Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-14
DOI: *10.15244/pjoes/206955* ONLINE PUBLICATION DATE: 2025-09-23

Review

Synergistic Effects of Sewage Sludge-Coal Co-Combustion: A Path to Sustainable Waste Treatment

Feng Wang, Yu Niu, Yanlin Wang*, Yingying Xiong, Yuqi Wang, Zhiqian Wang, Linbin Li

School of Electric Power, Civil Engineering and Architecture, Shanxi University, Taiyuan, 030006, P.R. China

Received: 7 August 2024
Accepted: 10 June 2025

Abstract

The co-combustion of sewage sludge from coal-fired power plants with coal represents a promising technology for the reduction, stabilization, harmlessness, and resourceful treatment of solid waste sludge. This paper summarizes the co-combustion characteristics of sludge and coal from aspects such as the basic combustion process, influencing factors of combustion properties, slagging/fouling, etc. Sludge can improve coal's ignition and burnout performance, while coal reduces slagging/ash deposition risk during sludge combustion. The interactions between sludge and coal during co-combustion are analyzed, with the intensity and manifestation of these interactions (synergistic or inhibitory) depending on factors such as the physicochemical properties of the fuels, mixing ratios, and combustion conditions. Additionally, the emission characteristics and control technologies for both conventional pollutants (nitrogen oxides, sulfur dioxide, and heavy metals) and unconventional pollutants (dioxins) during co-combustion are introduced. This mainly introduces the impact of combustion technology on nitrogen oxide emissions, as well as the role of mineral types and their interactions in the emissions of sulfur dioxide, heavy metals, and dioxins.

Keywords: sludge, waste disposal, coal, co-combustion, conventional pollutants, dioxins

Introduction

Sewage sludge (SS) is a byproduct of wastewater treatment that has both the utility as a resource and the risk of environmental pollution [1, 2]. As the global urbanization rate continues to accelerate, the amount of sludge disposal is on an upward trend. Currently, over 4000 sewage treatment plants have been constructed in China, resulting in an annual production of more than 50 million tons of sludge with an 80% moisture content. This figure is expected to grow at a rate of approximately 10% each year [3]. Sludge contains a significant quantity of organic pollutants, pathogens, heavy metals, and harmful substances. If not handled properly, it poses a severe threat to the ecological environment and public health [4, 5].

As the public's environmental consciousness grows, the proper disposal of sludge is increasingly being acknowledged, and China's regulations on

*e-mail: wangyanlin@sxu.edu.cn

sludge management are becoming more stringent. In 2017, the “Thirteenth Five-Year Plan” for national urban wastewater treatment and recycling facilities specifically suggested altering the wastewater treatment policy from “focusing on water and marginalizing sludge” to “focusing on sludge and water equally”. The revised version of the Law of the People’s Republic of China on the Prevention and Control of Environmental Pollution by Solid Wastes, which took effect in 2020, imposed stricter regulations, including a prohibition on unauthorized sludge dumping and a prohibition on using sludge with excessive heavy metals in agriculture. In September 2022, the “Implementation Plan for the Harmless Treatment and Resource Utilization of Sludge” was issued, setting a new requirement that the percentage of harmless sludge disposal in cities must reach more than 90% by 2025 and more than 95% in cities at the prefecture level and above.

China’s most common sludge disposal technology is shown in Fig. 1. Landfill treatment is still the most important sludge disposal method [6, 7] in China today due to its ease of operation and large treatment capacity; however, because landfill is typically preceded by only adding an appropriate amount of lime for stabilization, and most toxic components are not properly disposed of, it is prone to secondary pollution. Because of the organic matter, nitrogen, phosphorus, potassium, and trace elements contained in the sludge, land use of sludge is also a commonly used method of disposal [8]. The defects are similar to landfills in that the soil is susceptible to contamination by heavy metals and other toxic substances. These two methods of disposal are currently being restricted. With the advancement of technology and the concept of progress, the resource qualities of sludge have steadily gained attention, with incineration, pyrolysis, gasification, and anaerobic digestion being the most regularly employed sludge resourcing methods in China [9, 10]. Anaerobic digestion is the process of decomposing organic matter into biogas in an anaerobic or anoxic environment. Despite becoming more mature, the technique has not been widely pushed due to high investment and complex operations. Pyrolysis and gasification can reduce sludge volume, destroy pathogenic bacteria, stabilize sludge, and produce pyrolysis gas and pyrolysis oil for use as fuels; however, this technology still faces significant challenges in terms of fuel characteristics, equipment design, and operating conditions.

Incineration is a complete sludge treatment that maximizes sludge reduction and has seen an increase in the proportion of sludge treatment in recent years [11]. However, most Chinese cities have a severe shortage of incinerators due to technical reasons such as high capital investment costs, high energy consumption, high equipment maintenance costs, and so on, as well as social reasons such as resident opposition and limited policy support [12]. Compared to incinerators, large coal-fired power plants, and pulverized coal boilers, circulating fluidized bed boiler development is more mature, and while equipped with a complete flue gas purification system, it can effectively alleviate the fuel combustion process caused by SO_2, NO_x, dust, and other pollution problems. It will be an alternative to incinerator sludge incineration not only to achieve harmless disposal of sludge but also to be used for power generation. When sludge and coal are burned separately, they share many similarities. For instance, both generate acidic substances such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), as well as particulate matter (PM). If their waste products are not properly disposed of, they can contaminate the environment. When burned alone, coal is more inclined to produce acidic gases and other solid waste in large quantities, but the pollutants from coal combustion are stable and controllable. In contrast, sludge burned alone is more prone to generating highly carcinogenic substances such as heavy metals and dioxins, and sludge pollution is more complex and difficult to treat. Sludge incineration alone has significant environmental, energy, and economic impacts. In environmental terms, it generates 474.4 kg $CO_{2\text{-eq}}$/FU of greenhouse gases, mainly from the incineration of organic matter and the use of natural gas [13]. Eutrophication risks increase with high ammonia nitrogen and phosphorus emissions in wastewater after wet desulphurization. Heavy metals such as mercury are released directly, increasing water pollution.

