is organized as follows: Section 2 describes various wastes generated from the poultry industry, Section 3 characterizes the modeling and simulation studies of the treatment processes for realizing poultry waste-to-wealth, Section 4 presents the technological progress and application of various processes in poultry waste disposal and valorization, Section 5 deliberates the economic, environmental, and social benefits of converting poultry waste to wealth, and Section 6 draws some conclusions and makes some recommendations for future research.

2. Waste Generation from the Poultry Industry

As one of the most efficient livestock species for converting feed into food [15], poultry production also generates a considerable amount of waste from bird hatching to slaughtering, which not only brings difficult challenges for waste disposal and management, but also additional environmental and health risks [5–7].

2.1. Poultry Litter and Manure Waste

Poultry litter and manure waste is a mixture of poultry manure, spilled feed, and materials used as bedding in poultry production, and is the main waste generated in poultry production. It is estimated that a poultry bird would generate approximately 1 kg of poultry litter and manure waste within the 47-day growing-out period [16], and some studies even report a greater value varied from 1.5 to 5.7 kg within a 42-day production cycle for each poultry bird [17,18].

Poultry litter and manure waste contain rich nutrients such as nitrogen, phosphorus, potassium, and some other macro- and micronutrients for crops, and they can help increase the content of available nutrients in the soil [19]. Besides, applying poultry manure as a soil amendment also provides available organic substances and nutrients [19]. Thus, it is traditionally used as organic fertilizer or soil amendment in agriculture to improve both the physical and chemical attributes of soils after proper treatment [3,20]. In addition, it can also be used as a material for the production of animal feed or biogas after anaerobic digestion [21].

2.2. Feather Waste

Feather waste is another byproduct that is massively generated by the poultry industry globally [22]. It is estimated that a bird can hold approximately 5% to 10% of its total body weight in feathers [10,23], and millions of tons of feather waste have been generated from the poultry industry around the world [24,25].

Bird feathers are mainly composed of keratin, which is an insoluble, fibrous, recalcitrant protein [25], and it accounts for 85% to 99% of the total dried feather weight [26]. Keratin protein has a wide range of applications in agriculture, textiles, and leathering, and can even be used in the development of wood adhesives, biomaterials, biomedicines, bioremediation, flame retardants, and biocomposites [10]. However, feather waste is also a serious concern that may lead to environmental pollution [27] because a lot of pathogens and microorganisms such as Salmonella and Vibrio can be found in poultry feathers. Various pollutants, such as ammonia, nitrous oxide, and hydrogen sulfide, can also be emitted from feather waste, which has brought about threats and risks to both human health and environmental safety [10].

2.3. Mortality Waste

Mortality waste includes dead embryos, dead birds, and broken bird parts in poultry production. Mortality is unavoidable in poultry production, and a mortality rate of 5% during the 42-day production cycle is thought to be acceptable [28]. In fact, a survey indicates that approximately 83.34% of poultry farms in Nigeria have an average monthly mortality rate of 7.4% [29]. Even if an annual mortality rate of 2% is assumed, an estimated 85,000 tons of bird carcasses would be generated every year in the United States [30].

Although mortality waste contains a great amount of protein with substantial amounts of phosphorus and calcium due to the great amount of minerals in the bird's diet [31,32], the disposal of poultry mortality waste is an important and challenging task because the improper disposal of mortality waste may lead to great environmental and health risks [33,34]. Traditionally, landfilling and burning are the most used methods for dealing with poultry mortality waste [31,34–38]. The proper depth of the burial site is very important, especially for the birds that died of infectious or zoonotic causes [34]. Moreki and Chiripasi (2011) stated that mortality waste must be buried at least 0.91 m below the ground but no more than 2.44 m deep [36], and Paraso et al. (2010) thought that carcasses should be buried at least six feet (about 1.83 m) deep into the ground to prevent stray animals from excavating bird carcasses and exposing them to the environment, which may spread diseases and affect both human and animal health [34]. However, there is still a lot of the hazardous practice of disposing of carcasses by open dumping as refuse in the garbage with no specific disposal practice [31,34,35,38,39], and many poultry farmers even sell dead birds at a reduced price on a secondary market [31,34,35], or to other farmers who feed them to livestock [38].

2.4. Abattoir Waste

Abattoir waste is the waste by-product generated in poultry slaughtering, including offal, visceral organs, blood, and bones, which are usually defined as inedible by-products in a lot of countries [40]. The abattoir waste also contains viruses, bacteria, and residues, and it is reported that several hundred species of microorganisms are contained in poultry wastes such as feathers, feet, and intestinal contents [41]. Traditionally, the abattoir waste is usually treated as regular waste by disposing them into the nearby dumpsites [42], which, however, greatly increases the risk of disease and bacterial transmission.

Burning and burial seem to be practical ways for the disposal of abattoir waste [43]. However, rich nutrients and reused materials are contained in these wastes. For instance, offal is estimated to be composed of 54% lipids, 32% proteins, 5.3% total nitrogen, and 0.6% to 0.9% methane [44], which means simply burning or burying can cause great wastes of plentiful ingredients that can be recycled and reused. In fact, abattoir waste for poultry production can be used as a material for the production of meat and bone meal, which can be a promising alternative to natural, organic, and mineral nitrogen and phosphorus fertilizers due to the rich quantities of macro and micronutrients and organic matter [45,46]. From a sustainable perspective, these wastes can also be taken as materials for producing animal food and oils [40]. Thus, the valorization of offal, blood, and bones can help achieve great benefits for the environmental, social, and economic aspects by reducing environmental and health risks, as well as the reduction of the high cost of dietary ingredients and animal feedings [47,48]. In fact, poultry waste valorization for the production of animal meal and poultry oils from viscera, blood, and bones is considered a sustainable way of processing recycling wastes into value-added by-products [40], and the processing of animal ingredients has been an important part of improving poultry sustainability [49].

2.5. Poultry Hatchery Waste

In addition, there are also a lot of other wastes generated in poultry production. Among them, poultry hatchery waste is also generated in large amounts. The poultry hatchery produces plenty of solid and liquid waste in bird hatching, including egg shells, infertile eggs, dead-in-shell and decaying tissue, etc. [50], and these wastes should also be carefully treated and can be valorized.

