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Review

Significance and Challenges of Poultry Litter and Cattle Manure as Sustainable Fuels: A Review

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Abstract: Growing animal production results in a significant amount of waste, composed of manure, bedding, feed, feathers, etc., whose safe and cost-effective disposal becomes a troublesome challenge. The literature review points out that the higher heating value (HHV) of animal-origin waste reaches 19 MJ/kg (dry basis), which positions it as a promising renewable energy source. Various paths of energy recovery were investigated in the literature, but the thermal processes, particularly combustion and co-combustion, were indicated as the most effective from both technical and environmental points of view. The presented study reviews the fuel characteristics, possible combustion-related challenges, and ash disposal routes of the most popular animal-origin waste: poultry litter and cow (cattle) manure with a slight sight on piggery (swine) manure. When considering animal-origin feedstock as fuel, usually only animal species is given (poultry, cattle, etc.). However, according to the analyzed literature data, this is not sufficient information. Several more factors crucially influence the fuel and ash properties of animal waste and the most vital are: the housing system, type of bedding, and farming style. Animal litter is considered a "difficult" fuel, nevertheless, it does not always cause combustion-related problems. Some analyzed feedstock feature low chlorine concentrations and high ash melting temperatures, which makes them combustion-friendly.

Keywords: biomass; chicken litter; poultry litter; cattle manure; piggery waste; bioenergy; circular economy

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1. Introduction

The limited resources of non-renewable fuels, as well as the necessity to mitigate climate change, force us to seek for new, yet economically effective energy sources. At the same time, the growth of the global population, together with the developing economy, increases the demand for raw materials. It was understood that the development of new, diversified, and independent production systems is an urgent issue. Faced with this, the circular economy idea seems the practical and viable response, as it prevents the degradation of the natural environment, promotes responsible waste management, and favors actions crucial for the sustainable development [1]. The circular model is based on the reuse of products, reduction in landfilling, and the generation of energy from by-products that cannot be recycled, such as agricultural and food industry waste [2].

One of the available agricultural by-products is animal-origin biomass. It is mainly a mix of manure, bedding material, urine, feed, feathers, egg shells, etc., that is produced in large quantities all over the world during animal breeding. The use of cow manure, poultry litter, swine manure, or even goat manure for energy production was established as one of the circular economy and sustainable development goals [3]. The energy conversion of animal waste can be adopted in both developed and developing countries, as it is widely available to people living within agricultural and rural areas [4]. Animal waste may also be a source of fiber for various applications, e.g., pulp and paper, composite materials, manmade boards, fillers for composites, etc. [5].

Unluckily, the energy potential of animal-origin biomass is underestimated and its utilization as a renewable energy source is still not developed enough. Usually, non-energetic utilization is practiced, which comes to spreading fresh manure on land as fertilizer. Nevertheless, during the last years, the direct land application of animal waste became undesirable due to the emission of greenhouse gases (GHG), which are released into the atmosphere from the fermenting feces and urine. Animal waste was found to liberate nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), which contribute to global climate change [6]. Despite gaseous emission, ammonia and phosphorus can be dissolved by the rainwater, causing algal blooms in water bodies and adversely affecting the fish and aquatic life. Moreover, animal waste contains pathogens such as *Enterobacteriaceae*, *Salmonella*, and *Pseudomonas*, molds, and fungal species [7], which, when spread on the land, are a possible danger to human and animal health [8]. It is common to add antibiotics to animal feed and drinking water, such as oxytetracycline (OTC), which is poorly absorbed in the gastrointestinal tract of animals, making feces a potential path of dissemination [9]. This may cause not only the presence of antibiotics in the soil and groundwater, but also the development of resistant bacteria and affect the normal microbial processes in the soil. Moffo et al. investigated *Escherichia coli* isolated from poultry litter and found its high levels of resistance to various antimicrobial agents [10]. Similarly, Furtula et al. found the various bacteria contained in poultry litter isolates that were resistant to more than one antibiotic [11]. Microbiological safety of chicken litter and chicken litter-based organic fertilizers was widely reviewed by Chen and Jiang with a general conclusion that new treatment techniques should be developed to inactivate the most resistant and persistent types of threatening pathogens [12].

Last year, a shift to renewable energy resources was set to be a fundamental requirement of the sustainable development [13]. Thus, the energy potential of animal waste was noticed, and research was conducted to determine the best conversion paths. One of the first complex analyses was made ifn 2002 by Kelleher et al. [14]. Three main disposal routes were proposed: composting, anaerobic digestion, and combustion, with a focus on combustion as the most efficient and advantageous energy recovery path. In 2010, Perera and Bandara [15] took a deep insight into the environmental and social issues connected to the utilization of poultry litter for energy production by four different ways: anaerobic digestion, combustion, co-combustion, and gasification. Dalólio et al. [16] reviewed the characteristics and future perspectives of poultry litter as biomass and analyzed the main conversion paths, such as anaerobic digestion, combustion, gasification, and pyrolysis. Most lately, Tańczuk et al. [17] assessed the energy potential of chicken manure depending on the conversion variants with a detailed analysis of the energy degradation during the production of useful energy (such as heat), and pre-processing of the feedstock (such as drying). In general, combustion was indicated as the most efficient method, while the biggest energy degradation was found for anaerobic digestion. Anaerobic digestion, despite being not economically effective, was indicated as a source of methane emission. According to the research by Blade et al. emissions of CH_4 from dairy cattle manure and food industry waste digestate storage was 12% of its total production [18]. Despite this, a lot of interest was directed to the use of animal-origin waste as feedstock for biogas production via anaerobic fermentation by both researchers and industrial operators. Several extensive reviews, economic studies and research are available in the literature [19–24] and some full-scale installations are in operation around the world [25,26]. Thermochemical conversion methods are stable and more effective, but underutilized in animal waste management [27]. Among them, pyrolysis and gasification have questionable industrial potential due to several operation problems and high investment costs caused by the multi-stage process structure [28–32]. Hence, the anaerobic fermentation, pyrolysis, and gasification are not an issue of the presented review.