When combined with coal, sludge can effectively address the drawbacks of single-fuel combustion. This method is commonly used in power station boilers and only requires the establishment of a fuel mixing and delivery system [14]. The benefits of the study gradually draw more attention from researchers due to the sludge’s high water content, low calorific value, and high alkali (earth) metal content and surpass when combustion occurs alone; it can easily lead to combustion instability, slagging, and other issues.

The VOSviewer tool was employed to visualize the research trends, as depicted in Fig. 2. By searching for keywords such as ‘‘sewage sludge’’, ‘‘co-combustion’’, and ‘‘coal’’ in the ‘‘Web of Science’’ database, there has been a steady increase in research publications over the past few decades. The selection of 132 papers from 1990 to the present, with a co-occurrence frequency threshold of 5 or more instances, further indicates the significance and popularity of this research topic. By combining sludge with coal for co-combustion, we can harness the potential of sludge as a valuable resource while simultaneously achieving significant environmental and economic benefits.

Sludge blending technology in power plants is emerging as a new trend in municipal sludge treatment. China Energy Shenwan Chizhou Power Generation Co., Ltd. has blended more than 25,000 tons of municipal sludge into coal-fired boilers for combustion, successfully realizing sludge treatment reduction, harmlessness, and resourcefulness as of February 15, 2022 [15]. Currently, there is a dearth of systematic debate on the characteristics of co-combustion of sludge

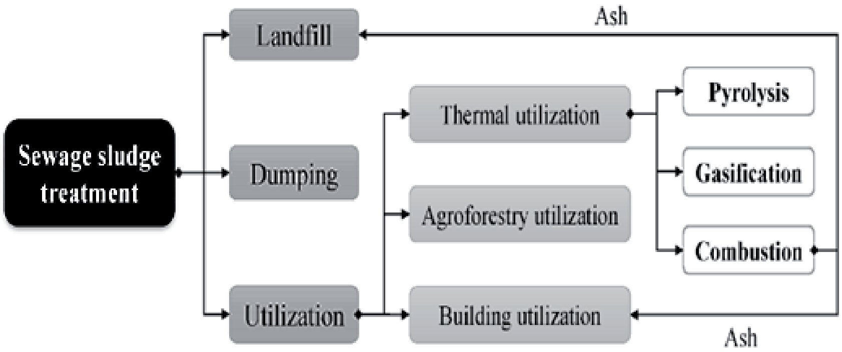


Fig. 1. Sludge disposal technologies.

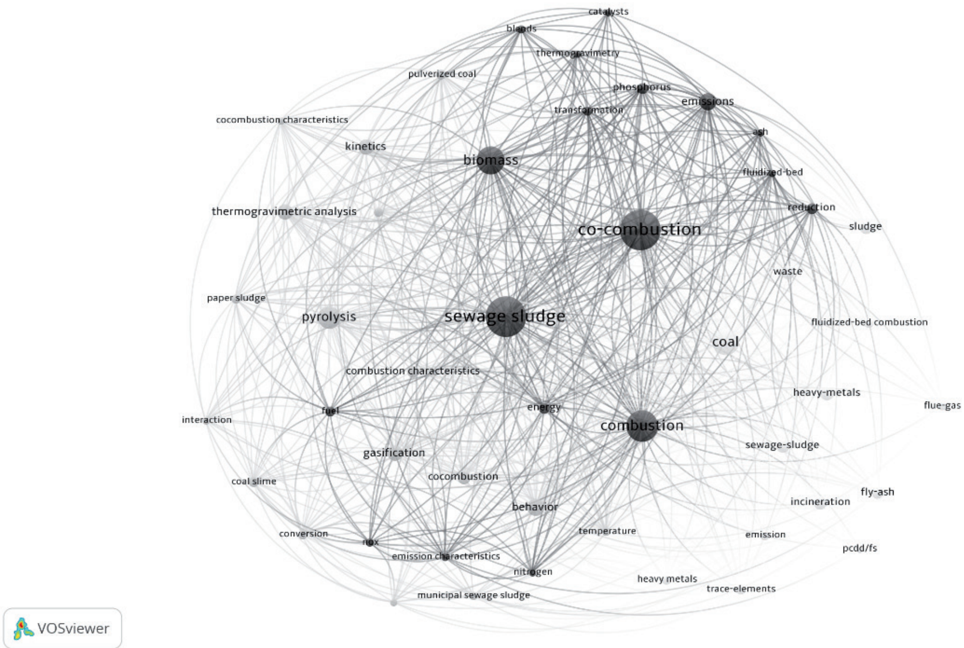


Fig. 2. Hot spots in sludge-coal combustion research.

and coal, pollutant emissions, and control, even though many academics have undertaken extensive research on the subject.

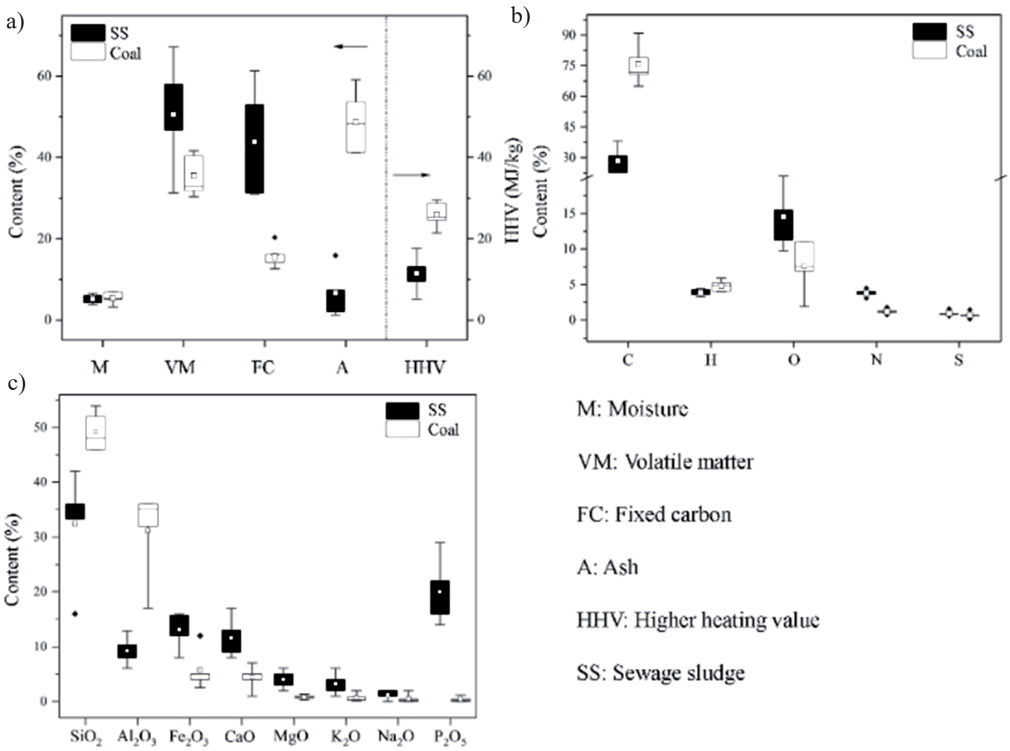
Based on a comparison of the differences in the physicochemical properties of sludge and coal, this paper summarizes the factors influencing the combustion characteristics during their co-combustion. It analyzes the interactions and interaction mechanisms during the co-combustion process. Furthermore, the emissions of conventional pollutants (NO_x, SO_2, and heavy metals) and non-conventional pollutants (dioxins) during the co-combustion of sludge and coal were explored, and appropriate abatement methods in the co-combustion process were presented. This study aims to advance our understanding of sludge-coal co-combustion technology and serve as a reference for its application in coal-fired power plants.