3. Modeling and Simulations of Poultry Waste Treatment Processes

Based on different treatment processes, poultry waste can be converted into different useful by-products. To investigate the feasibility and evaluate the economic-environmental results of poultry waste-to-wealth, various poultry waste treatment processes have been modeled and simulated from the perspectives of economic-environmental benefits and energy efficiency in the treatment processes.

Various treatment processes can be applied in poultry waste-to-wealth, and they can be designed, optimized, and combined by modeling and simulations. Ma and You (2019) designed a superstructure that consists of seven processing sections to treat poultry litter wastes and provided the strategies for maximizing economic benefits based on a mixed integer nonlinear fractional programming model to maximize the return on investment of waste valorization processes [51]. They believed that the economic cost and profit are important factors that need to be considered in the adoption and promotion of technological processes, and found that at the production scale of 150 kt/yr, the fast pyrolysis-based pathway has the highest value of return on investment, followed by hydrothermal liquefaction, gasification, and slow pyrolysis-based pathways. To conduct the technical and economic analysis of converting poultry litter waste into biochar and electricity or heat, Huang et al. (2015) designed a pyrolysis/gasification process integrated with an Organic Rankine Cycle by conducting a process simulation using the ECLIPSE software, and the simulation shows that when a reference poultry litter is used, the biochar yield from the process is around 398 kg/h with a 38% carbon content; the electricity generated by the ORC system is 388 kW h_e, and the recovered low-grade heat for space heating is estimated at 1831 kW h_{th} [52]. Topal et al. (2018) developed a trigeneration system and simulated this process with direct co-combustion of poultry wastes into three energy products, and showed that the co-combustion of poultry waste can be considered the best environmentally-friendly technique to treat chicken farm wastes while covering the energy demand within the facility [53]. Ayub et al. (2022) developed the simulation model of hydrothermal gasification for syngas production from poultry litter waste using Aspen Plus software and suggested that this process is economic-environmentally friendly and energy-saving compared with direct landfilling disposal, and the results indicated that the model has a better yield of hydrogen and methane gas with superior lower heating value at 540 °C, 25 MPa, and 20% feedstock concentration [54]. Isemin et al. (2021) developed a numerical model for the wet torrefaction of poultry litter waste and successfully estimated the optimal duration required for the completion of this process under different conditions of temperature, batch weight, reactor dimensions, etc., and showed that the wet torrefaction of poultry litter increased the carbon content by 17% and reduced the oxygen content 2.46-fold while raising the heat of combustion by 12.5% [55].

Some scholars also focused on simulating new process flows to improve conversion efficiency. For instance, by using the Superpro Designer process simulation program, Lima et al. (2008) developed a process flow to produce steam-activated broiler litter-based granular activated carbon; the optimal equipment parameters and mass flows were estimated, and the study found that the largest contributor to the cost of producing the activated carbon is the $1.2 million equipment cost of the combined pyrolysis/activation furnace, which contributes about $0.47 kg^{-1} to the production cost and indicates that activated carbon can be produced by this method at a cost of about $1.44 kg^{-1} [56]. Ayub et al. (2023) designed a novel tri-generation process that integrated gasification, a solid oxide fuel cell, and a combined heat and power system for poultry litter valorization, and found that an operating temperature around 600 °C and a 0.25–0.33 biomass-to-air ratio can generate an optimum hydrogen yield in syngas, indicating that this process had great potential as a better alternative for poultry litter valorization [57]. Apparently, the technological processes for converting poultry waste to wealth have been developed significantly, and great potential is endowed in transforming poultry waste to wealth through these technological processes.

To investigate and compare the performance and efficiency of different processes in converting poultry waste to wealth, the modeling and simulation of different poultry waste treatment processes are conducted and compared. Ma et al. (2022) developed four processes for transforming poultry waste into useful products: supercritical water gasification for hydrogen and electricity, supercritical water gasification for electricity, steam gasification for electricity, and steam gasification for hydrogen, and indicated the potential of multi-energy recovery from poultry litter waste; the study found that the energy/exergy efficiency of the process is positively correlated with the heat value of syngas, and suggested that steam gasification for hydrogen could be a better solution due to its high efficiency and low equipment cost [58]. To examine the economic-environmental performance of different combinations of poultry waste treatment technologies (including slow pyrolysis, fast pyrolysis, gasification, and hydrothermal liquefaction) and downstream processing options, Bora et al. (2020) conducted nine case simulations in New York State, which revealed that the economic performance for the nine cases with respect to the four technological processes varied greatly with largely overlapping net present values, and the two pyrolysis processes can reduce greenhouse gas emissions more than the other two options [59]. Adeniyi et al. (2020) developed three thermodynamic models as pyrolysis, in-line steam reforming, and gasification for treating poultry litter on Aspen Plus software, and the results showed that the optimal conditions for the in-line steam reforming of poultry litter were observed to be 400 °C temperature and 12 kg kg^{-1} steam-to-feed ratio, yielding a syngas composition of 70.2 mol% H_2, 29.4 mol% CO_2, 0.22 mol% CH_4, and a trace amount of CO; the optimal conditions for the gasification of poultry litter were 700 °C temperature and 0.2 kg kg^{-1}, yielding a syngas composition of 52.6 mol% H_2, 10.3 mol% CO_2, 2.77 mol% CH_4, and 34.3 mol% CO, indicating that gasification generated a higher syngas yield but with less quality, while steam reforming generates higher quality but a lower yield [60]. To investigate the potential of gas production for electricity generation from poultry waste by small-scale downdraft gasification, De Priall et al. (2022) simulated the process of poultry waste gasification with heat and electricity generation using the ECLIPSE simulation software by comparing it with anaerobic digestate and miscanthus as an energy source, and the simulation showed that the generated electricity from this poultry waste gasification system can support the farm to transform from fossil energy-based operations to renewable energy-based operations and solve the poultry waste disposal problems simultaneously [61].

