

From fuel potential to operational reality: barriers to energy recovery from animal husbandry waste

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Abstract:

The increasing interest in the thermal utilization of animal husbandry waste is driven by its potential for renewable energy production, yet its large-scale application remains limited by severe operational challenges. This study investigates the poultry litter (PL) and cattle manure (CM), including their fuel properties, ash characteristics, and high-temperature corrosion risk. The analyzed fuels are characterized by relatively high ash content, significant nitrogen and chlorine concentrations, and moderate heating values, which affect both their combustion performance and environmental impact. Despite relatively high ash fusion temperatures indicating low slagging propensity, the results reveal a high risk of ash-induced corrosion due to elevated levels of alkali metals and chlorine. The interaction of K and Cl species promotes chlorine-induced active oxidation, leading to the degradation of protective oxide layers on boiler materials. The findings demonstrate that chlorine-induced high-temperature corrosion, rather than general ash melting, constitutes the primary operational constraint for the thermal conversion of animal waste. The study highlights the need for integrated mitigation strategies, including fuel selection, ash chemistry control, and appropriate material choice, to ensure reliable and efficient energy recovery.

Keywords:

Biomass, Animal waste, Poultry litter, Combustion, Corrosion.

1. Introduction

Animal husbandry waste, including poultry litter (PL) and cattle manure (CM), represents a significant yet underutilized renewable energy resource. These materials are widely available, geographically dispersed, but often associated with environmental burdens when improperly managed. According to current data [1], there are 22.8 billion chickens, 1.5 billion cattle, 1.2 billion sheep, 1.2 billion ducks, 1 billion goats and 967 million pigs kept in global farms (Figure 1). These numbers are reflected in the high amount of waste generated annually, which consist mainly of manure and used bedding. In many European countries such as France, Germany, United Kingdom, Spain, Poland or Italy the annual production of livestock waste exceeds 100 million tons [2]. Their thermal conversion offers opportunities for decentralized energy production and circular nutrient management with reduced environmental risk.

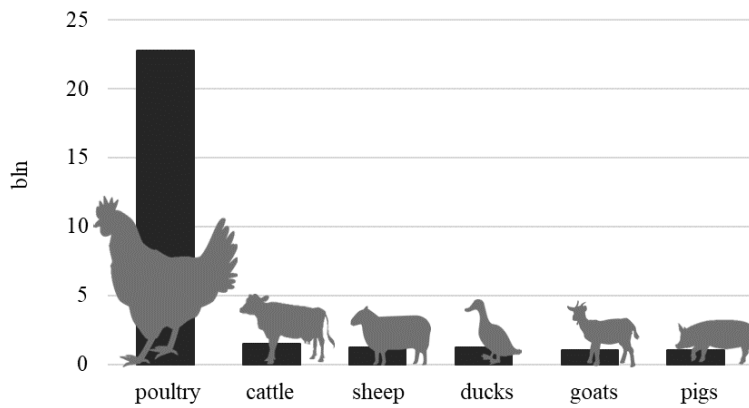


Figure 1. Number of farm animals in the World. Data based on [1].

Despite the intrinsic energy content of animal husbandry waste, their large-scale energetic utilization remains limited. This limitation is not driven by a single factor but rather by the interaction of fuel properties, ash chemistry and operational constraints. In particular, high ash content, high moisture content, ash-induced corrosion and deposit formation constitute major barriers that affect boiler reliability, availability and economic feasibility.

Most existing studies address separately fuel characterization, ash composition and melting tendencies or corrosion of animal waste-based fuels [3–7]. However, in practical energy systems these aspects are strongly coupled. Features such as high moisture content affect fuel handling, elevated nitrogen content causes NO_x emissions, ash chemistry influences melt formation and deposit behavior, which in turn governs corrosion kinetics and component lifetime. This interaction creates a feedback loop between material degradation and process instability.

The presented work provides an integrated assessment of the key barriers limiting the thermal utilization of poultry litter and cattle manure. Two types of PL (PL1 and PL2) and two types of CM (CM1 and CM2) are investigated. The literature data of other PL and CM are gathered, systematized and discussed. Figure 2 presents a schematic overview of the research context, illustrating the utilization of PL and CM as alternative fuels for bioenergy production, together with the associated operational challenges. The figure highlights the key issues related to these fuels, including high ash and moisture content, heterogeneity, elevated chlorine levels, and unfavorable ash chemistry - factors are known to significantly affect combustion performance and contribute to the formation of deposits as well as high-temperature corrosion.