Materials and Methods

Fundamental Fuel Properties of Sludge and Coal

The nature of the fuel is crucial for its suitability in the combustion process of power plant boilers. Fig. 3 summarizes the industrial analysis, elemental analysis, and inorganic component analysis of dried sludge and coal [16-20].

Fig. 3a) shows that sludge has a greater volatile matter content, with an average value of approximately 50%. This property causes the fuel to be highly reactive in the low-temperature zone, allowing for a lower ignition temperature. Sludge's ash content is comparable to its volatile matter content, which is substantially higher than coal. High ash content impairs the stability of the combustion process, increasing the danger of slagging and fouling. In addition, the fixed carbon content in coal slurry differs significantly from that of coal.



a. proximate analysis; b. Elemental analysis; c. Inorganic component content in ash

Fig. 3. Basic properties of sludge and coal fuel.

Most sludge has a fixed carbon concentration of less than 10%, indicating a lesser degree of carbonization, whereas coal ranges between 40% and 60% because of its various ranks. The sludge that has undergone high-temperature carbonization can increase its carbon content and enhance its calorific value [21]. The calorific values of the sludge from sewage tanks, septic tanks, and open defecation are 10.9649±0.2259 MJ/kg, 11.9370±0.5439 MJ/kg, and 9.6176±0.4142 MJ/kg, respectively [22]. The calorific value of coal is between 20 and 30 MJ/kg, which is higher than that of sludge (5-18 MJ/kg).

Carbon, hydrogen, and oxygen are the three fundamental elements considered in fuel. N and S are linked to acidic pollutants like NO_x and SO_x produced during combustion. Fig. 3b) depicts the elemental analysis of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) in sludge and coal. The main organic constituents in sludge and coal are C and O, with a large variation in carbon content; coal has up to 90% more carbon. Furthermore, the nitrogen level in sludge is much larger than that of coal, primarily obtained from protein nitrogen in sludge, while the disparities in H and S content between sludge and coal are not significant. C is one of the most essential elements in the fuel's molecular skeleton, predominantly found on condensed aromatic nuclei with a small quantity on aliphatic side chains, and serves as the primary source of heat release. H is mostly present on molecule side chains and functional groups, exhibiting high reactivity; O is found in oxygen-containing functional groups of fuels. The H/C ratio of sludge ranges from 0.12 to 0.16, and the O/C ratio ranges from 0.36 to 0.55, which are greater than the H/C ratio (0.06-0.07) and O/C ratio (0.02-0.15) of coal, meaning that sludge has lower aromaticity and condensation degree than coal, resulting in higher activity.

Fuel ash's inorganic components have a direct impact on slagging and ash deposition during combustion. Fig. 3c) depicts the common inorganic component contents in sludge and coal ash. The predominant inorganic components in coal ash are inert silica-alumina, followed by Fe_2O_3 and CaO, with minor MgO, K_2O, and Na_2O. SiO_2 and Al_2O_3 concentrations in sludge ash are approximately 35% and 10%, respectively, lower than those in coal. In contrast, alkaline oxides such as Fe_2O_3, CaO, MgO, K_2O, and Na_2O are significantly higher in sludge than in coal, with Fe_2O_3 introduced due to the use of Fe coagulants in wastewater treatment. During combustion, SiO_2 tends to react with alkaline oxides to generate low-temperature eutectics that lower the ash melting point and lead to slagging problems, while a large number of low-boiling alkali metal oxides also increase the risk of ash accumulation [23]. Furthermore, sludge ash can contain up to 20% P_2O_5, which is significantly greater than coal. Phosphorus is an important nonrenewable resource, and recent research has focused on phosphorus recovery from sludge.

Sludge and Coal Co-Combustion Characteristics

The Fundamental Combustion Process

The co-combustion of sludge and coal is comparable to that of solid fuels. First, there is an initial drying phase. When the fuel reaches a specific temperature, it distorts plastically, releasing volatile substances and forming porous coke. As the temperature rises, volatile matter begins to burn, generating heat that promotes coke ignition and combustion, as well as mineral change and trace element migration. These activities are intricately linked to the stable and efficient burning of fuels in power plant boilers [13].