Although various technological processes are available for disposing of poultry waste, the processing systems usually process poultry waste together with other wastes or materials for better economic efficiency. Fang et al. (2020) simulated the co-digestion of chicken manure with commercial yeast waste (*Saccharomyces cerevisiae*), and found that the maximum biomethane yield of 364.79 mL/gVS was obtained at the optimum co-digestion feedstock (*S. cerevisiae* of 0.69 g/gVS) with a significant reaction rate increased of hydrolysis, acidogenesis, acetogenesis, and methanogenesis [62]. By evaluating the techno-economic performance of bioenergy and organic fertilizer production from the anaerobic co-digestion of sewage sludge, wine vinasse, and poultry manure under different operational conditions based on laboratory-scale experiments, Sillero et al. (2023) found that the process produced the highest electricity (1058.99 MWh y^{-1}) and heat (4765.47 GJ y^{-1}) with the lowest cost of manufacturing for electricity (84.99 USD MWh^{-1}), heat (0.019 USD MJ^{-1}), and fertilizer (30.91 USD t^{-1}) and concluded that temperature-phase anaerobic co-digestion is an economically profitable and environmentally sustainable waste-to-energy process that can be utilized in the poultry sector to deal with the massive production of poultry waste [63]. Gelegenis et al. (2007) optimized the biogas production from the co-digesting of olive-mill wastewater and poultry manure at mesophilic conditions and the results showed that biogas production was slightly higher when olive-mill wastewater was added to diluted poultry manure up to a critical concentration, and the co-digestion of these two substrates is feasible without any dilution of the wastes or addition of any chemicals [64]. Tańczuk et al. (2019) proposed a co-gasification system of chicken manure and wood pellets on a fixed-bed gasifier in a laboratory-scale study, and the results indicated that this co-gasification system can be a promising technological option for converting poultry waste to wealth and reducing the negative effect of poultry production on environmental health [65]. By adopting this kind of co-processing procedure, additional benefits such as less energy consumption, shorter processing time, more economic outputs, and less emission of pollutants and greenhouse gases are possible, which means co-digestion, co-gasification, and co-combustion of poultry waste with other materials or wastes seem to be more efficient and beneficial than processes with a single raw material.

The process parameters are very important factors that determine the technical, economic, and environmental performance of poultry waste-to-wealth, and thus have attracted a lot of attention in modeling and simulation studies of poultry waste-to-wealth. For instance, Petric et al. (2009) examined the influence of the initial moisture content on the composting of poultry manure with wheat straw in terms of compost temperature, emissions of carbon dioxide and ammonia, and conversion rate of organic matter, and found that the most suitable initial moisture content for the efficient composting of poultry manure mixed with wheat straw is around 69% [66]. Ramzan et al. (2011) proposed a steady state equilibrium model for the co-gasification of municipal solid waste, food waste, and poultry waste using Aspen Plus software, and probed the influence of the operating parameters including temperature, equivalence ratio, moisture content, and steam injection on syngas composition, High Heating Value, and Cold Gas Efficiency as it relates to the efficiency of the co-gasification system, and found that increasing the equivalence ratio decreases the production of CO and H_2 which decreases the Cold Gas Efficiency; biomass moisture content is an important parameter affecting the heating value of the gas, and steam injection favors hydrogen production [67]. Aklilu et al. (2021) optimized the process parameters to achieve the best biogas yield from the anaerobic co-digestion of alkali-treated corn stover and poultry manure using a neural network and response surface methodology, and predicted that the co-digestion of these two substrates has the potential to increase biogas yield by ensuring nutrient balance; the optimum conditions were at a temperature of 37 °C, a hydraulic retention time of 13 days, a pH of 7, and an 80% blending ratio of poultry manure to alkali-treated corn stove, where a biogas yield of 745 mL/g total solids with a desirability value of 0.995 is expected [68]. The composition of the organic fraction in the wastes also has a great impact on poultry waste-to-wealth processes. To determine the process parameters and kinetics model in the composting of the organic fraction of municipal solid waste and poultry manure, Petric et al. (2012) conducted experiments with three different mixtures and found that the mixture of 60% organic fraction of municipal solid waste and poultry manure, 20% poultry manure, 10% mature compost and 10% sawdust can generate the best performance in the composting process, and the kinetic parameters have also been estimated [69].

In fact, poultry waste can be transformed into the same byproduct from different processes. However, even then, the product performance generated by different processes can still vary greatly. For example, by evaluating the two procedures of fertilizer production, Purnomo et al. (2017) found that pelletized slow-release fertilizer from poultry waste produced using an extruder has a longer capability to retain nutrient content than granule slow-release fertilizer [70].

4. Technological Progress of Poultry Waste-to-Wealth

The various categories of poultry wastes contain resourceful nutrients and materials that can be recovered and reused. As mentioned above, litter and manure wastes contain rich nutrients such as nitrogen, phosphorus, and potassium, poultry bird feathers are mainly composed of keratin protein, mortality wastes contain plentiful protein and minerals, and offal is mainly composed of lipids, proteins, nitrogen, and methane. With so many useful ingredients and nutrients, these wastes can be properly recycled, treated, and reused as materials in production. Before poultry waste is recycled and reused, necessary pretreatment processes are needed. Aerobic process and anaerobic process are the most common pretreatment techniques used in poultry waste management [71], and these two processes are also the most frequently used technique for realizing poultry waste-to-wealth. In addition, some other pretreatment processes can also be applied in poultry waste management. For instance, the electrochemical process is proven to be very effective for removing some physicochemical parameters such as turbidity, color, total suspended solids, total iron, aluminum, chemical oxygen demand, and biochemical oxygen demand [72]; Alkaline pretreatment can be an effective way of reducing the lignin content of lignocellulosic biomass, and it increases the bio-digestibility of poultry litters without a significant loss in carbohydrates [73].

Based on the modeling and simulations of poultry treatment processes mentioned in Section 3, seven conventional or emerging technological options are available for poultry waste valorization: composting treatment, anaerobic digestion, pyrolysis, gasification, hydrolysis, enzymatic treatment, and microbial conversion [74]. The comparisons of advantages and disadvantages of these technological processes are presented in Table 1.

Table 1. Advantages and disadvantages of various poultry waste treatment processes.