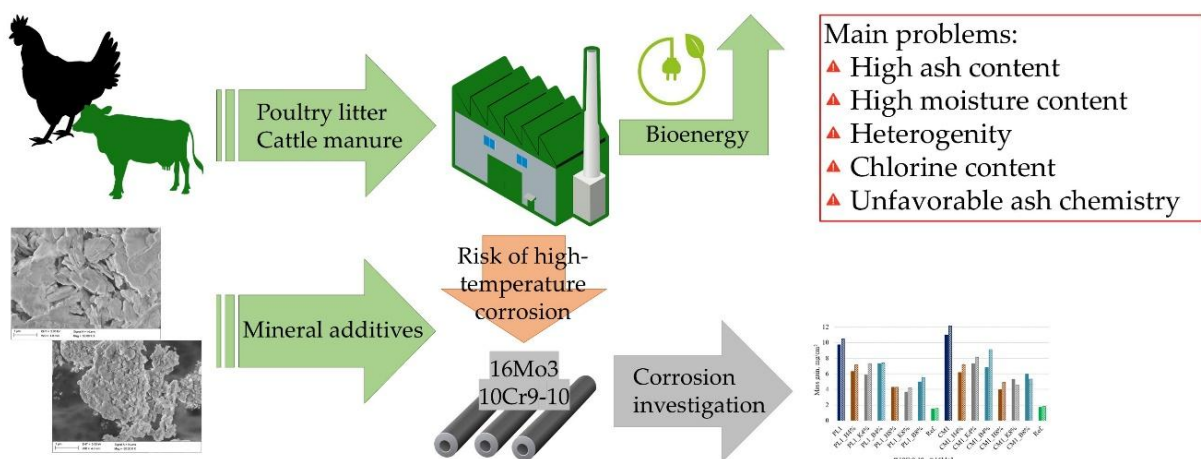


Figure 2. A schematic overview of the research context presented in this paper.

In addition to fuel-related challenges, the research also outlines the potential mitigation strategy based on the application of mineral additives, which may alter ash composition and influence high-temperature behavior. Particular attention is given to corrosion-related phenomena, as indicated by the inclusion of boiler steel grades 16Mo3 and 10Cr9-10 and the mitigation strategy by the use of aluminosilicate mineral fuel additives.

In this context, the present study aims to investigate the relationships between fuel composition, ash characteristics, and high-temperature corrosion risk during the combustion of manure-derived fuels. The work hypothesizes that ash-induced corrosion, governed by the interaction of chlorine and alkali species, represents the primary operational barrier limiting the reliable thermal utilization of animal husbandry waste, and that its mitigation requires an integrated approach combining fuel selection, ash chemistry control and material considerations. The findings are intended to support the safe and efficient utilization of PL and CM in thermal conversion systems.

2. Characteristics of animal husbandry waste as a fuel

2.1. Fuel heterogeneity and composition

Animal-derived waste differ substantially from conventional woody or herbaceous biomass. The main difference is fuel heterogeneity and composition, as presented in Table 1. Poultry litter and cattle manure usually exhibit elevated ash content, significant nitrogen concentration, and strong compositional diversity.

Table 1. Proximate and ultimate analyses of poultry litter and cattle manure (d.b. - dry basis).

Parameter	Symbol	Unit	CM1	CM2	PL1	PL2	CM literature data [8,9]	PL literature data [8,9]
Moisture			6.8	8.7	5.5	6.6	2.6-75.7	7.34-38.8
Ash			15.8	48.9	19.1	62.1	11.62-31.16	9.31-30.10
Higher heating value	HHV ^{d.b.}	MJ/kg	16.24	7.71	16.93	11.79	13.41-17.91	12.22-17.22
Carbon	C ^{d.b.}	%	40.9	18.5	43.8	30.3	32.52 - 50.43	28.2 - 42.72
Hydrogen	H ^{d.b.}	%	4.46	2.2	4.74	3.85	3.85-5.69	3.91 - 5.64
Nitrogen	N ^{d.b.}	%	1.58	1.27	1.53	2.60	1.60 - 2.59	3.40 - 9.96
Sulfur	S ^{d.b.}	%	0.08	0.17	0.09	0.36	0.18 - 0.65	0.31 - 1.32