The organic matter in sludge is mostly composed of lipids, proteins, and sugars. As the temperature rises, these materials undergo successive pyrolysis. The combustion process of sludge is separated into three stages: initial, major, and final. The initial decomposition stage relates to the sludge drying process and often lasts less than 200ºC. The major decomposition stage occurs between 180 and 580ºC, corresponding to a significant release of volatile components from the sludge and oxidation of the coke, which usually occurs in parallel without a clear boundary. The final decomposition step involves breaking down a minor amount of minerals (such as carbonates and sulfates) in sludge [24-28]. The organic structure of coal is primarily composed of aromatic clusters, side chains, fatty bridges, and rings. Compared to sludge, coal combustion is comparatively simple, with a single combustion stage (350-650ºC) that simultaneously releases volatile materials and coke burning. Due to differences in organic and inorganic components, sludge and coal combustion processes differ significantly. In the co-combustion process, sludge combustion is inhibited, and coal combustion is promoted [29]. Sludge combustion is mainly concentrated in the low-temperature zone; the combustion of volatile components is the dominant process of sludge combustion, and the maximum combustion rate usually occurs between 300-400ºC. Due to its low volatile content, coal is less reactive than sludge at lower temperatures, and the combustion of fixed carbon in the high-temperature region dominates the overall combustion reaction, usually reaching a maximum combustion rate at around 500ºC.

The Impact of Fuel Type on Combustion Characteristics

Sludge varies greatly due to regional, seasonal, and treatment process changes, which might impact its combustion properties. Aneta et al. studied the differences in combustion properties of sludge from several wastewater treatment plants, and the sludge utilized in the study was anaerobically digested, dehydrated, and thermally dried. They discovered that, while the overall combustion processes of different sludges were similar, variations in chemical composition caused by different sources resulted in variances in moisture content, initial decomposition temperature, maximum combustion rate, and temperature at which it occurs [30]. Anaerobic treatment can yield more complex organic compounds with greater molecular weights and combustion temperatures in sludge than aerobic treatment. This leads to discrete combustion stages in both low and high-temperature zones. Akdag [31] discovered that adding 10% sludge to coal decreased the combustion efficiency (the ratio of the amount of carbon converted to CO_2 to the total amount of carbon supplied to the fuel mixture) of the blend when compared to coal alone. Under the assumption of using an anaerobic digestion stabilization process, sludge generated by traditional A_2O (Anaerobic-Anoxic-Oxic) wastewater treatment processes had a greater negative impact on combustion efficiency than sludge generated by the University of Cape Town's (UCT) wastewater treatment process. Furthermore, the degree of coalification substantially influences the co-combustion properties of sludge and coal. Some characteristics of sludge, lignite, and bituminous coal are similar. When co-combustion takes place, the heat released by the sludge after ignition in the low-temperature zone is conducive to the release and combustion of the volatile components in the lignite and bituminous coal and also plays a preheating role for the combustion of fixed carbon. Sludge does not significantly improve the combustion of anthracite coal because of the substantial variations in characteristics between sludge and anthracite coal, which cause their combustion processes to be independent in temperature ranges during co-combustion [32]. According to Zhang et al.'s research [33], sludge performed better when combined with high-rank bituminous coal for co-combustion than with low-rank bituminous coal.

The Impact of the Mixing Ratio on Combustion Properties

One key variable affecting how mixes burn is the ratio of mixing ingredients. Selecting the right amount of fuel to blend with can maximize combustion, improve the synergistic impact of fuels, and reduce issues brought on by a single fuel's shortcomings. Li Yangyang et al. [34] discovered that when sludge was co-fired with coal, the weight loss during the volatile stage of the blending increased, the weight loss rate accelerated, and the temperature at which the maximum weight loss peak of the coke combustion stage appeared decreased with an increase in the blending ratio. Park [35] investigated the effect of adding up to 20% dry sludge on coal combustion and found that the thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of the co-mixture were similar to those of the coal; the apparent activation energy of the combustion process of the blends obtained using FWO (Flynn-Wall-Ozawa) is also close to that of the single coal combustion. Additionally, a great deal of research has used combustion characteristic factors to quantify how blending ratios affect certain aspects of combustion. With the sludge ratio as a point of reference, Fig. 4 displays the fluctuation of several combustion characteristic parameters [33]. According to the research, the blend's ignition and burnout temperatures typically steadily drop as the sludge blending ratio increases, but the stability and combustibility indices rise.

This is because when the amount of sludge in the blend increases, so does the amount of volatile matter. Since a lot of volatile matter burns at lower temperatures, the ignition temperature drops. At the same time, the heat released from the combustion of volatile components can provide activation energy for the combustion of fixed carbon, resulting in a lower combustion temperature. While Shao Zhiwei et al. [36] discovered that an increase in sludge ratio would result in a fall in the comprehensive combustion characteristic index, Zhang et al. [33] observed that an increase in sludge ratio progressively raises the fuel's comprehensive combustion characteristic index as well. The fuel's mass distribution of volatile and fixed carbon components, as well as the amount of combustible matter it contains, determines the comprehensive combustion characteristics. Sludge can reduce coal's ignition and burnout temperatures, but it still impairs the coal's comprehensive combustion feature when combined with coal that has a relatively low ash level and a relatively high combustible matter concentration. When high-ash coal is co-fired, the circumstances are reversed.

Sludge can significantly enhance the blend's burnout and ignite performance when co-fired with coal [37]. However, the majority of academics feel that blending less than 10% dried sludge is possible without altering the combustion equipment and operation technology of current power plants, as it has a detrimental effect on combustion efficiency, flue gas temperature, and pollutant emissions [38].

Slagging and Ash Deposition

Slagging and ash deposition are key challenges that arise during the co-combustion of sludge and coal. Ash deposition can reduce boiler thermal efficiency and, in severe cases, may even lead to boiler tube explosions [39]. When co-combusted with Zhundong lignite in Xinjiang, interactions between Na-based components in lignite and P-rich and Si/Al-rich minerals in sludge result in the development of high-melting phosphates and aluminosilicates, which increase the retention of Na in the residual ash and reduce the risk of fouling and reduce the risk of slagging when the combustion temperature is below 900ºC [40]. Zhao et al. [41] measured the ash fusion points following co-combustion of sludge and coal blends in varying proportions, observing a trend of lowering and then increasing ash fusion points as the sludge fraction grew from 10% to 50%. Adding a significant amount of CaO from high sludge proportions counteracts the drop in ash fusion points produced by Fe_2O_3 in low sludge proportion blends by interacting with SiO_2 in coal ash to form high-melting Ca_2SiO_4.