The aim of this paper is to take a deep insight into a prospective but still poorly explored topic: animal waste combustion and co-combustion, with a focus on fuel properties, ash-related issues (slagging, fouling, corrosion), and possible ash disposal, according to the scheme of energy recovery and nutrient recycling presented in Figure 1. These subjects are definitely less recognized and there is a leak of a comprehensive review of possibilities and challenges in this field.

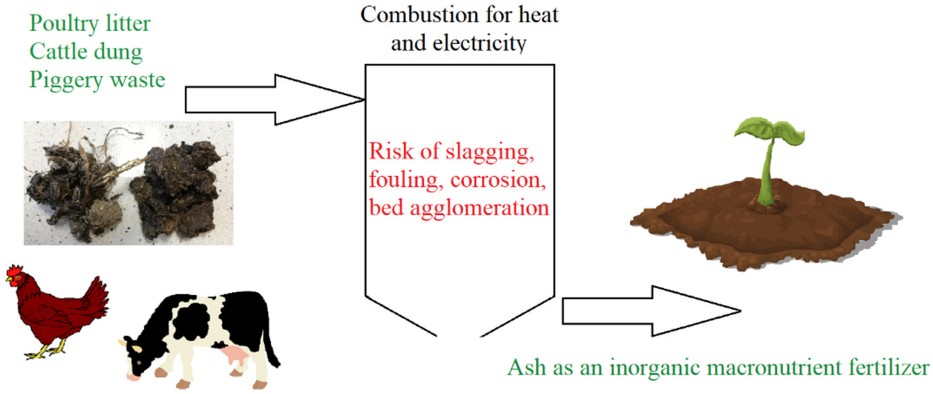

Figure 1. Scheme of energy recovery and nutrient recycling from animal waste.

2. Characteristics of Animal Waste

Recognition of fuel characteristics is a key issue when considering animal-origin feedstock as a renewable energy source. There is much research that presents the proximate and elemental (ultimate) analyses of animal waste, nevertheless, much of it lacks details of breeding conditions, farming style, or bedding material. These parameters may affect the physical and chemical properties of animal waste, as presented below.

2.1. Poultry Litter

Poultry litter is by far better recognized in terms of possible combustion potential than other types of animal waste. The reason is its highly centralized production, as poultry is commonly bred in large farms of broilers or laying hens. Poultry houses in Western Europe are cleaned between each flock, which generates piles of waste in regular periods of 7–10 weeks [33]. Bedding materials are usually plant-origin, such as straw, hays, wood shavings, sawdust, rice husk, or corn cob. Alternative methods, such as sand or gypsum are of minor importance [34,35]. Most common bedding material is suitable for thermal processing itself. What is more, it is advisable to use untreated wood products as bedding to minimize the health risk caused by wood preservatives such as sodium borate and copper chrome arsenate. All these features make poultry litter attractive and relatively safe for thermal treatment. Numerous records reported the proximate and ultimate (elemental) analyses of poultry litter, as presented in Table 1 and described below. The samples originated from various farming conditions are displayed to determine the relationship between the breeding parameters and the feedstock properties. Two samples of processed poultry litter were also taken into account: poultry litter pellets and poultry-derived fuel.

Table 1. Proximate and elemental (ultimate) analyses of poultry litter (a.r.—as received, d.b.—dry basis, and n.d.—no data).

Parameter	Basis	Unit	Poultry Litter with Sawdust [36]	Poultry Litter with Rice Husk [36]	Free-Range Chicken Litter [37]	Industrial Farming Chicken Litter [37]	Poultry Litter [38]	Chicken Litter [39]	Chicken Litter [40]	Poultry Litter Pellets [41]	Poultry-Derived Fuel [42]
Moisture	a.r.	wt%	18.16	32.57	12.10	11.10–38.8	8.5	11.3	21.20	n.d.	7.34
Ash	d.b.	wt%	16.64 (a.r.)	10.85	30.10	9.31–17.09	14.3	24.8	24.06	16.6	25.07 (a.r.)
HHV	d.b.	MJ/kg	n.d.	n.d.	12.22	15.60–17.22	18.00	n.d.	14.34	16.7 (LHV)	n.d.
	a.r	MJ/kg	12.53	11.31	10.97	11.40–15.31	n.d.	n.d.	11.30	n.d.	12.77
C	d.b.	wt%	37.41	39.9	31.19	37.7–41.85	42.72	28.2	34.11	41.4	31.84
H	d.b.	wt%	4.41	4.79	3.91	5.10–5.50	5.50	5.0	5.64	5.7	3.98
N	d.b.	wt%	9.96	8.70	2.90	4.70–4.89	3.93	3.4	4.16	4.8	3.52

Table 1. *Cont.*

Parameter	Basis	Unit	Poultry Litter with Sawdust [36]	Poultry Litter with Rice Husk [36]	Free-Range Chicken Litter [37]	Industrial Farming Chicken Litter [37]	Poultry Litter [38]	Chicken Litter [39]	Chicken Litter [40]	Poultry Litter Pellets [41]	Poultry-Derived Fuel [42]
S	d.b.	wt%	0.73	n.d.	0.50	0.31–0.97	0.64	0.9	1.32	0.8	0.75
Cl	d.b.	wt%	n.d.	n.d.	0.11	0.66–0.99	0.3	1.16	n.d.	n.d.	0.4 (a.r.)