The results clearly illustrate the significant variability of animal husbandry waste as a fuel. Even within the same waste category, large differences in ash content and calorific value can be observed. For instance, the ash content in cattle manure varies from 19.1% for CM1 to as high as 62.1% for CM2. Such large variations directly affect the energetic performance of the fuel, as reflected in the corresponding decrease of the higher heating value from 16.24 MJ/kg to only 7.71 MJ/kg. A similar trend can be observed for poultry litter samples. While PL1 exhibits relatively favorable fuel properties with an ash content of 15.8% and HHV of 16.93 MJ/kg, PL2 contains nearly three times more ash (48.9%) and its calorific value drops to 11.79 MJ/kg. Similar trend is described in previous research [8,10], indicating the big variety of ash content and its negative influence on heating value for both poultry litter (Figure 3a) and cattle manure (Figure 3b). These differences suggest the influence of bedding material, feed composition and manure management practices on the resulting fuel properties.

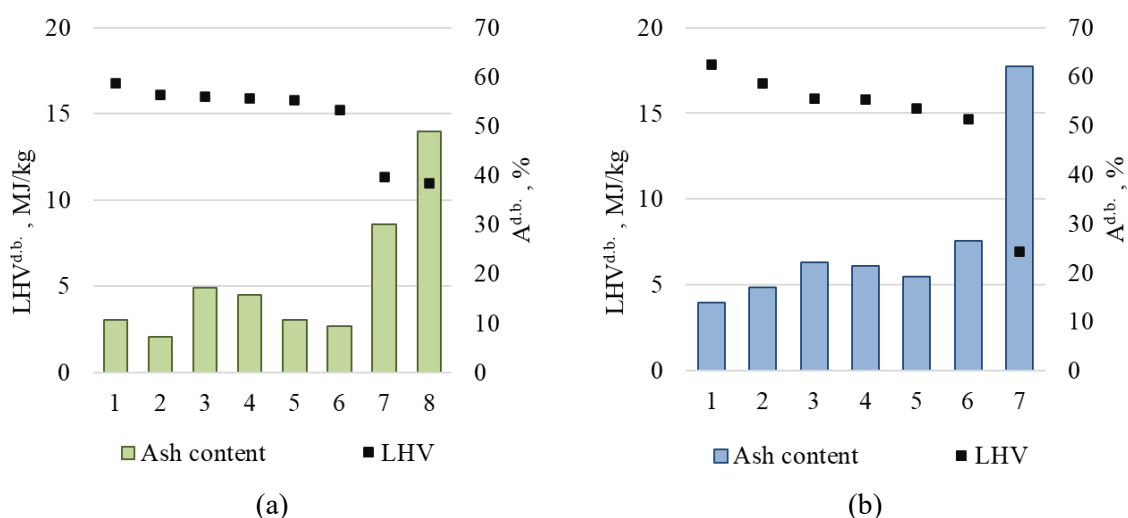


Figure 3. The correlation of lower heating values (LHV) and ash contents of (a) poultry litter samples and (b) cattle manure samples. Data based on [8,10].

The CM1-CM1 and PL1-PL2 samples investigated in this study were air-dried before further analysis, therefore the determined moisture contents are low (5.5-8.7%). However, the moisture contents of untreated animal waste is reported to be up to 75% for CM, with lower levels for PL, usually up to 38%.

The relatively high nitrogen content observed in poultry litter (up to 2.60% in investigated samples, up to 9.96% according to the literature data) is another important operational parameter. During thermal conversion, nitrogen compounds contribute to the formation of NO_x emissions, which requires advanced combustion control strategies or flue gas treatment systems.

The results confirm that manure-based waste should be considered highly heterogeneous fuels. This variability significantly complicates their large-scale energetic utilization and requires careful characterization before implementation in energy systems.

2.2. Ash-forming elements

The ash composition presented in Table 2 reveals several key features that determine the operational behavior of these fuels during combustion. First, the relatively high content of alkali metals, particularly potassium, can be observed in both poultry litter and cattle manure samples. Potassium oxide concentrations reach values above 10 wt% in some samples (e.g., CM1 and PL1) and can exceed 20% according to the literature data. Such elevated levels are known to promote the formation of low-melting alkali silicates and alkali chlorides [11].