In conclusion, slagging behavior during co-combustion of sludge and coal is mostly determined by combustion temperature and mineral content. Mixing sludge with coal typically exacerbates slagging/ash deposition issues during combustion, whereas interactions between sludge and coal minerals (such as the interaction between P-rich, Si/Al-rich minerals and Na-based components, as well as the interaction between CaO and SiO_2) promote the formation of high-melt compounds. As a result, mineral interactions play an important role in slagging and ash deposition difficulties, although research on the interactions between sludge and coal mineral compositions is still limited.

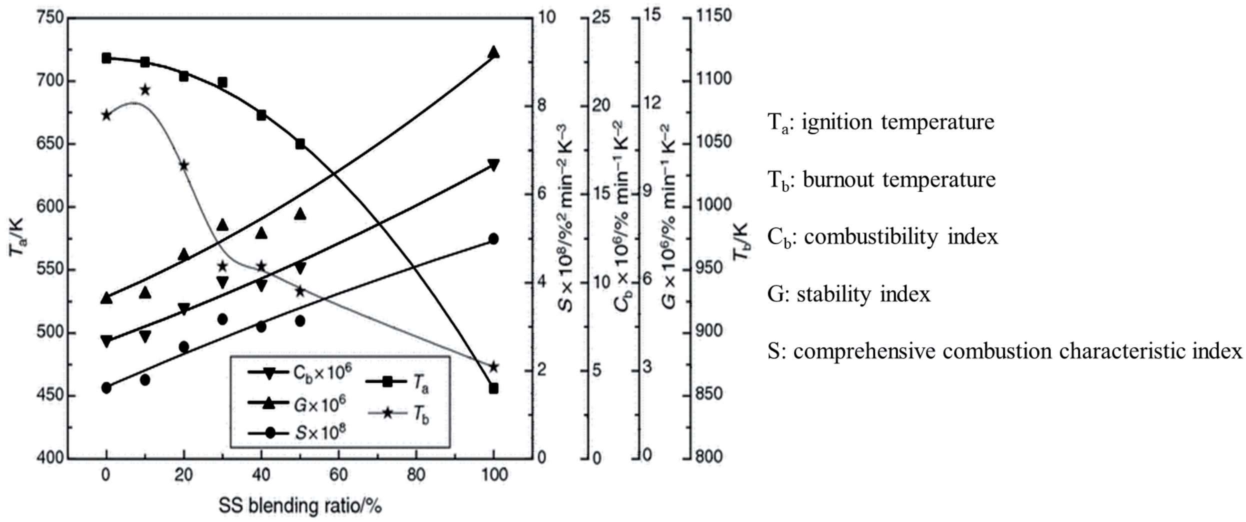


Fig. 4. Impact of sludge ratio on factors related to combustion characteristics.

Fuel Interactions

The co-combustion process is rarely a linear superposition of single fuels, and interactions between distinct characteristic fuels can occur, altering combustion performance. Investigating these interactions allows for a better knowledge of fuel combustion processes and establishes the theoretical groundwork for increasing synergistic effects during fuel co-combustion.

Changes in fuel characteristics fundamentally cause interactions. Sludge and coal are two very distinct fuels, with major variances in organic and inorganic components, particle characteristics, etc. Mixing them changes the combustion environment, mass, and heat transfer conditions compared to individual fuel combustion, resulting in interactions. Yang et al. [42] discovered synergistic benefits during the co-combustion of sludge and coal gangue in a tubular furnace, including improved ignition performance, desulfurization, denitrification, and trace element fixation. Thermogravimetric analyses showed significant interactions between the main combustion stages when sludge was co-combusted with bituminous coal. This leads to combustion lags that may originate from complex reaction mechanisms affecting combustion efficiency [43]. Acid washing removed carbonates and silicates from the sludge, shifting the blend's DTG curve towards the low-temperature zone, implying that ash in sludge inhibits the blend's combustion [44]. Components such as Ca, K, and Mg in sludge ash promote volatile matter breakdown and fixed carbon combustion [45-49]. Wang et al. [50] investigated the effects of various pretreatment methods on the interaction of sludge and coal during co-combustion and proposed interaction mechanisms between sludge and coal at various combustion stages, implying that different factors influence the interactions at different stages.

As illustrated in Fig. 5, it is widely assumed that fuel interactions are mostly due to non-catalytic and catalytic mechanisms: (1) Interaction of volatile substances. For instance, during thermal breakdown, sludge with a high H/C ratio produces a large amount of H and OH radicals, which, while promoting the breakdown of coal molecules, also prevents radical recombination and cross-linking. (2) Variations in physicochemical qualities lead to modifications in mass and heat transfer conditions. Because sludge includes a high concentration of low-boiling-point organic compounds, there is a greater pressure between the particles in the low-temperature zone, which prevents the volatilization of volatile stuff in coal. Concurrently, a rise in pressure during the first phase could lessen the oxygen's chemical adsorption on the coal surface, hastening the blend's weight loss. Furthermore, after combining big particle-size sludge and coal, the blend experiences notable temperature gradients due to the sludge's high hardness and difficulty grinding, which delays the volatilization of volatile materials. (3) Interactions of heat. While the heat from burning coal's fixed carbon can help the remaining materials in sludge decompose, the heat released by burning the volatile matter in sludge in the low-temperature zone can also preheat the coal's fixed carbon. Volatile materials are generally released in the blend when non-catalytic mechanisms mostly show their influence. The term "catalytic mechanisms" primarily describes how inorganic sludge constituents catalyze coal combustion processes. On the one hand, elements such as Ca, Mg, and K in sludge can catalyze the decomposition of volatile matter at lower temperatures, improving the ignition performance of the blend; on the other hand, they stimulate the breakdown of volatile materials at lower temperatures, hence enhancing the blend's ignition capability. However, alkali (earth) metals can efficiently catalyze the burning of fixed carbon. During the catalytic process, metal elements