2.1.1. Moisture Content

The moisture content of unprocessed poultry litter is not very consistent, ranging from 8.5% to 38.8%. Nevertheless, there are results on combustion and co-combustion of poultry litter that show that as long as the moisture content is below 25%, the direct combustion is possible and no addition of other fuels is needed [43]. Another study establishes the maximum advisable moisture content at 43% and points out that higher moisture levels would cause problems in the CFB and result in elevated emissions of SO_2 and NO_x [44]. The upper values are not desirable for the combustion process, therefore pre-processing of litter (drying, pelletizing, and torrefaction) may be needed, as these methods upgrade the fuel properties of biomass [45]. Poultry-derived fuel investigated by Jia et al. was characterized by a satisfactory moisture content of 7.34% [42].

2.1.2. Ash Content

The content of ash in poultry waste varies from 9.31% to 30.10% (dry basis). As indicated in previous research, it is correlated with farming style and reaches higher values for free-range animal droppings [37]. Compared to plant-origin biomass, whose ash contents usually range from 0.37 to 10.44%, animal waste can be considered ash-rich [46]. Some types of conventional biomass feature ash content reaching 25% [47] nevertheless their thermal utilization may be associated with ash-related problems, such as deposition on heated surfaces and in flue gas ducts, and bed agglomeration in fluidized-bed combustion boilers (FBC) [48–50]. Therefore, the combustion of poultry litter may require the special design of the heat exchangers and dust collection equipment.

2.1.3. Calorific Value

The calorific value of biomass is negatively correlated with ash content [46]. For low-ash biomass types such as straw or wood chips, the HHV is usually in the range of 17.70–20.34 MJ/kg, while for high-ash waste biomass is in the range of 14.80–18.45 MJ/kg [51–55]. The highest HHV of displayed poultry litter is 18.00 MJ/kg, nevertheless, the majority of samples represent lower values. This does not, however, significantly differ from the typical values of waste biomass.

2.1.4. Chlorine Content

Chlorine is the main contributor to the high-temperature corrosion process; hence its presence in fuels is not desirable [56–58]. Chlorine in biomass is present predominantly as NaCl and KCl, corrosive compounds with melting points of 801 °C and 771 °C, respectively. If sulfur is present at a high enough amount, it may react with potassium, forming less corrosive compounds, such as potassium sulfate K_2SO_4 [59–61]. Contrarily, relatively high chlorine and low sulfur contents result in a high chlorine-to-sulfur ratio. Under such conditions, the protective oxide scale formed on a heat exchanger steel surface is easily destroyed and chlorine passes through the metal pores, which favors forming of metal chlorides [62].

Poultry litter manure is claimed to be chlorine-rich, with the mean value established at 0.64% of Cl in dry basis [63]. This explains the low interest in the combustion and co-combustion of animal waste. Nevertheless, the chlorine content of displayed poultry litter samples varies significantly, starting from 0.11% and reaching 1.16%. Chlorine content is one of the so-called "slagging indices" used for the assessment of the slagging and fouling risk of fuel. The Cl content below 0.2% indicates low risk, 0.2–0.3% moderate risk, and

0.3–0.5% high risk [64–66]. Based on that, some poultry litter samples are characterized by low or moderate risk, while others are clearly highly risky.

2.2. Cattle and Piggery Waste

Cattle and piggery waste is still less recognized as a fuel than poultry litter. Nevertheless, the utilization of local cattle manure may be a promising energy source for rural communities [67]. The proximate and elemental (ultimate) analyses of cattle and piggery waste show great variability, as presented in Table 2 and described below. This occurrence is likely to be determined by factors such as breeding style, bedding system, feed composition, animal age, and country of origin [68].

Table 2. Proximate and elemental (ultimate) analysis of cow (cattle) and piggery (swine) manure (a.r.—as received, d.b.—dry basis, and n.d.—no data).