Processes	Advantages	Disadvantages
Composting treatment	Cost-effective [75], sanitation, mass and bulk reduction, and decrease of carbon to nitrogen ratio [76]	Significant nitrogen loss through ammonia volatilization [75]. Risks caused by heavy metals, pathogens, and ammonia toxicity [77]
Anaerobic digestion	Lower running costs, low energy consumption, low sludge production, no aerosols, useful by-products, lower nutrient requirements, and rapid re-start [78]	Expensive investment costs, retention periods usually more than 1 day, heating requirements, corrosive and malodorous by-products, potential risks of pathogens spreading, long start-up and recovery periods, and additional alkalinity requirements [78]
Pyrolysis	Higher commercial value, higher level in the reduction of initial waste, low demands for land, and easy control of process [79]	Necessity of waste pre-treatment and wastewater treatment, product disposal with further treatment, demand for high quantities of waste, and need for specialized personnel [79]
Gasification	Economic benefits, easy availability, low emissions [80], and wide application of products [81]	High investment cost [80], requirement on energy input [81], and technical problems caused by high viscosity of pyrolysis oil [80,81]
Hydrolysis	Carried out under optimal conditions, minimized interaction between steps, and can be applied to wide range of microorganisms [82]	High cost and contamination due to long period process [82]
Enzymatic treatment	Eco-friendly, low temperature and pressure, wide temperature and pH ranges, no nutrient supplementation, no sugars consumption, short time duration, high conversion efficiency, low waste generation, and low energy demand [83]	High enzyme costs, moderate enzymatic performances, enzyme recycling, enzyme immobilization, and enzyme activity improvement [83]
Microbial conversion	Low cost, eco-friendly, low temperature and pressure, no water and chemical agent requirement, no growth inhibitor formation, low waste generation, and low energy demand [83]	Long time duration, feedstock loss, and low conversion efficiency [83]

4.1. Composting Treatment

Composting is an aerobic biological process to decompose organic material that is carried out in either windrows or reactors [76], and it is an important waste treatment technique for recycling poultry litter and manure waste for agricultural applications [84]. Poultry manure and abattoir waste have been proven to be a valuable natural fertilizer and a rich source of macro- and micronutrients for crops [19] due to the high content of nitrogen, phosphorus, calcium, micronutrients, and organic matter [45,46].

Some studies have revealed that manure composts can significantly increase crop yields by improving soil quality, particularly soil organic matter content [85]. Using poultry manure and abattoir waste as fertilizer can increase soil pH, decrease hydrolytic acidity, and increase the sum of base cations and the cation exchange capacity of the soil, increasing the content of available nutrients in the soil [19]. Additionally, applying poultry manure as a soil amendment promotes the accumulation of soil carbon and accelerates the rate of nutrient turnover, providing available organic substances and nutrients [19], indicating its potential as a promising alternative to natural, organic, and mineral nitrogen and phosphorus fertilizers due to the rich macro and micronutrients and organic matters. In fact, poultry manures enriched with mineral-microbial deodorizing preparations based on perlite and bentonite as well as some microorganism strains had a more favorable effect on the physicochemical properties of the soil [19].

4.2. Anaerobic Digestion

Anaerobic digestion is the process in which organic matter is decomposed by microorganisms into biogas, the mixture of CH_4, CO_2, H_2O, and H_2S, which is also known as biogas, and some other solid and liquid organic residuals, under thermophilic or mesophilic conditions with the absence of oxygen [86,87]. Anaerobic digestion and decomposition with mixed cultures of microorganisms can contribute greatly to the destruction of organic matter in poultry litter and manure [88]. As a well-developed or quite mature technology, it can convert poultry wastes into biogas without too many pre-treatment procedures [74], and it can be used as an alternative source of energy and a fermentation sludge that can be used as fertilizer [87]. Anaerobic digestion has a long history of more than 100 years of being used to produce biogas from biomasses such as agricultural residuals, food wastes, sewage sludge, industrial and municipal waste, and even human and animal manure, which can be used for cooking, lighting, heating and even generating electricity [89,90].

Poultry litter and manure seem to have a higher energy density than other animal manure [91,92]. However, the high level of nitrogen content in poultry litter and manure can lead to the undigested proteins being converted into total ammonia nitrogen, which is one of the main drawbacks of this technology. In addition, the efficiency of biogas production with anaerobic digestion also depends on a number of parameters, including temperature, carbon-nitrogen ratio, organic load, and pH value [93], which brings additional challenges to its valorization.

To improve efficiency and accelerate the process of anaerobic digestion, some improved digestion techniques have been developed, including vermicomposting, thermophilic anaerobic treatment, and co-digestions. Vermicomposting, or earthworm composting, is a more efficient microorganism-based composting method for converting organic matter in poultry litters into nutrients that are easy to absorb, so as to accelerate compost maturity [94]. Thermophilic anaerobic treatment is another efficient digesting technique that can reduce composting time by increasing composting temperature, and Liedl et al. (2006) found that thermophilic anaerobic treatment of poultry litter can digest organic materials within 30 days and separate the effluent stream into solid and liquid fractions for use as a crop fertilizer [95].

In order to increase biogas yields during anaerobic digestion, a modern and popular method is the joint processing of organic wastes from different feedstocks, which is also known as co-digestion, by adding various ingredients to the feedstock substrate [87]. An experimental study showed that the biogas output from poultry waste can be increased by 47% based on a standard case when using the plant supplement from the Amaranthaceae family [96].

In fact, the performance of the anaerobic digestion of poultry litter and manure can be improved by various methods. For instance, the application of an improved anaerobic reactor or digester design or the pre-treatment of raw materials can speed up the decomposition of organic matter, and pre-treatment methods like grinding, hydrolysis, enzymatic, high-temperature hydrolysis, and treatment with acidic or alkaline agents have been proved to be effective [87]. Awasthi et al. (2016) investigated the co-digestion of gelatin industry sludge, the organic fraction of municipal solid waste, and poultry waste, and found that when these feedstocks are mixed in a ratio of 6:1:0.5, and then combined with 10% zeolite mixed with enriched nitrifying bacteria consortium, the maximum value-added products (nutrients) can be generated [97]. Adding inorganic additives of 3% aluminum sulfate and 2% rock phosphate in the digestion and composting of poultry waste and rice husk can reduce the decomposition time and carbon-nitrogen ratio, which improved nitrogen mineralization [98].