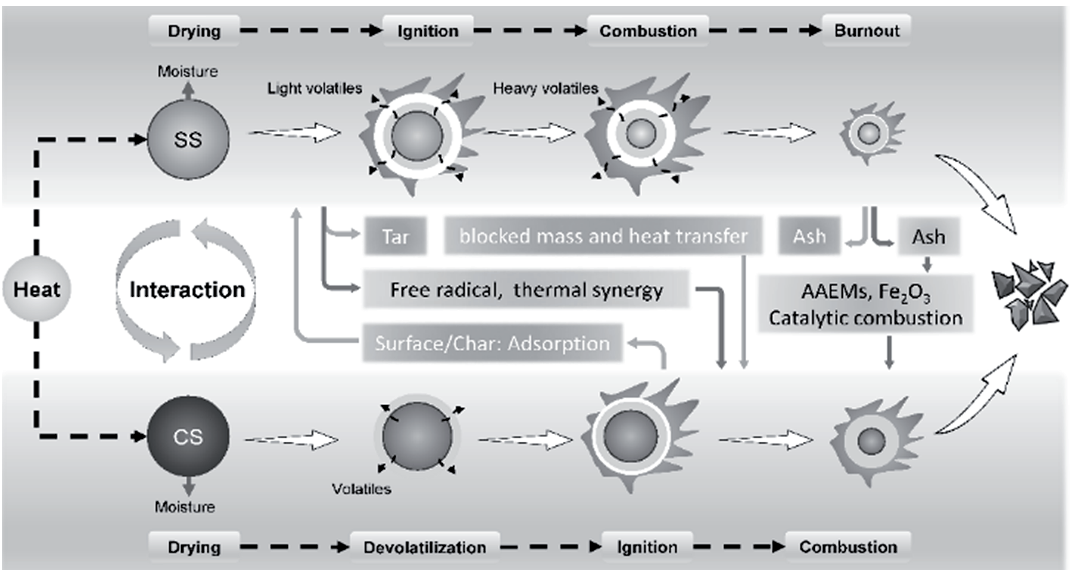


Fig. 5. Mechanism of interaction between sludge and coal slurry during co-combustion.

act as oxygen transporters, speeding up the oxygen's passage to the coke's surface and enabling the blend to burn more quickly.

In actuality, the fuel interaction mechanism during co-combustion has a great deal of complexity. The interaction's final effect results from several interaction mechanisms working together. While all fuels have the ability to create interactions, the degree and way in which these interactions manifest – as inhibition or synergy – depend on a number of variables, including the fuel's physicochemical qualities, mixing ratio, and combustion conditions. To increase the synergy in the combustion of sludge and coal, more studies on the interaction processes during the co-combustion of sludge and coal are required to elucidate the contributions of each interaction mechanism.

Results and Discussion

Pollutant Emissions and Control

NO_x Emissions

Sludge has a nitrogen concentration that is much higher than that of coal. The nitrogen content of sludge can reach 2.5 to 9.0%, much higher than the 0.5 to 2.5% in coal [51]. Additionally, sludge's inorganic and organic components differ from coal's, meaning the two fuel sources have different generation and emission properties. Therefore, the main area of concern during the co-combustion of coal and sludge is NO_x's emission and control technology.

Blending sludge with coal rich in volatile matter and nitrogen concentrations results in reduced NO emissions. Adding sludge to the combustion of lignite, bituminous coal, and lean coal increases NO emissions during the volatile combustion phase but decreases them during the coke combustion phase [52]. This phenomenon was attributed to reduced coke content and the catalytic effect of minerals in the sludge on NO reduction. A synergistic effect is produced when sludge and gangue are co-combusted at 800ºC. The denitrification reaction consumes the CaO in the blend, thus reducing the oxidation of N-containing substances by CaO, ultimately leading to a 10% reduction in NO emissions relative to the theoretical value [42]. Conversely, mixing less than 5% sludge lowers NO emissions and flame temperature, while blending more than 5% sludge increases the mixture's nitrogen concentration and NO emissions [53]. In addition, fuel properties, combustion temperatures, blending ratios, boiler type, and pretreatment techniques influence NO emissions [54]. For example, compared to bubbling fluidized beds, the deposition of sludge ash in circulating fluidized beds has less of an impact on NO_x levels [55]. Additionally, CaO during sludge dewatering pretreatment catalyzes the reduction of N_2O, which is more uniformly distributed in the sludge and more effective in reducing NO_x generation [56].

Coal NO_x abatement technology states that two types of NO_x abatement technology can be used with sludge combustion: flue gas treatment technology, which includes selective catalytic reduction and selective non-catalytic reduction, may not be as effective in treating NO_x in the flue gas due to the higher NO_x generated by sludge combustion than by coal. The other NO_x abatement technologies, which include flame cooling, air-graded combustion, low-oxygen dilution combustion, and flue gas recirculation, mostly focus on reducing NO_x generation within the furnace chamber [12]. Air-graded combustion and low-oxygen dilution combustion provide notable benefits over flue gas treatment systems in terms of technology and cost [57]. In air-graded combustion technology, air is fed into the burner in two stages: during the early stage of combustion, the fuel in the fuel-rich zone is combusted in an oxygen-deficient state, and the HCN and NH_3 produced during sludge combustion reduce the generated NO to N_2 in a reducing atmosphere; in the burnout zone, the fuel is combusted in an oxygen-rich state, and NO_x generation is limited due to the low flame temperature [58]. It has been shown that regulating the main air excess component may reduce 50-80% of the NO_x emissions [59]. This lowers the chamber's peak temperature and effectively inhibits the production of thermal nitrogen oxides. Furthermore, optimizing the combustor geometry and operating parameters reduces NO_x emissions from sludge combustion to less than 75 ppm when low-oxygen combustion technology is applied in a horizontal cyclone combustor [60]. These findings suggest that low-oxygen combustion technology is a potentially useful technique for lowering NO_x emissions from sludge combustion processes. The key to reducing NO_x emissions during sludge-coal co-combustion is to determine the burner geometry and operating parameters, such as setting parameters such as the primary air ratio and excess air coefficient in air-graded combustion technology, as well as designing the burner and optimizing the operating conditions in low-oxygen dilution combustion technology. To improve the combustion process, the influence of each parameter on NO_x emissions must be evaluated under specific fuel circumstances. This allows for tuning the combustion process, increasing its efficiency.

SO_2 Emissions

Together, the sulfur content and mineral sulfur-fixing capacity are the two most important parameters that determine SO_2 emissions from sludge and coal combustion. As the sludge proportion increases in the co-combustion process, the SO_2 emission tends to rise linearly [61]. The ratio of primary and secondary air has a significant effect on SO_2 emissions [62]. As the combustion temperature increases, SO_2 and HCl emissions increase [63].