Parameter	Basis	Unit	Dairy Cattle Manure [a] [69]	Beef Cattle Manure [b] [69]	Beef Cattle Manure 2 [70]	Free-Range Cow Manure (Straw Bedding) [37]	Industrial Farming Cow Manure (Straw Bedding) [37,71]	Yak Manure [72]	Pig Manure [69]	Pig Manure 2 [73–75]
Moisture	a.r.	wt%	75.59 ± 9.22	75.66 ± 7.82	13.08 ± 0.5	8.4–11.4	11.1–15.5	2.60–4.36	71.99 ± 9.65	91.26
Ash	d.b.	wt%	28.20 ± 16.28	22.64 ± 11.88	29.80 ± 2.8	21.4–22.06	13.86–16.99	11.62–31.16	24.18 ± 11.14	19.72–20.90
HHV	d.b.	MJ/kg	n.d.	15.21	15.93 ± 0.3	16.93–17.26	17.91–19.04	13.41–17.59	n.d.	n.d.
C	d.b.	wt%	34.42 ± 8.96	37.64 ± 6.16	50.43	38.93–41.94	44.07–45.26	32.52–42.87	37.74 ± 6.43	32.35–47.42
H	d.b.	wt%	4.91 ± 1.39	5.26 ± 1.12	7.18	4.89–5.38	5.45–5.53	3.85–5.69	5.62 ± 1.00	4.82–6.40
N	d.b.	wt%	1.92 ± 0.50	2.16 ± 0.64	2.55	2.59–1.61	2.5–2.79	1.60–1.84	2.79 ± 0.71	1.90–4.11
S	d.b.	wt%	0.65 ± 0.4	0.59 ± 0.28	0.57	0.32–0.34	0.32–0.47	0.18	0.63 ± 0.30	0.71–0.94
Cl	d.b.	wt%	n.d.	n.d.	n.d.	0.086–0.33	0.54–1.02	0.14–0.20	n.d.	n.d.

[a] 217 dairy manure samples from China. [b] 139 beef manure samples from China.

2.2.1. Moisture Content

Cattle waste is extremely varied in terms of moisture content. It ranges from 2.60% in the case of yak to 75.66% in the case of beef cattle manure. It is clear that the samples can be divided into two groups: with relatively low moisture content (<15%) and with extremely high moisture content (>70%). Unfortunately, usually there is no information about bedding style; nevertheless, the bedding material is likely to be the factor that determines the moisture content. When straw or other plant-origin material is used as bedding, the moisture content is expected to be correlated negatively, as bedding should be possibly dry to avoid caking [76]. In bedding-less systems, the manure does not contain bedding material and is often rinsed with water. Font-Palma indicates that cattle manure with the moisture content of above >70% is not suitable for direct thermochemical processes to generate energy [16].

Pig manure is characterized by the highest moisture content exceeding 90%. The possible way of valorization of such humid animal manure is mixing it with relatively dry agro-industrial biomass (e.g., cotton stalk or rapeseed oil cake) to produce pellets or other types of solid biomass-derived fuel [77].

2.2.2. Ash Content

Ash content does not vary as remarkably as moisture content. It can be expected in the range of 13.86 to 29.80% (dry basis). Similarly to moisture content, ash content can be correlated with bedding as well. In Europe, the most popular bedding materials are straw, wood carvings, or sawdust, but in the USA, the most recommended bedding material is sand, which unquestionably elevates the ash content, as Nam et al. reported the ash content of dairy cattle manure with sand bedding to be 48.8 ± 3.1% [78]. High ash content positions animal manure closer to sewage sludge than plant-origin biomass [79–82].

2.2.3. Calorific Value

The HHV of cattle manure starts from 13.41 MJ/kg and ranges to 19.04 MJ/kg (dry basis). The values are close to poultry manure and do not differ significantly from typical waste biomass.

2.2.4. Chlorine Content

When it comes to the chlorine content in cattle and piggery waste, only limited data can be found in the literature. From the author's experience, chlorine content depends strictly on the farming style and varies from 0.086 to 0.33% for free-range farming to 0.54–1.02% for industrial farming cattle manure (all with straw bedding) [37,71]. In the literature, there is some information on chlorine content in yak excrements [72], which was determined to be in the range of 0.14–0.2% and can be taken into account since yak can be considered cattle. According to the evaluation used in Section 2.1.4., the chlorine content of both free-range cattle and yak manure positions them as low-to-moderately risky. Industrial farming manure can be, however, more prone to chlorine-related issues.

3. Combustion and Co-Combustion: State of the Art

The literature review points out that the thermal processes, particularly combustion and co-combustion, are the most effective disposal routes from technical, economic, and environmental points of view. They allow converting animal litter into useful energy with reasonable investment costs, controlled emissions, and high efficiency. In contrast to this high potential, not so many studies researched the combustion and co-combustion of animal waste. As indicated in Section 2, animal waste is a very heterogeneous material, which is most likely a result of various breeding conditions. Nevertheless, co-combustion with other fuels or pre-treatment methods, such as pelletizing, may be applied to improve its morphology and the stability of the combustion process [83]. The energetic utilization of such fuels requires financial investments, nevertheless favors the technoeconomic progress based on sustainability and human-oriented development [84].

3.1. Direct Combustion

The very first analysis of animal manure combustion was conducted by Sweeten et al. back in 1986 [85]. Feedlot manure containing 14–18% moisture, 16–42% ash, and with a heating value of 12.40–14.95 MJ/kg (as received) was combusted in a fluidized bed unit. The unit was operated in recirculating bed mode with a combustion temperature of 620 °C to avoid problems of slagging and fouling. Further analysis of animal waste combustion was conducted by Bowen et al. [44]. The authors investigated the combustion of chicken litter and pointed out some bullet advice for farmers and operators of combustion units. The circulating fluidized bed was suggested as it offers strong fuel flexibility with good efficiency and performance factors. The construction of the latest CFB boilers allows stable and relatively low temperatures in the combustion chamber, e.g., the average flue gas temperature can be maintained in the range of 800–900 °C for minimization of thermal nitrogen oxide (NO_x) formation and avoiding the issues of low ash melting temperatures [86,87], which is particularly important for some types of animal-origin waste. The high content of nitrogen in poultry litter and cattle waste may be a source of increased NO_x emission [88], thus the application of advanced deNO_x methods may be required [89].

