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Prediction of slagging potential of sewage sludge ash using Fu and AFI indices

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Abstract

The co-combustion of sewage sludge with coal offers environmental and operational benefits, but also presents significant challenges related to the slagging and fouling of heat exchanger surfaces. This study presents a comprehensive physicochemical characterisation of sewage sludge ash, focusing on chemical composition and ash fusion behaviour under oxidizing and semi-reducing conditions. Two empirical indices — the Fouling Index (Fu) and the Ash Fusibility Index (AFI) — were applied to assess slagging and fouling risks. The results indicate that Fu may underestimate slagging tendencies due to its omission of phosphorus pentoxide (P_2O_5), which plays a critical role in lowering ash fusion temperatures. In contrast, AFI, based on direct measurement of ash behaviour, provides a more helpful assessment of operational risks. The study highlights the necessity of using fusion-based indices for accurate evaluation of alternative fuels like sewage sludge.

1. INTRODUCTION

One of the key challenges associated with the treatment of industrial and municipal wastewater is the generation of waste in the form of sewage sludge, which, due to its physicochemical properties, requires appropriate and safe management [Kacprzak et al. 2017], [Vambol et al. 2022]. In 2023, approximately 950,000 Mg of dry matter (d.m.) of sludge was produced in Poland from industrial and municipal wastewater treatment plants, with municipal sludge accounting for 58% of the total mass [Statistics Poland (GUS) 2024]. Among the wide range of available sludge-management methods — such as agricultural application or land reclamation — thermal treatment plays a significant role as an effective method of waste neutralization [Płonka et al. 2025], [Salva et al. 2025].

Energy recovery from sewage sludge, both through mono-incineration and co-incineration with fossil fuels, constitutes an important tool for implementing environmental policy in the context of the ongoing energy transition. In light of current EU regulations (including the RED III Directive [Directive (EU) 2023/2413], the "Fit for 55" package [European Commission 2021], and the EU Taxonomy [Regulation (EU) 2020/852], increasing the share of alternative fuels and reducing greenhouse gas emissions from the heating and energy sectors have become strategic priorities. In Poland, the potential for the agricultural and land-reclamation use of sewage sludge is expected to be progressively more limited, making energy recovery an increasingly important pathway for sustainable sludge management. It is worth noting that in Switzerland, the agricultural use of sewage sludge has already been prohibited [Swiss Federal Council 2003], and similar regulations are likely to be introduced in other European countries in the near future.

As part of its research and development activities, the Institute of Energy and Fuel Processing Technology (ITPE) also conducts work focused on optimizing thermal treatment processes, including analysis of how the mineral composition of sludge affects the operational parameters of energy systems. For example, the Institute conducted Poland's first pilot-scale co-firing trial involving sewage sludge and hard coal in an OP-230 pulverized fuel boiler [Stelmach, Wasielewski 2008].

The thermal treatment of municipal sewage sludge in Poland is currently carried out in 11 dedicated incineration facilities, seven of which use fluidized bed combustion technology, while the remaining four operate with mechanical grate combustion [Ministry of Climate and Environment 2022], [Ostojski, Swinarski 2018], [Wojciechowska 2024]. They have a combined maximum processing capacity for approximately 160,000 Mg/year of dry matter, although actual throughput depends on the operational status of each facility. Under conditions of full operational capacity, these systems allow for the thermal conversion of only about 25% of the total municipal sewage sludge generated in the country. In 2023, just 89,800 Mg d.m. of municipal sludge was treated thermally, representing only 16% of the amount produced. In the same year, approximately 139,000 Mg d.m. of industrial sewage sludge underwent thermal treatment, accounting for 35% of the total industrial sludge generated [Statistics Poland (GUS) 2024].