Another critical parameter is chlorine. In samples CM1 and PL1 the chlorine content exceeds 6 wt%, which is extremely high compared to typical woody biomass. Chlorine plays a crucial role in high-temperature corrosion mechanisms by forming volatile metal chlorides and promoting active oxidation processes [12].

At the same time, some of the ashes can be characterized by high silica content (up to 77.7 wt% in CM2). Silica may interact with alkali metals forming alkali silicates, which can reduce ash melting temperatures and contribute to deposit formation and bed agglomeration [13].

Calcium and phosphorus are also present in considerable amounts, originating mainly from feed additives and manure composition. Ca and P may increase the fertilizing value of ashes [14,15] but their presence can also influence ash melting behavior and deposit formation.

Table 2. Proximate and ultimate analyses of poultry litter and cattle manure (d.b. - dry basis).

Component	CM1	CM2	PL1	PL2	CM literature data [8]	PL literature data [8]
Cl	6.84	0.48	6.38	0.42	0.65 - 7.56	0.90 - 5.67
SO ₃	0.91	0.70	1.37	1.30	0.88 - 4.45	0.82-9.68
K ₂ O	10.90	4.60	11.2	6.10	3.19 - 18.6	2.61-25.20
SiO ₂	62.70	77.70	59.20	65.90	18.3 - 75.60	3.66 - 57.11
Fe ₂ O ₃	2.27	1.20	2.60	1.90	1.06 - 1.52	0.92 - 7.42
Al ₂ O ₃	3.32	5.30	3.51	4.80	1.31 - 4.28	0.48 - 4.9
Mn ₃ O ₄	0.12	0.06	0.12	0.08	0.12 - 0.51	0.13-1.92
TiO ₂	0.19	0.17	0.25	0.26	0.09 - 0.24	0.04-0.63
CaO	6.18	2.70	6.53	5.30	2.11 - 30.60	13.5 - 34.07
MgO	1.45	1.00	2.20	1.70	1.56 - 8.14	2.15 - 7.45
P ₂ O ₅	3.30	1.50	5.02	5.20	4.09 - 17.50	7.81 - 23.74
Na ₂ O	0.68	1.23	0.68	0.80	0.73 - 3.57	1.68 - 6.80
BaO	0.03	0.04	0.03	0.03	0.02 - 0.05	0.02-0.17
SrO	0.02	0.01	0.02	0.01	0.02 - 0.04	0.02-0.39

The ash fusion temperatures, involving the shrinkage starting temperature (SST), deformation temperature (DT), hemisphere temperature (HT), and flow temperature (FT) is presented in Table 3. They indicate moderate to relatively high melting behavior of the investigated ashes: SST range from 1040°C for PL1 to 1240°C for CM2. Although these temperatures are relatively high compared to some woody and herbaceous biomasses [16], deposit formation can still occur at significantly lower temperatures due to the formation of low-melting eutectic compounds involving alkali metals and chlorine. Consequently, even though the measured ash fusion temperatures appear relatively high, local melting phenomena may still occur under real boiler conditions.

Table 3. Proximate and ultimate analyses of poultry litter and cattle manure (d.b. - dry basis).

Sample	SST	DT	HT	FT
PL1	1040	1170	1330	1370
PL2	1140	1240	1390	1490
CM1	1070	1100	1360	1410
CM2	1240	1290	1440	>1500

The observed ash behavior can be interpreted in terms of the interactions between major inorganic constituents, particularly calcium, alkali metals, chlorine, and phosphorus, which exert competing effects on ash melting and slagging propensity. A high contents of both SiO₂ and CaO together can have a stabilizing effect on ash thermal behavior: calcium promotes the formation of high-melting mineral phases with silicon or iron, such as calcium silicates [17], which increase the ash fusion temperatures. In calcium-rich ashes, Ca can also react with sulfur and chlorine, reducing the availability of alkali chlorides and thereby mitigating their detrimental impact on slagging and corrosion [18]. As a result, fuels with elevated SiO₂ and CaO content, such as PL and CM, tend to exhibit high thermal stability despite the presence of other problematic elements.

In contrast, elevated levels of alkali metals (K, Na) and chlorine have a destabilizing effect on ash behavior. These elements form low-melting compounds, particularly alkali chlorides (KCl, NaCl) and alkali silicates, which significantly reduce ash fusion temperatures [19]. Moreover, alkali chlorides play a key role in high-temperature corrosion through the so-called active oxidation (chlorine cycle), involving the formation and volatilization of metal chlorides and the subsequent breakdown of protective oxide layers on metallic surfaces. Consequently, fuels rich in K and Cl are typically associated with increased slagging, fouling, and corrosion risks.