Meanwhile, research dealing with a thermogravimetric experimental study on the ignition and combustion characteristics of animal waste appeared. Yurdakul found the thermal decomposition profiles of poultry litter to be different from those of coal, with slightly different values of activation energies [90]. Jiang et al. investigated the ignition and combustion characteristics of cattle manure particles under various oxygen concentrations and temperature of 873–1073 K [91]. The results show the clear effect of these parameters on the ignition and combustion characteristics of cattle manure, with the main conclusion that the volatile matter ignition precedes the particulate matter ignition, and the rise of temperature and oxygen concentration improve the ignition and combustion process, together with the reduction in the ignition delay and volatile combustion time. Pu et al. conducted the kinetic analysis of chicken manure in air and oxygen atmospheres and found a great influence of bedding material (sawdust) on the thermal decomposition process [92]. Thermogravimetric analysis conducted by Atimtay and Yardakul indicated a positive influence of torrefaction on the combustion characteristics of poultry litter [93]. What is interesting is that the combustion performances of lignite poultry litter blends investigated in this study were better than those of pure lignite samples.

3.2. Co-Combustion with Fossil Fuels or Plant-Origin Biomass

Combustion of animal waste alone could result in some problems connected to the high moisture and ash contents, as well as low heating values. Therefore, co-combustion with fossil fuels (coal, lignite, peat, and natural gas) or plant-origin biomass can be considered a reasonable alternative.

Experimental results published by Topal and Amirabedinn [36] reveal that the co-combustion of poultry waste (manure and sawdust or rice husk used as bedding) with coal in an existing combustion unit can be considered an environment-friendly remedy for animal waste disposal. The authors conducted experiments in a bottom feed 80 kW combustion unit and indicated the optimal excess air ratio in the range of 1.45–1.6 for minimizing the emissions of NO_x, CO, and CH_4. Due to the low sulfur content in the feedstock, the emission of SO_2 was almost unnoticeable. Li et al. investigated the co-combustion of chicken litter with coal in a laboratory-scale fluidized bed combustor [39]. The effect of chicken litter on pollutant emissions (CO, SO_2, H_2S, and NO) was determined. The results show that the introduction of chicken litter increases CO emissions with a simultaneous reduction in the SO_2 emission caused by chicken litter ash-derived natural desulfurization. Poultry litter ash contains large amounts of Ca and Mg, which results in significant retention of sulfur and reduction in SO_2 in flue gas.

Co-combustion of poultry litter with peat was investigated in an atmospheric bubbling fluidized bed by Abelha et al. [43], as well as by Henihan et al. [94]. The emissions of atmospheric pollutants were strictly connected to the ratio between fluidizing and secondary air, and maintaining the correct ratio is a key factor in fulfilling the emission standards.

Co-combustion of poultry litter with plant-origin biomass was investigated by Turzyński et al. The addition of straw or wood improved the combustion process and increased the flame temperature from 600 °C to 800 °C (straw) and 900 °C (wood) [95]. Similarly, the combustion behavior of poultry litter and its mixtures with straw was investigated by Polesek-Karczewska et al. [96]. The research pointed out the possible problems during the combustion of poultry waste, such as strong non-homogeneity and high porosity (low bulk density) of the fuel bed. The blend of 95% of litter and 5% of straw was determined as promising in terms of the optimal process temperature.

Co-combustion of poultry litter and natural gas was studied as a viable alternative for producing heat and electricity [97]. This process was analyzed in a pilot-scale installation in terms of performance evaluation of the water-to-air heat exchanger. Results indicate that the specific heat of flue gas during co-combustion was only slightly lower than the specific heat of flue gas from fossil fuel combustion. It was concluded that hot water production from poultry litter and natural gas co-combustion processes can be considered advantageous due to several factors: reduction in poultry waste disposal costs, energy savings, and avoiding environmental problems. The process was claimed as a pathway toward a beneficial and sustainable waste management option for poultry farmers. Electricity output and emission characteristics during the co-combustion of poultry litter and natural gas were also evaluated by Qian et al. [40]. The process took place in a lab-scale swirling fluidized bed integrated with a Stirling engine. It was found that increasing the content of poultry litter and the mixing ratio to 4.51 could potentially reduce the emissions of SO_2 and NO_x. The study shows that the co-combustion of poultry litter and natural gas has the potential to be a cleaner alternative to converting conventional fuels into electricity with simultaneous reduction in emissions.

3.3. Existing Full-Scale Combustion Units

When it comes to full-scale application in combustion units, animal-origin biomass is gaining popularity. The company BINDER Energietechnik succeeded in developing a dedicated boiler for the combustion of chicken litter with strictly controlled emission levels [98]. The combustion takes place on a hydraulically or electro-mechanically operated grate, allowing for the combustion of wet materials with high ash content. The combustion system is available in two different sizes with three power stages, ranging from 800 to 2000 kW.

In the Moerdijk power plant in the Netherlands, poultry litter from local chicken farms is used as fuel in a bubbling fluidized bed boiler. This substoichiometric bed operation allows for maintaining the bed temperature in the range between 650 °C and 820 °C. Therefore, the low ash melting temperature of animal waste is not an issue and does not cause any sintering problems in the bed. The boiler with a thermal capacity of 118.5 MWth is equipped with an electrostatic precipitator and a SCR system. The fuel input reaches 440,000 tons of poultry litter per year and the plant produces 270 GWh_{el}/year of green electricity for households [99–101].