Although a portion of sewage sludge produced in Poland is thermally treated, considerable volumes remain to be managed or safely neutralized. The construction of new, dedicated thermal treatment facilities is, unfortunately, highly capital-intensive, though it is likely unavoidable in the long term. A faster-to-implement and more cost-effective solution may be the co-incineration of sewage sludge with fossil fuels in existing power boilers. This approach offers several potential advantages, including a reduction in the volume of sludge sent to landfills, partial substitution of fossil fuels with waste-derived material, and improved energy balance in wastewater treatment plants. Co-incineration may also contribute to the overall reduction in greenhouse gas emissions, especially when the sludge is classified as waste biomass, the combustion of which is considered carbon-neutral under EU sustainability criteria [Directive (EU) 2023/2413]. Utilizing existing boiler infrastructure also reduces capital investment and shortens the implementation timeline for new technologies.

The co-combustion of sewage sludge in energy installations, apart from meeting environmental and process requirements, presents numerous operational challenges. Among the most critical are the risks of slagging on boiler heating surfaces and changes in ash characteristics, which in some cases may affect the usability of the ash as a commercial product. Due to the significantly higher mineral fraction in sewage sludge compared to fossil fuels, the contribution of sludge-derived ash can strongly influence the overall ash composition in coal-sludge fuel mixtures as well [Pająk 2007], [Pronobis 2005].

During the combustion of fuels, including sewage sludge, various physicochemical processes lead to the formation of ashes with differing chemical compositions, thermal resistance levels, and propensities for slagging and deposit (encrustation) formation on the heat-exchange surfaces of power boilers [Werther, Ogada 1999]. These phenomena can result in various operational issues, such as impaired heat-transfer efficiency [van Beek 2001], [Shi et al. 2021]. In fluidized bed boilers, there is an additional risk of bed agglomeration, which may significantly disrupt the fluidization process and lead to system malfunction [Urciuolo et al. 2012], [Hartman et al. 2005]. Grate-fired and pulverized fuel boilers, on the other hand, are primarily affected by excessive slagging and fouling, which can lead to increased pressure drop, reduced heat exchange efficiency, and accelerated wear of boiler components [Åmand et al. 2006], [Nielsen et al. 2000]. Key chemical components influencing mineral behaviour during combustion include alkali and alkaline-earth metals (Na, K, Ca) and non-metals (Cl, S, P). Under high-temperature conditions, especially in pulverized fuel boilers, alkali metals (particularly Na and K) volatilize and react with flue gas components to form low-melting compounds that deposit on heat-exchanger surfaces [Nielsen et al. 1999], [Mlonka-Mędrala et al. 2020]. Although this mechanism differs in fluidized bed boilers, the fouling effects that result can be similar. The presence of ash-forming elements — particularly potassium (K) and sodium (Na) — is known to promote high-temperature corrosion, further compromising the integrity and longevity of boiler surfaces [He et al. 2016], [Maj et al. 2021], [Maj, Pronobis et al. 2022]. The type and severity of deposit formation largely depend on the S/Cl ratio in the fuel, since chlorine and sulphates accelerate high-temperature corrosion [Sharp 2010], [Hardy et al. 2019], [Nielsen et al. 2000].

Alkalis further enhance the formation of deposits and corrosion of heat transfer surfaces. Deposits reduce heat transfer efficiency, and the associated corrosion can cause superheater damage and unscheduled outages. Particularly problematic are alkali metal salts in fly ash, which lower the ash melting point and increase viscosity, intensifying any fouling phenomena. Rapid corrosion is often associated with the presence of molten phases on tube surfaces, while intense slagging presents a risk of waterwall damage [Maj, Pronobis et al. 2022], [Bryers 1996].

To evaluate the slagging and fouling tendency of fuels, various empirical indices have been used in both scientific literature and engineering practice. These indicators are typically based on the proportions of basic and acidic oxides in the ash, or on the ash fusion temperatures. The most frequently used are the Fouling Index (Fu) and the Ash Fusibility Index (AFI) [Dunnu et al. 2010], [Garcia-Maraver et al. 2017], [Maj et al. 2021], [Maj et al. 2022], [McLennan et al. 2000], [Lachman et al. 2021].