The role of phosphorus is more complex and depends strongly on the overall ash composition. Phosphorus can contribute to both stabilization and destabilization mechanisms [20]. On one hand, it may form high-melting calcium phosphates, which enhance ash stability in Ca-rich systems and on the other hand, in the presence of alkali metals, phosphorus can participate in the formation of low-melting alkali phosphates or complex eutectic mixtures, thereby reducing ash fusion temperatures [21]. Therefore, its effect cannot be considered in isolation and must be evaluated in the context of the full inorganic matrix.

All these interactions demonstrate that ash behavior is governed not by individual components but by the synergistic effects between major oxides, which control the formation of mineral phases and ultimately determine corrosion tendencies. Therefore, the experimental corrosion research are vital to determine the corrosion risk in thermal conversion systems.

3. Experimental corrosion studies and mitigation strategies

High-temperature corrosion is primarily driven by alkali chlorides, causing the so called active oxidation and as a result, the breakdown of protective oxide scales formed on the metal surface [22–24]. The metal chlorides form beneath the oxide layer subsequently re-oxidize, leading to continuous scale degradation. This process significantly reduces component lifetime and increases maintenance frequency.

To assess material degradation in the presence of deposits of ash derived PL and CM, corrosion tests were performed under boiler-relevant conditions. The experimental setup presented in Figure 4 included a controlled temperature exposure of boiler alloy specimens 16Mo3 and 10CrMo9-10. The elemental compositions of investigated steel grades are presented in Table 4. These steel grades are commonly used for the manufacturing of heat exchangers in power boilers and thus have been selected for investigation.

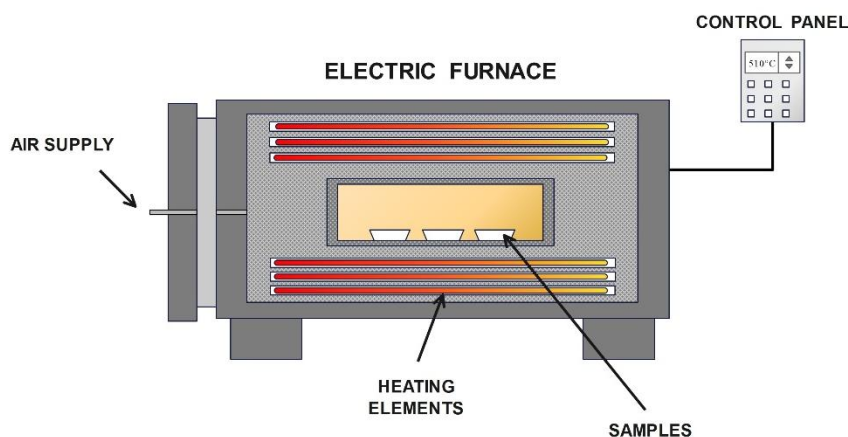


Figure 4. Schematic diagram of setup for corrosion investigation.

Table 4. Proximate and ultimate analyses of poultry litter and cattle manure (d.b. - dry basis).

Element	16Mo3	10CrMo9-10
C	0.12–0.20	0.08–0.14
Cr	<0.3	2.0–2.5
Ni	<0.3	-
Mn	0.4–0.9	0.4–0.8
Mo	0.25–0.35	0.9–1.1
Si	<0.35	<0.50
P	<0.025	<0.020
S	<0.010	<0.010
Cu	<0.3	<0.3
N	<0.012	-

The steel specimens were covered with PL1 and CM1 ash deposits with and without additives. The additives were investigated in two doses of 4 and 8%, as presented in Table 5. The additives selected for investigation: kaolin, halloysite, and bentonite are natural clay minerals, described in detail in [25] and characterized by high specific surface area, high porosity, high reactivity, safety of operation, and non-toxicity. They do not impact the combustion process negatively by reducing combustion efficiency or generating pollutants [26]. When used as fuel additives, they affect the ash chemistry by bonding potassium and sodium in compounds with high melting points, while chlorine is released as gaseous hydrogen chloride (HCl), less reactive than molecular Cl₂ [19]. The incorporation of additives into thermal conversion of fuels is proved to mitigate operational challenges such as ash deposition and bed agglomeration in fluidized bed systems, as well as reduce slagging and fouling on boiler heat exchange surfaces [27]. They are expected to mitigate the risk of high-temperature chlorine-induced corrosion by reducing the chlorine content in the ash deposits, and affecting the melting tendencies of ash.