4.3. Pyrolysis

Pyrolysis is the degradation and decomposition of biomass by heat in the absence of oxygen, which converts the biomass into a series of solid, liquid, and gaseous products including bio-charcoal, biocrude oil, and syngas (mainly biogas) [99]. Numerical analysis has demonstrated the existence of additional thermal energy apart from the consumption in the pyrolysis process [100].

Animal wastes are important biomass resources for biogas production; however, varied components and alkali metal contents bring extra complexity to biogas production from various animal manures with pyrolysis [101]. A study has compared the biogas yields from five different animal manures and litters and found that swine manure, dairy cattle manure, and beef cattle manure produced higher levels of CH_4, CO, and H_2 (the main components of biogas) yields than broiler and layer chicken litter due to the higher level of cellulosic and alkali metal contents in swine manure [101]. In fact, it is believed that poultry manure is characterized by much higher alkali content than the manures obtained from other farm animals [19], so the comparison of biogas yields from various animal manure still needs to be discussed.

In addition to being used as feedstock for biogas production with pyrolysis, poultry litter and waste can also be used as organic fertilizers after decontamination with pyrolysis. Since fresh poultry wastes and litter contain a lot of pathogenic microorganisms which may preserve viability and virulence for a long time, they cannot be applied directly as a fertilizer in the soil. Isemin et al. (2017) suggested that a pelleted mass of poultry litter can be fully decontaminated when processed with low-temperature pyrolysis at 250 °C for an hour, and a series of experiments indicated that the fertilizer utilization of a decontaminated pelleted litter mass can improve the yield productivity and reduce the time for germination and fruit formation of several vegetables and crops [102].

4.4. Gasification

Gasification is the process of converting the organic matter in poultry wastes into value-added secondary products under specific conditions of temperature, moisture, and oxygen, and the secondary products are mainly composed of syngas, liquid fuels, and solid residues, which can provide additional material for energy production and environmental remediation [103]. With increasing concerns about environmental sustainability and energy supply security, gasification has become a popular method for biomass waste disposal and energy production [104]. With this process, thermal energy can be achieved by burning the generated syngas rather than directly burning the solid residues, which can reduce the release of nitrogen into the atmosphere by the exhaust flue gases and reserve it in the ashes [105].

In practice, gasification has been widely used in the disposal of municipal solid waste [106], agricultural waste [107], and even medical waste [108]. Since poultry carcasses may have been exposed to highly pathogenic avian influenza and some other pathogens, the disposal of poultry waste, especially carcass waste, needs to consider the possible effects on human health, disease transmission, and ecological safety [109]. Therefore, some scholars have designed waste-to-energy systems based on the gasification process to process poultry waste. For instance, Zang et al. (2019) designed two systems for poultry waste disposal and evaluated and compared their economic and energy potentials [110]. De Priall et al. (2022) investigate the potential of energy recovery from poultry litter wastes with gasification systems based on feedstock analysis, process modeling, and experimental analysis [61].

Ayub et al. (2022) designed a hydrothermal gasification system in supercritical water for converting poultry litter into value-added products, and the best yields can be achieved as hydrogen and methane gas with a superior lower heating value [54]. Singh and Tirkey (2011) designed and simulated a system for processing waste poultry litter with a biomass gasifier for the production of enriched hydrogen syngas, and the experimental results confirmed the feasibility of this process system [111].

In addition to energy recovery, the gasification ashes of poultry waste have also been investigated. Pandey et al. (2021) investigate the transformation, release, and result of inorganic matter during the gasification of poultry litter, and assessed the potential of utilizing gasification ashes as fertilizer products in the EU [112].

4.5. Hydrolysis

Hydrolysis is the process of breaking the peptide bonds of animal carcasses and wastes by putting them in a special solution under high temperature and pressure to denature proteins into amino acids, hydrolyze fats, and dissolve carbohydrates [113]. With the procedure of hydrolysis, poultry waste can be used for producing a value-added secondary product, including high-quality protein and bioactive ingredients, which can provide available materials for the food and feed industry, bring additional economic benefits, and help mitigate the negative effects of poultry waste disposal on the environment [114].

Poultry feathers can be utilized as an important protein source if properly treated. In fact, poultry secondary products such as keratin and collagen can be used as a material for producing protein feed additives, which can not only help improve broiler productivity but also achieve a higher antioxidant status for better preservation [115]. However, the pretreatment of poultry feathers is a major difficulty in poultry feather valorization. Cheong et al. (2018) found that thermal-alkaline pretreatment can be a promising technique for improving the enzymatic hydrolysis of chicken feathers and for producing protein-rich hydrolysates [116]. Therefore, hydrolysis is seen as a promising process which can produce protein feed additives for the food and feed industry from poultry wastes.

4.6. Enzymatic Treatment

Poultry offal and feathers are usually high in protein, which provides material for the food and feed industry. However, the conversion of such wastes into value-added materials and products requires protein recovery, which is a major difficulty [7].

By using enzymes for bioconversion, this protein recovery process can be achieved [7]. Keratinase enzyme can be obtained from microorganisms, and it can be used to process feather waste, and can convert them to feather feed hydrolysates, natural fertilizers, and bioactive peptides [117], which can then be used as improved feeds with better nutritional characteristics and as soil manures [118]. It has been found that adding 10% of poultry offal meal as a substitute for soybean meal in the diets of Japanese quails is an effective substitute, and only 5% of poultry offal meal is required with the supplementation of the enzyme [119]. In addition to being used to produce animal food and feed [31], the value-added protein byproducts generated from enzyme-digested poultry waste can also be used to make high-quality meals in aquaculture [7,120].

Despite these findings, the application of microbial keratinase extracted from poultry waste is still restricted by the high cost and the fermentation conditions required by the enzyme [121]. In addition, the experimental results at the laboratory still need to be investigated and improved to transfer the technology to the industrial scale [116].