The Fu index is based on the base-to-acid ratio ($R_{B/A}$) of the ash and its sodium and potassium oxide content — the primary agents promoting surface contamination [Pronobis 2005]:

$$Fu = R_{B/A} \cdot (K_2O + Na_2O) = \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{SiO_2 + TiO_2 + Al_2O_3} \cdot (K_2O + Na_2O) \quad (1)$$

According to its value, fouling potential can be assessed in four ranges: $Fu \le 0.6$ = low risk, $0.6 < Fu \le 1.6$ = medium risk, $1.6 < Fu \le 40$ = high risk, and $Fu > 40$ = very high risk, with potential for deposit sintering [Pronobis 2005].

This method is particularly applicable to biomass fuels, which often have high alkali content that contributes to fouling. However, a key limitation of the Fu index is that it does not account for the presence of phosphorus pentoxide (P_2O_5). In phosphorus-rich fuels such as sewage sludge, omitting P_2O_5 may lead to an underestimation of actual slagging and fouling risks. Although it is classified as an acidic oxide, P_2O_5 has a pronounced impact on the formation of molten phases and their interaction with alkalis, facilitating deposit formation and sintering [Beck et al. 2005], [Wang et al. 2012].

An alternative to composition-based indices like Fu is the Ash Fusibility Index (AFI), which is more directly related to the actual behaviour of ash at high temperatures. AFI is calculated using ash fusion temperatures measured under oxidizing or reducing conditions in accordance with fuel testing standards. One widely used formula was developed by Gray and Moore [1974]:

$$AFI = \frac{4 \cdot IDT + HT}{5} \tag{2}$$

where: IDT (Initial Deformation Temperature) = temperature at which the ash cone begins to deform (equivalent to softening temperature t_A), and HT (Hemispherical Temperature) = temperature at which the ash assumes a hemispherical shape (equivalent to melting temperature t_B).

Based on AFI values, slagging potential is categorized as follows [Gray and Moore 1974], [López et al. 2003]: AFI < 1149 °C = very high risk, 1149 °C ≤ AFI < 1232 °C = high risk, 1232 °C ≤ AFI < 1343 °C = medium risk, and AFI ≥ 1343 °C = low risk.

Unlike the Fu index, AFI reflects the actual behaviour of the ash sample under thermal stress, incorporating the effects of all ash components, including P_2O_5. This is especially important for sludge and other non-conventional fuels where phosphorus content is significant. AFI takes into account the impact of complex chemical and phase interactions occurring between ash components, which can lead to the formation of low-melting compounds and sintering phenomena [Zhang et al. 2013].

The aim of this study was to evaluate the applicability and reliability of empirical indices used to predict slagging and fouling tendencies of sewage sludge ash, with a particular focus on the limitations of the Fouling Index (Fu) and the advantages of the Ash Fusibility Index (AFI). The analysis was based on detailed physicochemical characterization of ash samples, including their chemical composition and fusion behaviour under oxidizing and semi-reducing conditions, in order to assess their relevance to real co-combustion scenarios in coal-fired boilers.

2. MATERIALS AND METHODS

2.1. Sewage sludge

A total of 17 sewage sludge samples were analysed. They originated from various water and wastewater management facilities, including both municipal wastewater treatment plants and industrial sites. The samples differed in terms of sludge type and the degree of processing. The analysed set included municipal sewage sludge (raw, stabilized, and post-digestion) — classified under waste code 19 08 05 — as well as industrial sludge from the chemical, dairy, and food processing industries — classified under codes 19 08 14 and 02 05 02, respectively. The diversity of sample sources and classifications allows for a broader analysis of the chemical and physical properties of sludge in the context of its potential co-combustion with fossil fuels. For all analysed samples, measurements were performed to determine moisture and ash content, elemental composition (C, H, N, S) and calorific value. The chemical composition of the ash and its characteristic ash fusion temperatures were also determined.