Table 5. A matrix of corrosion experiments

Feedstock sample	Exposition temperature	Exposition time	Additive	Additive dose
			Pure (no additive)	
CM1	560 °C	168 h	Halloysite (H)	4%
PL1	510°C		Kaolin (K)	8%
			Bentonite (B)	

To determine the corrosion rates, the total mass gains of the samples after 168 hours of exposure at 560 °C were determined and presented in Błąd! Nie można odnaleźć źródła odwołania.. The mass increase of the reference samples (not covered with ash) does not exceed 2 mg/cm² while in the case of pure PL1 ash, mass gains of about 10 mg/cm² were recorded for both 16Mo3 and 10CrMo9-10. For pure CM1 ash, the mass increases are slightly higher, 10.98 and 12.15 mg/cm² for 16Mo3 and 10CrMo9-10, respectively. In the case of PL1 ash, the presence of halloysite, kaolin and bentonite at a dose of 4% reduces the final mass gain of 16Mo3 by 35% (halloysite), 39% (kaolin) and 25% (bentonite), respectively, and by 32% (halloysite), 30% (kaolin) and 29% (bentonite) for 10CrMo9-10. An increase in the dose of additives to 8% results in mass gains

reduced by 56% (halloysite), 62% (kaolin) and 49% (bentonite), respectively, for 16Mo3 steel and by 59% (halloysite), 60% (kaolin) and 47% (bentonite) for 10Cr9-10.

In the case of CM1 ash, the trend is similar. The addition of halloysite, kaolin and bentonite in a dose of 4% reduces the final mass gain of the samples by 44% (halloysite), 33% (kaolin) and 38% (bentonite), respectively, for 16Mo3 steel and by 41% (halloysite), 33% (kaolin) and 25% (bentonite) for 10CrMo9-10. An increase in the dose of additives to 8% causes a decrease in the weight gain of the samples by 64% (halloysite), 52% (kaolin) and 45% (bentonite), respectively, for 16Mo3 and by 59% (halloysite), 62% (kaolin) and 56% (bentonite) for 10CrMo9-10. In the case of a 4% dose, similar effectiveness of halloysite and kaolin can be observed, while bentonite differs from them, showing weaker effect, probably related to less effective dispersion of bentonite platelets in the ashes.

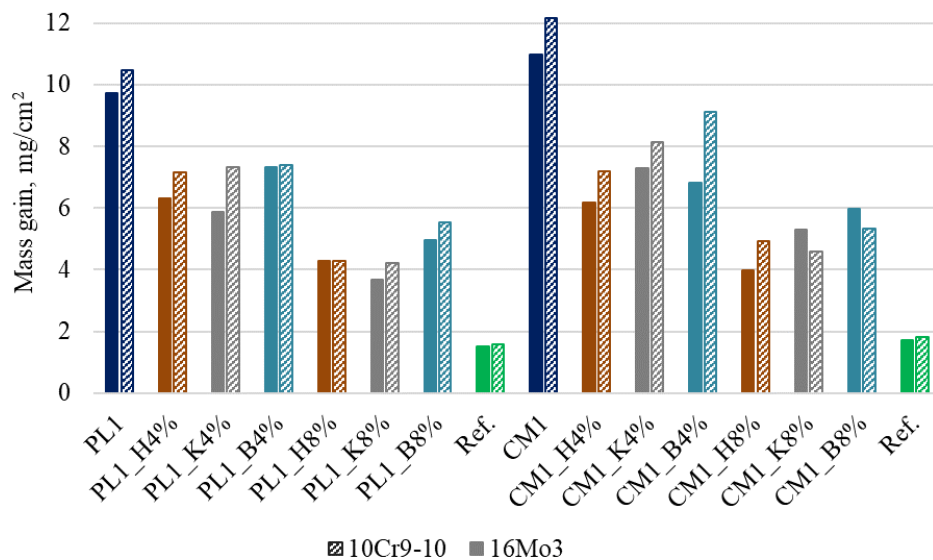


Figure 5. Total mass change of steel samples under ash deposits after exposition at 560 °C for 168 h.