4.7. Bioconversion

Various microorganisms can be isolated from poultry wastes and can be used to investigate their application for the remediation of biowaste and waste management [23,25]. For instance, Gurav et al. (2016) isolated a novel feather-degrading microorganism from poultry waste and found it is of great potential to be used in waste management and can even lead to the generation of value-added byproducts from wastes [23]; Bhari et al. (2018)

isolated 73 bacterial strains from poultry dump sites and one of them is identified with high keratinolytic activity, which can provide an environmentally friendly approach for the bioconversion of poultry waste [25].

In addition, poultry wastes can also be used in the cultivation of *Chlorella* sp., a potential feedstock for a variety of products in the food, nutraceutical, medical, pharmaceutical, agricultural, and bioenergy industries, and as a renewable material for various applications in biotechnology. Agwa and Abu (2014) evaluated the biomass and lipid production of using poultry waste for the cultivation of this microalga and found that poultry waste has great potential as a suitable renewable medium for the growth of *Chlorella* sp., which can be further utilized in the production of renewable and green energy [122].

Additionally, using poultry waste for the production of insect protein has also been a promising method in recent years. Poultry litter contains a lot of nutrients and pollutants that may create environmental problems if not properly treated, and they can be stabilized and removed using earthworms and insects [123]. Using poultry waste as a material for cultivating and rearing insects and earthworms has been intensively investigated as a circular bioeconomy technique [124]. Insects and earthworms are voracious eaters of decaying organic matter, and they have been used to decompose organic wastes including livestock manure, human excreta, slaughterhouse waste, and other organic wastes [125,126]. By using poultry waste for rearing insects, especially black soldier fly larvae, the waste can be recomposited into high-quality compost fertilizer, and the insects and earthworms are also high-quality sources of animal protein which can be used to produce feed for pets, fish, and poultry [126].

Based on the above-mentioned analysis, the suitable technologies for various poultry waste types are summarized. Poultry litter and manure waste can be valorized by almost all of the technological processes, and composting and anaerobic digestion seems to be the most practical and economically feasible methods for agricultural applications, energy recovery, and feed production; enzymatic treatment and pyrolysis are more suitable to deal with feather waste for feed production. As various bacteria and pathogens are contained in poultry mortality waste, abattoir waste, and hatchery waste, gasification, pyrolysis, and microbial conversion can fully decompose or remove these harmful substances and recover energy and protein from these wastes. However, the performance of these technologies in treating different poultry wastes still needs to be validated by process simulations and laboratory research.

5. Impacts of Poultry Waste-to-Wealth

Conversion of poultry waste to wealth can not only solve the tricky problem of waste disposal in poultry farms but also bring multifaceted impacts and benefits, such as low cost and high environmental efficiency from the various technological pathways to process poultry waste, as well as considerable economic profits and social benefits from the by-product production in agriculture, energy recovery, and social governance.

5.1. Economic Benefits

The various value-added by-products produced from poultry waste have great potential to be applied as materials and resources in a lot of fields and industries.

The application of by-products generated from poultry waste-to-wealth in agriculture is connected to economic and ecological benefits. Poultry litter and manure have contributed the major part of the waste generated by poultry farms; rich nutrients including nitrogen, phosphorus, and potassium are contained in this waste, which has great potential for bio-fertilizer production from poultry litter and manure [19]. Meanwhile, the biochar prepared from poultry feathers, mortality waste, and abattoir waste can also be utilized as a soil conditioner or as a compost to improve soil quality and improve crop yields [118]. In addition, poultry feather meal is a readily available and affordable source of nitrogen (up to 15% total nitrogen) and functions as a potential organic fertilizer [127]. Using poultry waste for fertilizer production is ideal not only because of its rich nutrient content but also due to its low cost and availability of materials [3]. Zhang et al. (2016) found that during a three-year application of manure compost, crop yields tended to increase, particularly in the second and third years, with an average growth rate of 7–15% [128]. They also found that replacing 30% of nitrogenous fertilizer with manure compost is an effective nutrient management strategy to maintain nitrogen uptake and crop yield, reduce nitrogen loss, and increase soil fertility [128]. When poultry litter and manure are utilized as an organic fertilizer, the associated costs for the collection and transportation of waste material are estimated to be approximately 30 to 50 British pounds (about 36 to 60 US dollars) per ton [129], and the cost generated in the conversion process, especially in the composting process, can be very cost-effective and environmentally friendly [130]. In fact, agricultural products fertilized by organic matter are sold at almost double-price compared to those grown using chemical fertilizers [131], which means more profit can be derived from organic fertilizer production utilizing poultry litter and manure. Biochar can be used as a soil conditioner to improve soil quality, and it can be sold in the market at an average price of 150 British pounds (about 180 US dollars) per ton, indicating its great economic potential [52]. To summarize, lower production costs and higher product prices make organic fertilizer production utilizing poultry waste an attractive option in agricultural production.

Energy recovery from poultry waste has a great potential to be useful in various processes: for instance, biogas, biodiesel, and electricity production. Arshad et al. (2017) believed that the adoption and promotion of energy recovery from poultry waste would provide an additional source of renewable energy to the energy systems of underdeveloped countries like Pakistan, and estimated that about 280 MWh of electricity can be generated from the biogas produced from poultry waste in Pakistan every day [132].

To investigate the economic feasibility of this approach, some studies have estimated the cost of energy recovery from poultry waste. For instance, Zang et al. (2019) estimated that the variable operating cost of poultry gasification systems is about 477 US dollars per ton, which is 30 US dollars lower than that of poultry drying systems, and the poultry gasification system seems to show better certainty than the poultry drying system in terms of economic performance [110]. However, this study also indicated that labor costs and variable factors can greatly affect the waste elimination cost [110]. By adopting the processing system of pyrolysis/gasification integrated with an Organic Rankine Cycle, poultry litter can be used to produce electricity and heat; Huang estimated that the levelized cost of electricity generation from this process system would be 46 British pounds per MWh, which is comparable to the electricity generated from fossil fuels [52].