2.2. Methodology of the study

The sewage sludge samples were subjected to the previously described analyses at the accredited laboratory complex of ITPE, in accordance with procedures approved by the Polish Centre for Accreditation. Total moisture content was determined by drying the samples in air to a constant weight at a temperature of 105 ± 3 °C. Ash content was measured at 815 ± 15 °C using a TGA 701 thermogravimetric analyser (LECO, USA). Total sulphur content was determined by high-temperature combustion with infrared detection using a CHNS 628 analyser (LECO, USA). The calorific value was calculated based on the combustion heat measured with an AC 500 calorimeter (LECO, USA).

To obtain ash samples, all sewage sludge samples were incinerated in a standard muffle furnace at 815 °C. The resulting ash was ground to a particle size below 0.063 mm using an RM 100 grinder (Retsch, Germany). In the prepared ash samples, the concentrations of silicon, aluminium, calcium, iron, magnesium, sodium, potassium, phosphorus, sulphur, manganese, titanium, barium, and strontium were determined and expressed as the respective oxides: SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, Na_2O, K_2O, P_2O_5, SO_3, Mn_3O_4, TiO_2, BaO, and SrO. The chemical composition of the ash was determined using inductively coupled plasma optical emission spectrometry (ICP-OES) with an iCAP 6500 Duo spectrometer (Thermo Scientific, USA). For the analysis, ash samples were fused with lithium tetraborate ($Li_2B_4O_7$) in a mass ratio of 2:10. The resulting fused samples were then dissolved in 3 mol/dm^3 hydrochloric acid, and the resulting solutions were subjected to analysis.

To determine the characteristic ash fusion temperatures of the sewage sludge ash samples, a PR-1750 device manufactured by the Institute of Tele- and Radiotechnics (Poland) was used. The measurements were carried out in both oxidizing (air) and semi-reducing atmospheres, the latter consisting of a mixture of carbon monoxide and carbon dioxide in a volumetric ratio of 3:2. Four characteristic temperatures were determined:

sintering temperature (t_S): the temperature at which partial melting begins at the contact points between ash grains, accompanied by shrinkage of the sample without a change in its original shape;

softening temperature (t_A): the temperature at which the first signs of softening appear, observable through

Table 1. Statistical characterisation of the basic properties of the studied sewage sludge samples

Parameter	Average value	Standard deviation	Median	Minimum value	Maximum value
Total moisture content (as received) [%]	45.1	31.9	41.2	3.7	86.6
LHV[1] (as received) [kJ/kg]	6,849	5,475	7,710	0.0[2]	15,215
Ash content (dry) [%]	35.0	9.8	32.8	20.7	57.7
Carbon content (dry) [%]	33.2	5.7	34.5	20.4	39.7
Hydrogen content (dry) [%]	4.5	0.7	4.5	3.0	5.5
Nitrogen content (dry) [%]	4.9	1.0	5.0	3.5	6.5
Sulphur content (dry) [%]	1.4	0.3	1.3	0.8	1.9

[1] LHV – Lower Heating Valuee

[2] A value of 0 was assumed, as the energy balance of sludge combustion is negative due to its high water content.

rounding of the edges or initial deformation of the contours;

melting temperature (t_B): the temperature at which the ash specimen melts into a shape approximately resembling a hemisphere, with its height equal to half the base diameter;

flow temperature (t_C): the temperature at which the ash flows to form a layer with a thickness equal to half the height of the hemisphere observed at t_B.

The analytical results served as the basis for evaluating the slagging and fouling behaviour of the ash samples, using both empirical indices and fusion temperature measurements.

3. RESULTS

The sewage sludge samples were comprehensively analysed to determine their basic physical and chemical characteristics, ash composition, and ash fusion behaviour. This section presents the key findings derived from these analyses, which provide the basis for further evaluation of slagging and fouling tendencies using empirical indices.

Table 1 shows the set of basic parameters in the studied sewage sludge.

Table 2 presents the ash composition of the samples.

Table 3 presents the ash fusion temperatures of the ash samples obtained from the analysed sewage sludge samples.

For these sewage sludge ash samples, both indices were calculated — with the AFI values determined for both oxidizing and semi-reducing atmospheres — in accordance with the determination of characteristic ash fusion temperatures. The calculation results are presented in Table 4.