The presence of extracellular polymeric molecules in sludge can inhibit the release of bound water, making dehydration more difficult. Inorganic conditioning agents such as CaO, $FeCl_3$, and coal ash are widely utilized to improve sludge dewatering efficiency while lowering storage, transportation, and subsequent processing costs. These conditioning chemicals also help to reduce SO_2 emissions from coal burning. Specifically, as earlier research has shown, CaO in sludge can react with SO_2 to generate $CaSO_4$, lowering SO_2 emissions. However, $FeCl_3$ can increase the volatilization of Na and K during co-combustion, lowering the sulfur-fixing rate of alkali metals. Furthermore, synthesizing calcium ferrite from Fe_2O_3 and CaO might impede SO_2 reduction efforts. As a result, Fe has a bidirectional effect on SO_2 emissions. Zhang et al. [56] discovered a CaO conditioner could collect practically all SO_2 when sludge is combusted alone, lowering SO_2 emissions by 15.8-48.4% when co-combusted with coal. The optimum desulfurization temperature for sludge combustion was 800ºC in an oxygen atmosphere [64]. Varying the doping ratio of sludge to coal results in differing levels of reduction in polluting gas emissions [65].

In conclusion, the S content of sludge plays an important role in determining SO_2 emissions when sludge and coal are co-combusted. When the S content in sludge is significantly higher than that in coal, blending sludge will increase SO_2 emissions during coal combustion; when the S content in sludge and coal is comparable, the sulfur fixation of minerals in the sludge can effectively reduce SO_2 emissions. Furthermore, the conditioning agent added to the sludge dewatering pretreatment process can efficiently collect SO_2 during the combustion process, reducing SO_2 emissions.

Heavy Metal Emissions

The level of heavy metal content in sludge is considerable, and the issue of heavy metal emission during co-combustion warrants attention. Heavy metals in sludge are generally classified into three groups based on their volatility: volatile elements (Hg and Se), semi-volatile elements (As, Sb, Pb, Cd, and Zn), and non-volatile elements (Cr, Ni, Cu, and Mn). The fuel properties and combustion parameters largely influence the emission of heavy metals during co-combustion. The two components, CI and S, have an impact on the volatility of heavy metals. Research has demonstrated that Cl in sludge reacts with heavy metals at high temperatures to produce low-boiling chlorides, accelerating the movement of heavy metals to flue gas. Among chlorides, $CaCl_2$ can significantly decrease the volatilization temperature of heavy metals such as As and Cu, while $FeCl_3$ can promote the volatilization of Cu, Zn, and Pb [66, 67]. The influence of NaCl on the volatilization of heavy metals is in the order of Pb>Zn>Cr>Cu>Mn>Ni. The removal of most heavy metals was efficient in the presence of $CaCl_2$ and $MgCl_2$ among the different types of combustors [68]. S mainly controls the emission of heavy metals in two ways: first, sulfur-containing minerals have a certain fixed effect on heavy metals; second, some heavy metals can combine with SO_2 produced during the combustion process to form sulfates [69]. Additionally, moisture and ash can affect the volatilization of heavy metals. The release rates of As, Se, and Pb increase with the temperature rise, and the final release rate is Se>As>Pb [70]. It is proposed that during the co-combustion process of sludge and slime, the interaction between minerals poses a barrier to the migration of heavy metals into the gas phase. A combination of physical and chemical effects shapes this phenomenon. In addition to fuel characteristics, combustion temperature is a crucial factor affecting the volatility of heavy metals. For instance, as the temperature rises from 850ºC to 1000℃, the volatilization rate of Pb and Zn doubles, and the volatilization rate of Cr also increases from 65.7% to 74.9%. However, the volatilization rate of Mn, Cu, and Ni remains insensitive to temperatures in the same temperature range [71].

Although some metals are highly volatile during combustion, most are retained in the fly ash and captured by the dust collector in practical power plant applications. Thus, it is essential to pay special attention to the problem of heavy metal pollution in the ash reuse process following sludgy-coal co-combustion.

Dioxin Emissions

Sludge combustion generates a significant amount of unconventional pollutants, including dioxins. Dioxins are two types of tricyclic aromatic organic compounds, namely PCDDs (Polychlorinated dibenzo-p-dioxins) and PCDFs (Polychlorinated dibenzofurans). These compounds are highly toxic and capable of causing teratogenic, carcinogenic, and mutagenic effects.

There are four primary sources of dioxins in the sludge combustion process: (1) inherent dioxins present in the sludge, (2) de novo synthesis of residual carbon and chlorine macromolecules in fly ash at low temperatures [72], (3) chlorinated precursors such as chlorobenzene and chlorophenol in the gas phase that are pyrolyzed and rearranged at 500-800ºC, and (4) incomplete combustion or heterogeneous catalytic reactions that synthesize dioxin-like precursors. The formation of dioxins can be inhibited based on their formation mechanism, mainly by sulfur compounds, CaO, and nitrogen compounds. Sulfur-containing compounds produce SO_2, which deactivates the catalyst and inhibits the formation of dioxin-like precursors in the combustion process.

The study of the impact of S and CaO on dioxin formation during co-combustion of coal and organic solid waste has revealed that both substances can limit dioxin production [73]. Additionally, sludge combustion has been found to reduce dioxin emissions, and nitrogen-containing compounds have been shown to have an inhibitory effect on dioxin formation [74]. The mechanism behind this is primarily due to nitrogen compounds inhibiting the formation of dioxins by poisoning metal catalysts, reacting with chlorine to decrease chlorine sources, and releasing free radicals to replace CI or H [75].

Table 1. Pollutant Emissions from Co-firing Sludge.