A similar trend of weight gain reduction was noted after exposition at 510 °C, as shown in Figure 6. The weight gain of the reference samples does not exceed 1.5 mg/cm². In the case of pure PL1 ash, weight gain of about 3.11 mg/cm² was noted for 10Cr9-10 and 2.72 mg/cm² for 16Mo3. For pure CM1 ash, the weight gains are similar, 3.32 and 2.74 mg/cm² for 10Cr9-10 and 16Mo3, respectively. In the case of PL1 ash, the additives reduced the mass gain of samples by 49% (halloysite), 56% (kaolin) and 44% (bentonite) for 10Cr9-10 and by 46% (halloysite), 37% (kaolin) and 31% (bentonite) for 16Mo3. In the case of CM1 ash, the trend is similar. The addition of halloysite, kaolin and bentonite reduced the mass gain of samples by 61% (halloysite), 53% (kaolin) and 35% (bentonite) for 10Cr9-10 steel and by 45% (halloysite), 54% (kaolin) and 31% (bentonite) for 16Mo3.

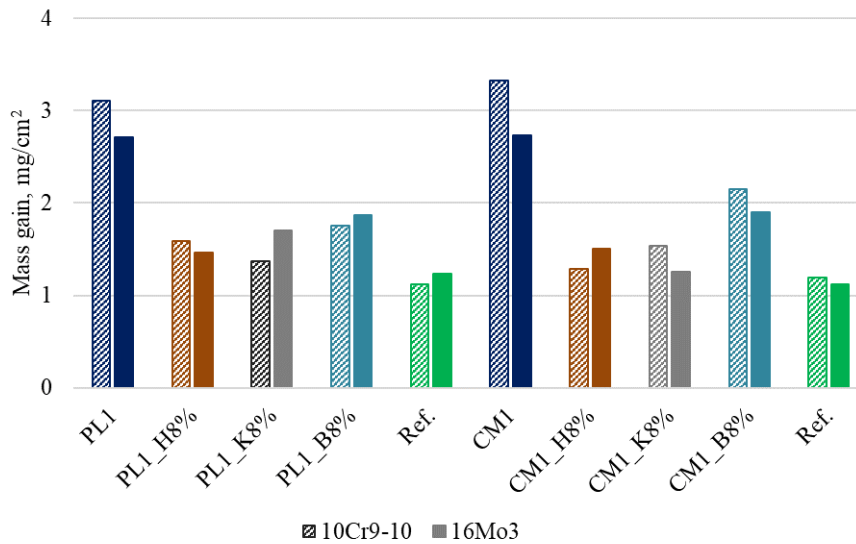


Figure 6. Total mass change of steel samples under ash deposits after exposition at 510 °C for 168 h.

Surface morphologies of 10CrMo9-10 after exposure at 560 °C are presented in Figure 7. The reference sample (Figure 7a) exhibits a relatively compact surface with limited oxide growth, indicating stable behavior in the absence of ash deposits. In contrast, exposure under unmodified PL ash (Figure 7b) leads to extensive surface degradation, characterized by thick, fragile corrosion products and large areas of disrupted oxide layers. This severe surface damage reflects the highly aggressive nature of untreated PL ash and highlights corrosion as a major operational constraint during PL combustion.

The addition of aluminosilicate minerals significantly modifies the surface morphology. Samples exposed under PL ash modified with kaolin (Figure 7c) and halloysite (Figure 7d) show less surface damage and more homogeneous corrosion layers compared to the pure PL ash. The corrosion products are thinner and not fragile. Bentonite addition (Figure 7e) also reduces the extent of surface degradation, although localized irregularities are visible.