The obtained results highlight significant variability in the physicochemical properties of sewage sludge ash, which has important implications for its behaviour during thermal conversion. These findings form the basis for a detailed discussion on slagging and fouling risks associated with sewage sludge co-combustion.

4. DISCUSSION

The results of the analyses presented in the previous chapter provide a comprehensive characterization of the physicochemical properties of sewage sludge and its combustion residues, with particular emphasis on ash composition and fusion behaviour. The considerable variability observed in key parameters, such as ash content on dry basis (ranging from 20.7% to 57.7%) and lower calorific value as received (from 0.0 to 15,215 kJ/kg), reflects the heterogeneous nature of the sludge generated across different treatment systems and industrial sectors. This heterogeneity highlights the need for individualized assessment of co-combustion feasibility depending on sludge origin and pre-treatment stage.

Ash analyses revealed a high content of SiO_2 (average 31.6%), CaO (average 14.0%), and P_2O_5 (average 17.7%), with significant contributions from Fe_2O_3 and Al_2O_3. These oxides play a critical role in influencing ash fusibility. Notably, elevated levels of phosphorus and calcium — common in sewage sludge ash — are known to reduce ash melting temperatures and increase the risk of slagging and fouling on heat-exchange surfaces. This observation is supported by the relatively low sintering temperatures that were recorded in both oxidizing and semi-reducing atmospheres (average 906.5 °C and 838.2 °C, respectively), which may approach but fall below typical furnace operating temperatures in coal-fired boilers.

It is worth emphasizing that the mineral composition of sewage sludge ash differs significantly from that of conventional fossil fuels. The dominant ash-forming components in hard coal are typically SiO_2, Al_2O_3, and

Table 2. Characteristics of ash composition in the tested sewage sludge samples

Sample No.	Parameter												
	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	CaO [%]	MgO [%]	P_2O_5 [%]	SO_3 [%]	Mn_3O_4 [%]	TiO_2 [%]	BaO [%]	SrO [%]	Na_2O [%]	K_2O [%]
1	25.90	11.49	8.64	18.99	1.57	16.19	4.20	0.12	1.02	2.09	0.13	0.98	1.64
2	25.29	11.87	9.55	17.19	2.05	20.64	1.94	0.12	0.84	2.59	0.14	1.04	1.66
3	31.73	12.35	7.93	17.36	5.24	19.68	1.64	0.16	0.90	0.16	0.08	0.94	2.50
4	29.24	8.37	5.16	11.64	5.07	21.81	1.33	0.11	0.92	0.11	0.06	1.07	5.20
5	29.98	7.00	16.87	16.40	2.54	19.78	2.45	0.16	0.90	0.09	0.07	0.85	1.86
6	30.80	10.02	14.89	8.34	4.34	5.38	24.15	0.55	0.18	0.71	0.04	0.81	0.09
7	32.29	17.13	7.07	15.70	2.72	1.54	17.59	2.86	0.23	0.67	0.09	0.69	0.12
8	48.93	5.87	5.12	9.34	3.96	4.07	17.49	0.96	0.26	0.47	0.07	0.80	0.09
9	6.23	4.29	26.83	17.60	1.97	30.70	2.88	0.14	0.26	0.09	0.06	3.58	5.89
10	26.12	8.55	19.58	13.36	2.60	20.49	3.06	0.18	0.95	0.14	0.05	1.05	1.85
11	25.52	6.00	26.98	11.82	2.77	21.70	1.65	0.11	1.28	0.06	0.05	1.36	2.90
12	21.50	8.18	13.76	20.55	4.26	26.72	2.14	0.19	0.86	0.21	0.06	1.08	2.41
13	36.13	3.28	16.98	8.67	6.10	22.60	1.47	0.17	0.37	0.05	0.05	0.65	1.25
14	44.09	5.58	11.35	11.26	3.06	19.14	1.17	0.16	0.55	0.07	0.05	0.97	2.08
15	39.54	8.50	10.77	12.04	2.63	13.31	3.55	0.35	0.70	0.06	0.03	0.94	2.14
16	37.03	6.53	11.70	15.17	2.93	19.12	2.10	0.15	1.00	0.11	0.05	0.81	1.78
17	46.08	5.48	12.88	12.86	2.89	17.65	1.11	0.14	0.59	0.07	0.06	1.05	1.60