In fact, the recovered energy from poultry waste can also be used in the transportation industry. Diesel is an important transportation fuel around the world, with a high consumption rate and an insufficient supply [133]; Gohil et al. (2021) confirmed that adding an optimal amount of biogas generated from poultry waste to the gas mixture from the carburetor can reduce the consumption of diesel fuels [134]. In addition, biodiesel can also be produced from high-quality chicken fat extracted from poultry slaughter waste with low free fatty acids using acid/alkaline trans-esterification [135]. Mozhiarasi and Natarajan (2022) stated that biodiesel produced from poultry and slaughterhouse wastes blended with commercial diesel is technically feasible with additional environmental and economic benefits, and they estimated that about 736,000 tons of poultry slaughter waste are generated in Iran each year, and these wastes could be utilized to produce 112 million liters of biodiesel by a trans-esterification process with a production cost of around 14,277 Iranian Rial (about 0.34 US dollars) per liter [136]. In India, the cost of producing biodiesel using the centrifugal method and the solvent extraction method is even less than 0.5 US dollars per liter [137], and about 200,000 liters of biodiesel could be produced from poultry carcasses in the Namakkal district [138].

In addition, poultry waste can also be utilized in other industries. For instance, McGauran et al. (2021) estimated that the total profits to the polymer industry would be 1,96 million British pounds if poultry bones, meal, and feathers were used as materials for production in the United Kingdom, indicating the possibility of improving the economic benefits of both the polymer and poultry industries [139]. Besides, cheap edible or inedible fat and grease can be produced from the waste of poultry-rendering plants, which have a great potential to be used in producing non-livestock animal feed, chemical industrial products, and fuel blending agents with a much lower cost than vegetable oils [140]. The protein production from the rearing of insects and earthworms by using poultry waste as base material provided both additional high-quality animal protein sources for feed production and organic fertilizers or soil amendments for crop production [126].

5.2. Environmental Benefits

The traditional poultry waste disposal techniques, such as direct dumping, landfilling, and burning, are widely adopted in underdeveloped countries, which is quite harmful to environmental sustainability [31]. The negative effects of improper disposal of poultry waste on the environment include the release of ammonia and nitrous oxide, the emission of greenhouse gases, and the contamination of groundwater and surface water by nitrates, phosphates, and pathogens.

Some studies have been conducted to estimate or calculate the greenhouse gas emissions of the poultry sector. For instance, Seidavi et al. (2019) calculated that greenhouse gas emissions from poultry production including poultry waste decomposition only accounts for a very small share of 0.64% of agricultural greenhouse gas emissions [141]. Despite that, using various processes to generate different energy products, such as biogas, biodiesel, and electricity, to convert poultry waste to wealth can still reduce greenhouse gas emissions, which can be part of the efforts for mitigating global climate change. By comparing the processes of electricity generation from poultry litter pellets, digestate pellets, and miscanthus pellets with natural gas for power generation, it is found that the process of electricity generation from poultry litter pellets generates the least carbon emissions [61]. The mixture of diesel fuel and rendered chicken oil converted from broiler slaughterhouse waste can not only be used as an alternative fuel in conventional diesel engines, but can also decrease smoke emissions by 47.14%, which can help reduce pollutant emissions and mitigate climate change [142]. In addition, using poultry litter waste for biochar production is also a promising solution, and it is capable of being used for CO_2 absorption, which provides an attractive option for minimizing the environmental damage caused by CO_2 emissions [143]. In the UK, it is estimated that about 1697 tons of dry poultry waste are generated every day [139]. When using poultry waste (mainly poultry bones, meal, and feathers) to produce polypropylene feedstock, the required energy input is about 47.0–65.5 MJ for producing 1 kg of polymers, which is 30% to 50% lower than that required by the conventional methods, resulting in a reduction of 40% to 60% of emissions of CO_2 equivalent, and a total of 6645 t CO_2 equivalent could be saved per day through the use of poultry bones, meal, and feathers [139].

In fact, land and water are the most vulnerable to the impact of poultry waste, as they are the final receiving site for poultry waste, although treatment measures such as anaerobic digestion or composting can be undertaken. Poor management of poultry waste can damage crops and lead to the pollution of surface and groundwater resources [17]. By using poultry slaughterhouse waste in ruminant nutrition as a cleaner product for animal feeding, poultry waste has a huge potential for reducing food consumption and preventing environmental pollution [144]. Although poultry waste-to-wealth can help improve environmental sustainability from a life-cycle perspective, the environmental performance of different processes can still vary. Thus, it is necessary to compare the environmental impact of different waste disposal processes. Composting through anaerobic incorporation for the treatment of poultry feather waste is an environmentally sustainable and economically viable waste management technique with the environmental effects of reducing greenhouse gases emissions, preventing soil and water pollution, mitigating the dependence on fossil fuels, and improving soil quality by providing more organic fertilizer with rich nutrients [145]. However, there are also some scholars who believed that using poultry waste as fuel causes less pollution to the environment than using it as fertilizer [3].

Beyond that, poultry feather waste can also be applied to the sector of environmental remediation and pollution removal. For example, Chiramba et al. (2020) discussed the possibility of using poultry feathers to prepare activated carbon to remove heavy metal ions, and the study showed that the removal rate of heavy metal ions from wastewater in Lake Chivero by using poultry feathers as a raw material for synthesized activated carbon was up to 97% [146]. Feather keratin has more applications in environmental remediation. For instance, the alpha helix and hollow fibers presented in poultry feathers build a uniform structure of micropores which can be used as an electrode material due to their high surface area and eco-friendliness [147], and the keratin-based material outperforms the bio-based eco-friendly material due to its biocompatibility, mechanical durability, and natural abundance [148].

5.3. Social Benefits

The social benefits of poultry waste-to-wealth can be multifaceted, such as the reduction of infectious diseases, the improvement of air quality, and the creation of more job opportunities.

Poultry birds serve as an ideal substrate for the growth of several pathogenic bacteria [149], and poultry waste is a hub of pathogens that can infect both humans and animals, such as zoonotic avian influenza [136]. Moreover, food or water contaminated by poultry waste may contain various pathogens and water pollutants that may cause gastrointestinal diseases like typhoid fever, cholera, and *hepatitis E* infections [150,151].