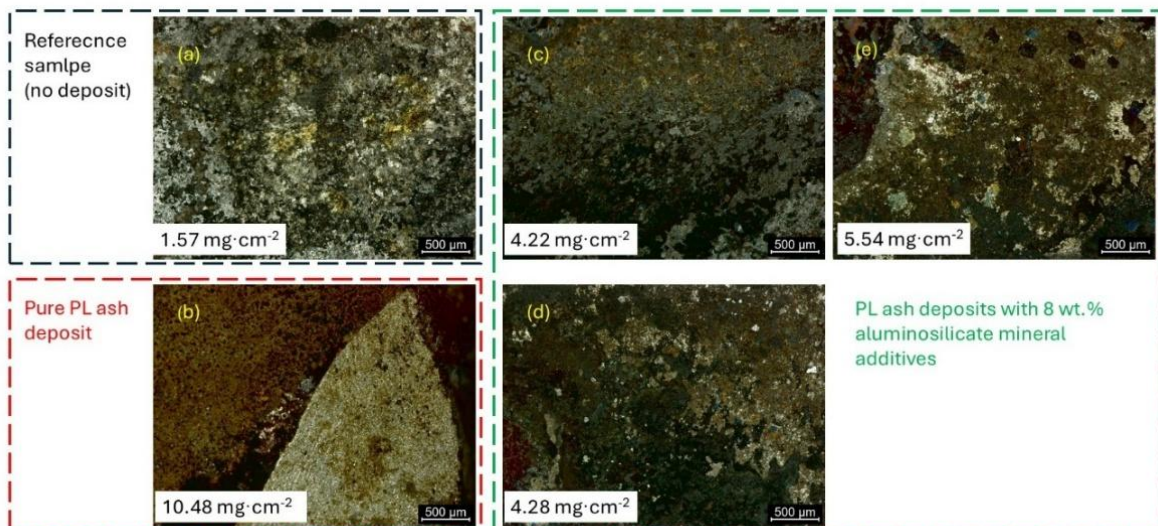


Figure 7. Surface morphologies of 10CrMo9-10 steel after exposure at 560 °C under different deposit conditions: (a) reference sample without deposit, (b) pure PL1 ash deposit, (c) PL1 ash with kaolin addition, (d) PL1 ash with halloysite addition, and (e) PL1 ash with bentonite addition. The corresponding total mass gains are indicated for each sample.

4. Ash utilization and regulatory constraints

The PL and CM ashes are rich in nutrients, particularly phosphorus and calcium, suggesting potential use in agriculture. However, the possible limitations arise due to elevated concentrations of trace metals and their potential leaching behavior.

The trace metal concentrations presented in Table 6 indicate that both PL and CM ashes contain several heavy metals, including Zn, Cu, Cr and Pb. Among the analyzed elements, Zn exhibits the highest concentrations, reaching up to 3400 mg/kg in poultry litter ashes. Cu concentrations also remain relatively high, reflecting the widespread use of Cu-containing feed additives in poultry production. Although the concentrations of highly toxic elements such as mercury remain very low, the overall metal content may still represent a regulatory challenge for agricultural utilization of the ashes.

Table 6. Trace metals concentration in poultry litter and cattle manure [10].

Element	Unit	CM literature data	PL literature data
Zn	mg/kg	493-938	846-3400
Hg	mg/kg	<0.05	<0.05
Cu	mg/kg	35-138	109-612
Cr	mg/kg	22-178	24-73
As	mg/kg	1.38-8.86	<1.0-9.99
Cd	mg/kg	2.23-4.35	<0.05-2.93
Ni	mg/kg	14.1-22.6	16.0-99.0
Pb	mg/kg	16.40-40.00	2.37-49.30

The variability observed between the analyzed samples further highlights the heterogeneous nature of animal waste-derived ashes. Consequently, careful monitoring of metal concentrations is necessary before considering ash recycling pathways.

5. Conclusions

Present study provides a comprehensive assessment of the poultry litter and cattle manure as sustainable fuels, with particular emphasis on fuel characteristics, ash-related phenomena, and high-temperature corrosion risk. Based on the obtained results, the following conclusions can be drawn:

- (1) The analyzed fuels are characterized by high ash content and elevated concentrations of nitrogen and chlorine, which significantly influence both combustion performance and environmental impact.
- (2) Despite relatively high ash fusion temperatures indicating a low slagging propensity, both fuels exhibit a high risk of ash-induced corrosion.
- (3) The dominant mechanism governing material degradation is chlorine-induced active oxidation, driven by the presence of alkali metals and chlorine, leading to the breakdown of protective oxide layers.
- (4) The results clearly demonstrate that chlorine-induced high-temperature corrosion, rather than general ash melting, constitutes the primary operational barrier to the reliable thermal utilization of animal husbandry waste.
- (5) The safe and efficient use of these fuels requires an integrated approach, including fuel pre-treatment, control of ash chemistry, and appropriate selection of corrosion-resistant materials.
- (6) From a system perspective, the identified limitations directly affect the operational window and long-term reliability of combustion units, and must be considered in the design and optimization of waste-to-energy systems.

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