Table 3. Characteristic ash fusion temperatures of the tested sewage sludge samples

Sample No.	Parameter							
	oxidizing atmosphere				semi-reducing atmosphere			
	sintering temperature (t_S) [°C]	softening temperature (t_A) [°C]	melting temperature (t_B) [°C]	flow temperature (t_C) [°C]	sintering temperature (t_S) [°C]	softening temperature (t_A) [°C]	melting temperature (t_B) [°C]	flow temperature (t_C) [°C]
1	960	1,080	1,300	1,320	900	1,170	1,280	1,300
2	910	1,110	1,220	1,250	850	1,090	1,200	1,300
3	950	1,090	1,200	1,210	890	1,070	1,160	1,180
4	930	1,050	1,200	1,300	900	1,130	1,220	1,310
5	910	1,130	1,260	1,270	870	1,030	1,140	1,180
6	920	1,040	1,180	1,230	900	1,080	1,160	1,220
7	920	1,180	1,220	1,240	870	1,180	1,220	1,240
8	940	1,160	1,290	1,410	890	1,230	1,360	1,450
9	700	1,120	1,240	1,300	670	1,030	1,080	1,220
10	920	1,080	1,230	1,260	820	1,030	1,080	1,110
11	900	1,090	1,260	1,310	850	1,050	1,120	1,190
12	890	1,030	1,240	1,270	810	1,030	1,150	1,200
13	910	1,300	1,390	1,450	740	1,080	1,290	1,380
14	930	1,220	1,310	1,390	880	1,170	1,310	1,400
15	880	1,160	1,240	1,250	730	1,030	1,150	1,180
16	930	1,150	1,250	1,270	860	1,050	1,180	1,230
17	910	1,160	1,320	1,370	820	1,050	1,280	1,390

Table 4. Evaluation of slagging and fouling tendencies of tested sewage sludge samples

Sample No.	Fu	risk	AFI (oxidizing)	risk	AFI (semi-reducing)	risk
1	2.17	high	1,124	very high	1,192	high
2	2.24	high	1,132	very high	1,112	very high
3	2.60	high	1,112	very high	1,088	very high
4	4.58	high	1,080	very high	1,148	very high
5	2.76	high	1,156	high	1,052	very high
6	0.62	medium	1,068	very high	1,096	very high
7	0.43	low	1,188	high	1,188	high
8	0.31	low	1,186	high	1,256	medium
9	49.08	very high	1,144	very high	1,040	very high
10	3.13	high	1,110	very high	1,040	very high
11	5.95	high	1,124	very high	1,064	very high
12	4.81	high	1,072	very high	1,054	very high
13	1.61	high	1,318	medium	1,122	very high
14	1.74	high	1,238	medium	1,198	high
15	1.80	high	1,176	high	1,054	very high
16	1.88	high	1,170	high	1,076	very high
17	1.59	high	1,192	high	1,096	very high

Fe_2O_3, and lignite ash is primarily composed of SiO_2, Al_2O_3, and CaO. Sewage sludge ash, on the other hand, is characterized by notably higher concentrations of P_2O_5, which is not typically present in fossil coal ash. This fundamental difference in ash chemistry is of particular importance in predicting and managing the behaviour of the ash during thermal conversion processes, especially with regard to its slagging potential.

Furthermore, the data indicate a clear atmospheric effect on ash fusion behaviour: in semi-reducing conditions, all characteristic temperatures (t_S, t_A, t_B, t_C) were consistently lower compared to those in oxidizing conditions. This is particularly important when considering the dynamic and locally reducing environments that may occur in industrial boilers, especially under partial combustion conditions or load variations.