In the Skokloster heat plant (Sweden) horse dung is co-combusted for heat production. The plant uses 365 tons of manure per year together with wood chips and wood pellets. The combustion process is two-stage, with the fixed bed primary combustion zone where fuel drying, devolatilization, and char oxidation take place at a temperature limited to 850 °C, and the secondary combustion zone, which secures complete combustion at a temperature of above 1000 °C [102].

3.4. The Use of Animal-Origin Biomass in the Metallurgy and Cement Industry

Similar to the power sector, the metallurgy and cement industries are seeking ways to reduce greenhouse gas emissions. One of the possibilities is to substitute the classic coke used in metallurgy with bio-coke made entirely or partially of various biomass types [103,104]. Among them, animal-origin biomass seems promising, but nevertheless, is still not recognized enough. Just recently, Rath et al. introduced a novel approach for reduction roasting of iron ore slime using cow dung [105]. In comparison to the conventionally used charcoal, cow was proven to be a better reductant. When it comes to the cement industry, in the United Arab Emirates (UAE), camel dung is being used to fuel cement production in facilities run by the Gulf Cement Company. Utilizing camel dung is promoted by the Ministry of Climate Change and Environment of UAE as an excellent way to cut emissions and prevent animal waste from landfilling [106].

4. Ash Composition and Possible Application

The land application of combustion by-products (mainly ash) is in line with the idea of the recycling and up-cycling of biomass [107]. Animal litter ash usually contains significant amounts of nutrients, such as phosphorous and potassium; nevertheless, their content can vary depending on the breeding style, type of feed, feed supplementation, type of bedding material, flock size, and combustion conditions [72,73]. The detailed ash compositions of various animal-origin biomass types are presented in Table 3. All the displayed ashes contain remarkable amounts of phosphorous, up to 24.00% P_2O_5. Some alkalis are present as well in the form of sodium (0.73–6.80% Na_2O) and potassium (2.61–25.20% K_2O). The relatively high content of calcium is noteworthy (up to 34.70% CaO). This feature is likely to favor the natural desulfurization of flue gas [108,109] and may indicate the low erosive potential of the fly ash [110].

Table 3. Animal-origin waste ashes compositions (n.d.—no data).

Parameter	Unit	Poultry Litter with Sawdust [36]	Free-Range Chicken Litter [37]	Industrial Farming Chicken Litter [37]	Chicken Litter [39]	Free-Range Cow Manure [37]	Industrial Farming Cow Manure [37,71]	Beef Cattle Manure [a] [69]	Dairy Cattle Manure [b] [69]	Pig Manure [69]	Pig (Swine) Solid Waste Bottom Ash [111]	Horse Manure [112]
SO_3	wt%	6.0	1.02	0.82–9.68	5.8	0.88–1.18	2.63–4.45	n.d.	n.d.	n.d.	8.95	n.d.
K_2O	wt%	10.86	2.61	13.04–25.20	12.2	3.19–8.64	5.56–18.6	7.02	4.79	8.99	12.5	11.5
SiO_2	wt%	n.d.	57.11	3.66–13.26	35.6	59.63–75.60	18.30–33.60	n.d.	n.d.	n.d.	6.24	42.6
Fe_2O_3	wt%	7.42	1.94	0.92–4.11	2.1	1.11–1.52	1.06–1.24	1.89	2.03	2.11	3.92	4.24
Al_2O_3	wt%	2.28	4.15	0.48–2.81	4.9	2.65–4.28	1.31–1.95	n.d.	n.d.	n.d.	1.38	7.75
Mn_3O_4	wt%	n.d.	0.13	0.63–1.92	n.d.	0.12–0.18	0.16–0.51	n.d.	n.d.	n.d.	n.d.	n.d.
TiO_2	wt%	n.d.	0.23	0.04–0.63	0.2	0.21–0.24	0.09–0.15	n.d.	n.d.	n.d.	0.14	0.44
CaO	wt%	15.82	13.55	18.30–34.07	13.5	2.11–11.85	13.6–30.60	7.95	8.90	11.46	25.70	15.4
MgO	wt%	3.28	2.15	5.72–7.45	4.6	1.56–2.72	5.55–8.14	5.42	6.24	9.50	7.42	8.85
P_2O_5	wt%	10.19	7.81	19.23–23.74	15.3	4.09–8.21	10.8–17.50	7.19	19.13	21.49	24.00	4.27
Na_2O	wt%	1.68	3.21	3.87–6.80	5.8	0.73–3.57	2.66–3.20	2.29	1.44	1.63	2.08	2.59
BaO	wt%	n.d.	0.02	0.03–0.17	n.d.	0.04–0.02	0.03–0.05	n.d.	n.d.	n.d.	n.d.	n.d.
SrO	wt%	n.d.	0.02	0.05–0.39	n.d.	0.02	0.03–0.04	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	wt%	n.d.	0.90	5.67	n.d.	0.65–7.56	2.57–6.55	n.d.	n.d.	n.d.	3.29	n.d.

[a] 217 dairy manure samples from China. [b] 139 beef manure samples from China.