By comparing the physical, chemical, and microbial characteristics of four different poultry wastes (dead birds, hatchery waste, offal waste, and a mixture of all wastes) in two different composting systems, Irfan et al. (2020) found that the microbial counts of *Salmonella*, *Escherichia coli*, mycoplasma, and total plate numbers in all types of composting processes have decreased to the lowest level [152], indicating the beneficial effect of composting processes in eliminating pathogens and bacteria.

Additionally, an unpleasant smell is usually generated from untreated or improperly handled poultry waste, which can also affect the daily life of nearby residents. It was reported that residents living within 1 km of a poultry farm usually complained about restlessness, malaria, sneezing, and/or nausea caused by the smell of poultry waste [29]. People with high quality requirements for living conditions will not accept unpleasant odors or smells from the storage or use of poultry waste [16]. The effective utilization and management of poultry waste can reduce these unpleasant smells and negative effects, improving an area's quality of life [153].

In addition, the industrialized development of poultry waste-to-wealth would create a considerable amount of job opportunities, which can support the livelihood of thousands of families. For example, more than 20 million poultry birds are provided to markets in the United Kingdom every week, resulting in approximately 1400 tons of poultry litter waste per week, which would provide more than 37,000 job positions within the poultry waste-to-wealth industry across this country [61]. In Louisiana, USA, a poultry power plant that generates electricity from poultry waste has provided 48 jobs and affected the economy in eleven counties, and it is expected to generate 2.6 million US dollars in labor income, 7 million US dollars in gross value added, and 14.5 million US dollars in industrial output [16].

6. Conclusions

As a major source of meat supply, the poultry industry has witnessed a fast-increasing market scale, alongside an increase in the generation of poultry waste. Due to the potential effects on climate change, environmental safety, and human health, how to deal with this large amount of poultry waste has become an important topic for the sustainable development of the poultry industry. To solve this problem, converting poultry waste to useful by-products seems to be a promising option for generating valuable products from poultry waste disposal for better sustainability. Thus, this paper summarized the waste generation from the poultry sector, and the modeling and simulation studies of poultry waste treatment processes. Based on that, the technological progress of poultry waste-to-wealth was presented, and the economic, environmental, and social impact of poultry waste-to-wealth were discussed. By conducting such a review of poultry waste-to-wealth, the following conclusions can be drawn:

- Waste generation from the poultry industry is varied and occurs in huge amounts. Presently, waste generated from poultry production includes litter and manure waste, feather waste, mortality waste, and abattoir waste, which can be widely used in various industries and converted into multiple value-added by-products with great potential.
- Modeling and simulations of waste treatment processes serve as convenient tools for exploring the feasibility of converting poultry waste to value-added products. By using simulation software such as Aspen Plus and ECLIPSE, poultry waste treatment processes can be simulated, and the economic and environmental effects can be calculated, evaluated, and compared.
- A variety of technological processes are available for converting poultry waste to wealth. Due to the various categories and the resourceful nutrients and materials contained in poultry waste, different processes can be applied for the production of different value-added by-products. Usually, six main technological options are available for poultry waste valorization: anaerobic digestion, pyrolysis, gasification, hydrolysis, enzymatic treatment, and microbial conversion.
- Great economic, environmental, and social benefits can be derived from the conversion of poultry waste to wealth. From an economic perspective, poultry waste can be utilized for organic fertilizer production, energy recovery, animal feed production, and even for materials used in industrial production, environmental remediation, etc. From the environmental perspective, poultry waste-to-wealth can help reduce emissions of greenhouse gases, prevent environmental pollution, absorb pollutants and heavy metal ions, and repair the ecological environment. In terms of social benefits, these include the reduction of infectious diseases, the improvement of air quality, and the creation of job opportunities.

7. Recommendations for Further Research

Based on this study, some recommendations for future studies and government policymaking are provided:

- Presently, research on poultry waste-to-wealth is mostly conducted based on theoretical calculations, computer-based modeling, and simulations, which have proven the technical-economic feasibility and the environmental effects. Further studies can be conducted based on poultry waste-to-wealth projects in different regions to compare their differences and verify the proposed systems or models.
- To investigate the performance of the laboratory-scale experiments of different poultry waste-to-wealth processes, a lot of process simulations have been designed and presented. However, the actual operation of poultry waste-to-wealth projects can also be affected by many social-political factors as a lot of stakeholders are involved, such as investors, governments, poultry farmers and slaughterhouses, local residents, consumers of by-products, and even the individuals involved in third-party logistics. Thus, the behavior strategy of different stakeholders and the interactions between them should also be considered and simulated in further studies.
- As different processes may bring different economic benefits, the initial investment cost of plant establishment has contributed the largest share to total costs. It is suggested to build one centralized biorefinery or plant with a larger capacity rather than building multiple smaller biorefineries. In addition, poultry wastes can be utilized with other wastes, such as municipal solid waste, sewerage sludge, animal and human excreta, and even agricultural residues, to generate better economic performance.
- Present studies focus on process simulations and laboratory-scale experiments, and there is still a long way before poultry waste-to-wealth can be commercialized

and marketized. Therefore, policymakers need to formulate detailed and forward-looking plans to motivate the industrialized development of poultry waste-to-wealth. In addition, more favorable policies and incentives are required to attract the attention and participation of investors, poultry farmers and slaughterhouses, and by-product consumers.

- As one of the sectors of broad agriculture, poultry production has generated numerous solid wastes. From the perspective of circular economy, the waste generated from agriculture should be reused for agricultural production at the very beginning, followed by other sectors. Thus, it is suggested to use poultry waste to produce organic fertilizer or soil amendment with priority.

Author Contributions: Conceptualization, J.R.; formal analysis, L.Z. and W.B.; writing—original draft preparation, L.Z. and W.B.; writing—review and editing, J.R. and L.Z.; supervision, J.R.; project administration, J.R.; funding acquisition, J.R. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key R&D and Promotion Project (Soft Science Research) in Henan Province, China (grant number 222400410122) and a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China-General Research Fund (Project ID: P0037749, Funding Body Ref. No: 15303921, Project No. Q88R).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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