These findings underscore the importance of careful thermal and chemical evaluation of sludge-derived ash before implementing large-scale co-incineration. While co-firing sewage sludge with coal offers environmental and economic benefits, including waste volume reduction and partial substitution of fossil fuels, the risk of operational issues such as slag formation and heat-exchanger fouling must be mitigated through proper fuel blending strategies and boiler system adjustments.

It is worth emphasizing that chemical reactions occurring between hot ash components are extremely complex and difficult to predict. The ultimate outcome in terms of melting temperature and deposit formation tendency depends on multiple interactions among oxides, their proportions, the presence of volatile elements, and specific combustion conditions. Therefore, despite its empirical simplicity, AFI may be a very helpful diagnostic tool for assessing ash behaviour under real boiler conditions, as it is based on experimental observations of component interactions at high temperatures.

Analysis of the Fu and AFI results for 17 sewage sludge ash samples, under both oxidizing and semi-reducing conditions, clearly indicates high or very high slagging and fouling potential in the vast majority of cases. It is important to note that the Fu index does not account for the presence of P_2O_5 in sewage sludge ash, even though phosphorus pentoxide significantly influences the formation of molten phases and their interactions with alkali metals. This limitation is particularly relevant in the case of sewage sludge, which, as chemical data show, often contains considerable amounts of P_2O_5, sometimes exceeding 30%. Consequently, for some samples (6-8), the Fu index suggests a low or medium risk, while AFI values clearly indicate a generally high slagging potential. This may imply that the Fu index underestimates the risk in samples with high phosphorus content. For most samples, both Fu and AFI indicate high or very high risk, confirming that in samples with significant content of Na_2O, K_2O, Fe_2O_3, and CaO, both indices can lead to consistent conclusions.

It should be emphasized that both Fu and AFI are empirical indicators, and cannot be regarded as direct substitutes for experimental data. Their application to waste- or biomass-derived fuels is characterized by considerably varying results, and this has also been demonstrated in the literature [Maj et al. 2021], [Maj et al. 2022], [Magdziarz et al. 2016]. In the present study, AFI values proved to be more consistent with the phosphorus content in sewage sludge ash — however, this does not imply that the index can be considered universally more reliable. A definitive assessment requires validation under laboratory and industrial conditions, which was beyond the scope of this study.

5. CONCLUSIONS

The results of this study confirm that sewage sludge ash exhibits substantial variability in both chemical composition and ash fusion behaviour, and this significantly influences its potential impact on the co-combustion process in coal-fired boilers. The average ash content, high concentrations of phosphorus pentoxide (P_2O_5), and relatively low sintering and melting temperatures clearly indicate an increased risk of slagging and fouling when such material is introduced into combustion systems. These findings underscore the importance of proper ash characterization prior to its implementation in co-combustion scenarios.

Among the evaluated empirical indices, the Ash Fusibility Index (AFI) proved to be a more helpful tool for predicting operational risks, as it is directly based on the actual melting behaviour of the ash under thermal load. In contrast, the Fouling Index (Fu), although widely used in biomass combustion diagnostics, appears to underestimate slagging and fouling risks in phosphorus-rich fuels due to its omission of P_2O_5, a compound with a well-documented influence on ash fusibility.

Furthermore, the study emphasizes the importance of accounting for reducing conditions in the combustion environment, which significantly lower ash fusion temperatures and may lead to enhanced deposit formation. The results obtained for semi-reducing atmospheres were, in most cases, even more indicative of slagging potential than those determined under oxidizing conditions.

In conclusion, when sewage sludge is considered as a co-fuel, particularly in coal-based power systems, a thorough evaluation of its ash behaviour is essential. It is worth using AFI supported by ash fusion temperature measurements and supplementing it with composition-based indices such as Fu, especially for sludge types with elevated phosphorus content. This approach enables more accurate risk prediction, contributing to the safe and efficient integration of sewage sludge as an alternative fuel into existing combustion infrastructures.

It should be underlined that the AFI and Fu indices, despite their usefulness, remain simplified tools and cannot replace direct experimental verification. Future studies should therefore include dedicated combustion tests to validate the predictive capability of these indices for sewage sludge and other phosphorus-rich fuels.

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