When it comes to utilization paths, animal-origin biomass ash can be considered a biologically safe source of nutrients for land application [113,114]. The thermal treatment of poultry litter increased the mobility and availability of microelements for plants with a simultaneous decrease in the pathogenic microflora [115]. In raw (untreated) poultry litter, about 20% of phosphorous is water-soluble [116]; while, according to research by Tan et al. it is almost insoluble in poultry litter ash [117]. Similarly, research by Codling [118] found water-extractable phosphorous to be about 1.5% of the total phosphorous in poultry litter ash. This prevents the contamination of groundwater and eutrophication of water bodies caused by the soil application of water-soluble phosphorous. However, potassium is highly water-soluble in both raw poultry litter and ash [119]. Moreover, animal-origin ash contains almost no nitrogen, as it is converted to N_2 and NO_x during the combustion process [120].

The content of nutrients in ash is dependent on the incineration temperature, according to the study by Huang et al. [121]. Various types of animal manure (laying hen manure, cattle manure, pig (swine) manure) were incinerated in a muffle furnace at the temperature of 400–900 °C and their properties were determined, including the ash yield (%), total nitrogen recovery, total potassium (K_2O) recovery, and total phosphorus (P_2O_5) content. The first three factors decreased with increasing incineration temperature. However, total phosphorus content in the ashes increased with incineration temperature, resulting in P_2O_5 contents of 20.7–24.0% for pig manure, 4.5–7.5% for layer manure, and 4.5–7.5% for laying hen manure.

The possible application of fly ash from the co-combustion of chicken litter with natural gas was analyzed by Quian et al. [40]. The ash showed high nutrient content: 10% of phosphate and 6% of potassium. The fertilizer efficacy of turkey litter ash blended with lime and gypsum as fillers was studied by Bauer et al. [122]. The ash investigated in this study was characterized by high amounts of calcium, phosphorous, and potassium: P and K contents were equivalent to 15.5% P_2O_5 and 7.0% K_2O, respectively. The fillers were tested in terms of improving the uniformity of application with commercial fertilizer application equipment; nevertheless, the desired distribution of plain poultry litter ash on the field is possible and does not require adding any substances.

The effects of poultry litter biochar on soil properties and the growth of water spinach were tested by Yu et al. [123]. The application of >1.0% of biochar was proven to influence the available inorganic N, available P, and exchangeable K in the soil, which consequently enhanced the growth of the plants. Similarly, the research by Netherway et al. [124] shows that biochars are a suitable substitute for P fertilizers as an integrative remediation strategy in Pb-contaminated soils, enabling soil biological restoration. The application of biochars produced from poultry litter positively affects the activity of soil enzymes, at the same time improving the soil quality. The authors tested several process temperatures in the range of 300–500 °C and found that the biochars prepared at the higher temperature tested showed the best results, so the further temperature increase would probably cause a further improvement in fertilizing properties. Hence, ash from combustion and co-combustion of animal waste is expected to be a promising alternative to standard phosphorus-based fertilizing products.

Nevertheless, biochar application in the soil must meet the certification requirements in terms of organic pollutants (PAHs) and trace metals [125]. Similarly to biochar, animal manure ash can be highly enriched in heavy metals, such as copper (Cu) and zinc (Zn), as they are in wide use as feed additives. This may cause potential risks of heavy metal accumulation in the soil when such ash is used as a fertilizer. This problem was already observed for untreated animal manure. Zhang et al. reported Zn concentration in unprocessed chicken manure reaching up to 1063.32 mg/kg [126]. Lan et al. applied pig manure on land and investigated the Cu and Zn contents in the soil and rice roots [127]. Their concentrations were significantly higher in samples fertilized by the pig manure than those of the non-fertilizer control. These metals may also be present in animal-origin ash, as they do not volatilize during the combustion process. Nordin et al. [128] determined the Zn concentration in ash from the combustion of a mixture of horse manure and sewage sludge to be 1400 mg/kg. On the other hand, Park et al. determined Zn in the swine waste bottom ash to be 31.279 mg/kg [111]. The concentration of metals is likely to be correlated with dietary supplements applied to animals [129] and should be taken into account when considering the land application of animal-origin ash.

5. Problems and Challenges

Animal waste is claimed to be a "difficult" type of fuel. Its low attractiveness is caused by fears of slagging, fouling, chlorine corrosion, ash agglomeration, and deposition in the combustion chamber. These issues are with no doubt undesirable, nevertheless, their occurrence is not obvious, as they are mostly determined by the ash composition and melting tendencies [130,131].

The characteristic ash fusion temperatures (AFT) of animal waste are displayed in Table 4 and include the initial deformation temperature (IT), softening temperature (ST), hemispherical temperature (HT), and fluid (flow) temperature (FT). The ash fusion temperatures of biomass ash typically range from 1100 °C to 1300 °C [132]. These values can, however, vary depending on the biomass type. The deformation temperatures of hay pellets and corn cob ashes were determined to be below 1000 °C, while for ashes of sunflower husks and rice husks, it exceeded 1500 °C [133]. The initial deformation temperature for animal waste ranges from 910 °C for free-range cow manure to 1400 for industrial farming chicken litter, while the flow points range from 1140 °C for yak dung to >1500 °C for poultry litter and free-range cow manure.

Table 4. Ash fusion temperatures (AFTs) of animal-origin biomass (n.d.—no data).

Parameter	Unit	Poultry Litter with Sawdust [36]	Poultry Litter with Rice Husk [36]	Free-Range Cow Manure [37]	Industrial Farming Cow Manure [37,71]	Free-Range Chicken Litter [37]	Industrial Farming Chicken Litter [37]	Yak Dung [72]
Initial deformation temperature (IDT)	°C	1258	1360	910–1260	1130–1230	1060–1140	1303–1400	n.d.
Softening temperature (ST)	°C	1417	>1500	1150–1310	1170–1270	1170–1210	1380–1500	1110–1120
Hemisphere temperature (HT)	°C	>1500	>1500	1340–1460	1200–1320	1300–1330	1430–1500	1130–1160
Flow temperature (FT)	°C	>1500	>1500	1370–1500	1310–1440	1320–1360	1490–1500	1140–1210

Low AFTs of some animal waste may indicate problems in the combustion chamber. The issues of ash agglomeration and deposition during the combustion of poultry litter in a bubbling fluidized bed combustor were firstly described in detail by Lynch et al. [134]. Bed agglomerates were investigated and found to be double-layered. The inner layer (<0.09 mm thick) was formed in a reaction of SiO_2 and K, resulting in low-melting potassium silicates. The outer layer was composed of fine ash particles stuck to the inner layer. Slag formation in the combustion chamber was defined as highly temperature-dependent. The thermodynamic equilibrium calculations predicted an over four-times increase in slag formation after lifting the combustion temperature from 600 °C to 1000 °C. SiO_2 and K_2O were the dominant phases in the slag (95%), which points out the vital role of potassium silicates in initiating bed agglomeration.

Contrary, Jiang et al. investigated the ignition and combustion characteristics of cattle manure together with ash analysis and concluded that the tendency of slagging and fouling of cattle manure ash is very low [91]. In another study, the ash deposition tendencies of high-alkali low-rank coal were investigated with the addition of chicken or pig manure [135]. Chicken manure with high potassium and calcium contents favored the formations of a high melting point $Ca_3P_2O_8$ and $KCaPO_4$, which inhibited alkali silicate generation, and as a result made the deposition process decrease. Li et al. investigated the ash fusion characteristics and the variation in cattle and swine manure mixed with two coals (long-flame coal and lignite) [136]. An increase in the ash mass ratio of the manure increased the sintering temperature of both coals. Swine manure elevated the temperature more than cattle manure. The limit point of the cattle manure ash was ∼60% and swine manure ash was ∼40% for the long-flame coal mixture, and cattle manure ash: ∼70% and swine manure ash: ∼50% for the lignite mixture. The melting properties of ash mixtures were determined mainly by ash composition. The fluctuation of the ash fusion temperatures was caused by the formation of low melting eutectic (e.g., binary systems for K_2SiO_3–$Na_2Si_2O_5$ and Na_2S–FeS) and high melting-point phosphates (e.g., $KCaPO_4$, $K_2CaP_2O_7$) [137,138].

As presented in Tables 2 and 4, some types of animal waste are characterized by relatively low chlorine concentrations together with high ash fusion temperatures. These features are expected to positively influence their combustion behavior and make them less prone to unwanted issues in the combustion chamber.

6. Conclusions

Literature data clearly point out that the thermal processes, particularly combustion and co-combustion, are the most effective routes of animal-origin waste disposal from both technical and environmental points of view. The main conclusions are as follows:

(1) The thermal utilization of animal waste has the following advantages:
- Reduction in fossil fuel consumption;
- Minimization of the waste stream, reduction in landfilling;
- Availability on a small scale, for local heat and power generation, even in rural areas;
- Reduction in pathogens;
- Decrease in the anaerobic release of GHG: CH_4, NH_3, and H_2S.

(2) Both poultry and cattle waste are highly heterogeneous materials. The ash content in displayed samples varied significantly from 9.31 to 30.10%, while moisture content varied from 2.60 to 91.26%. These properties indicate possible difficulties associated with direct combustion. Therefore, the co-combustion with plant-origin biomass (such as wood) or fuel pre-processing (such as palletization or torrefaction) may be promising solutions.

(3) When considering animal-origin waste as fuel, usually only animal species is given (poultry litter, cattle manure, etc.). However, according to the analyzed literature data, this is not sufficient information. Several more factors may influence the fuel and ash properties of animal waste. The most important are:

- Housing system (with bedding or bedding-less);
- Type of bedding (plant-origin such as straw, wood, etc., or alternative);
- Range style (free-range or industrial farming).

(4) Some animal-origin biomass types are not as prone to combustion-related issues as others. The ash fusion temperatures may exceed 1500 °C, indicating low deposition and slagging risks. The chlorine content of displayed samples was in the range of 0.086–1.16%, placing some of them as low or moderately risky for combustion. In some points, manure addition can even mitigate the unwanted issue of ash deposition during the thermal conversion of low-rank coal.

(5) Low sulfur and high calcium contents in animal waste are beneficial for combustion. The SO_2 emission is reduced as a result of ash-derived natural desulfurization of flue gas.

(6) The ash from animal waste combustion has the potential for soil conditioning. It may be applied as a fertilizer due to the high levels of macro- and micro-nutrients. Nevertheless, the possible elevated concentration of metals and metalloids (such as Zn and Cu) should be taken into account. The land application of animal-origin ash is still not recognized enough and requires further investigation.

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