Mixed combustion ratio	Conditions	NO_x	SO_2	Heavy metal	Dioxin emissions	References
Mixing municipal sludge (SS) with coal slime (CS)						
Municipal sludge (SS)	Temperature: 700-1000ºC	-	-	As the temperature increases, the content of heavy metals decreases.	-	Wang et al. [76]
Coal slime (CS)						
SS:CS = 8:2				The larger the proportion of CS, the fewer the heavy metals.		
SS:CS = 5:5						
SS:CS = 2:8						
Mixing Sludge (SS) with Coal						
Sludge 0%	Temperature: 800ºC	415 ppm	35 ppm	-	-	Qu et al. [77]
Sludge 5%		452 ppm	44 ppm			
Sludge 10%		463 ppm	48 ppm			
Sludge 15%		482 ppm	67 ppm			
Sludge 20%		514 ppm	85 ppm			
Mixing Sludge (SS) with Wood Chips (WS)						
WS:SS = 1:0	Oxygen content: 8.8%	154.3mg/m³	2.5 mg/m³	-	-	Elbl et al. [78]
WS:SS = 0.95:0.5	Oxygen content: 9.4%	360.1 mg/m³	141.2 mg/m³			
WS:SS = 0.9:0.1	Oxygen content: 7.9%	427.8 mg/m³	607.3 mg/m³			
WS:SS = 0.85:0.15	Oxygen content: 8.5%	524.3 mg/m³	472.3 mg/m³			
WS:SS = 0.8:0.2	Oxygen content: 8.6%	556.8 mg/m³	602.1 mg/m³			

In conclusion, optimal combustion conditions such as more complete combustion, a reducing atmosphere, lower chlorine content in the fuel, and less catalytic metal can help reduce dioxin formation. Furthermore, the interaction between S/N/CI and the catalytic metal may also affect the pathway of dioxin formation. Despite receiving extensive attention, dioxin's formation mechanism and emission characteristics are still unclear, and more in-depth research is needed. A suitable reduction technology should be sought to reduce dioxin emissions during sludge and coal co-combustion in coal-fired power plants. A comparison of some of the literature data is shown in Table 1.

For the pollutants generated by the co-combustion of sludge and coal, emission reduction can be achieved through the following comprehensive measures: In terms of NO_x control, low-temperature combustion is adopted, and iron sludge (Fe_2O_3) is added. This way, fuel-nitrogen can be catalyzed to convert into N_2, reducing NO. For SO_2 emission reduction, the calcium-based component (CaO) in sludge is used for co-combustion with coal gangue to generate $CaSO_4$ for sulfur fixation. At the same time, the ratio and temperature are optimized to achieve the purpose of emission reduction. In terms of heavy metal pollution prevention and control, a multi-stage dust removal system is used to capture fly ash, landfills are carried out according to the heavy metal concentration classification, and CaO or high-sulfur coal is added to form sulfides to reduce the migration of heavy metals. The incineration temperature is controlled above 600 ºC for dioxin pollutants to decompose dioxins. High-temperature cyclone dust removal is combined to block its resynthesis path, and then activated carbon or sulfur/iodine adsorbents are used to remove residues.

Conclusions

Co-combustion of sludge and coal is a potential solution for sludge reduction, stabilization, and recycling. During this process, sludge improves coal ignition and burnout performance, while coal reduces the risk of slagging and ash deposition during sludge combustion. The interaction of sludge's organic and inorganic constituents with coal is determined by a variety of factors, including the fuel's physical and chemical qualities, mixing ratio, and burning circumstances. Air staging and low oxygen dilution combustion technologies can be applied to address the issue of high NO_x emissions produced by high nitrogen content sludge combustion. Mineral types and interactions are also important in reducing SO_2, heavy metal, and dioxin emissions. For example, calcium-based conditioners used during sludge dewatering can effectively trap SO_2 during combustion, lowering SO_2 emissions. The Cl, S, and CI ratios to metals and their interaction with catalytic metals can influence heavy metal volatility, whereas S/N/CI and catalytic metals can limit dioxin production. When sludge and coal slime are co-pyrolyzed in a ratio of 5:5 or 6:4, the significant synergy generated by the interaction between volatile coke and minerals can improve the pyrolysis efficiency and reduce NO and SO_2 emissions [62]. The higher the temperature, the higher the metal release rate [5]. Although the co-combustion of sludge and coal has significant advantages, its widespread implementation requires a strong policy framework and a long-term strategy. In addition, various scientific and technical difficulties must be addressed, as explained in this work.

The current emphasis on the interaction of sludge and coal co-combustion processes is focused on determining the end impact of the complex mechanism. However, it is unclear what role each system plays. As a result, in the next research stage, it is critical to improve the quantitative investigation of the interaction mechanism and get a better knowledge of the microscopic process of co-combustion. Furthermore, the effect of high ash and high alkali (earth) metal fuels on pollutant emissions during co-burning with sludge has not been thoroughly investigated. Doping with other organics also works well [79, 80]. Lignite is more suitable for blending with sludge than bituminous coal [81]. It is more appropriate to mix sludge with the upper burner [82]. As a result, more research is required on this topic. To achieve large-scale sludge treatment, it is critical to investigate fuel's combustion and pollutant emission properties at high sludge mixing ratios. This should be followed by evaluating the transformation plan for combustion equipment, optimizing combustion conditions, conducting a feasibility review of the overall process, and examining the life cycle of sludge and coal co-combustion in different furnace types.

Acknowledgments

This work was supported by the Shanxi Province Basic Research Program (Free Exploration) (202103021223031).

Conflict of Interest

The authors declare no conflict of interest.

References

1. DENG W.Y., LI X.D., YAN J.H., WANG F., CHI Y., CEN K.F. Moisture distribution in sludges based on different testing methods. Journal of Environmental Sciences. **23** (5), 875, **2011**.
2. LEI H., QIAO J., WANG R., ZHAO Z., YIN Q., GE L. Combustion Characteristics and NO_x Generation of Hydrochar from Co-hydrothermal Carbonization of Sewage Sludge and Corn Straw. Journal of Chinese Society of Power Engineering. **44** (2), 181, **2024**.
3. ZHAO X.G., JIANG G.W., LI A., LI Y. Technology, cost, a performance of waste-to-energy incineration industry in China. Renewable & Sustainable Energy Reviews. **55**, 115, **2016**.
4. DONG B., LIU X.G., DAI L.L., DAI X.H. Changes of heavy metal speciation during high-solid anaerobic digestion of sewage sludge. Bioresource Technology. **131**, 152, **2013**.
5. LU P., XIE J., ZHANG X., WANG J., FENG C., SONG X., BU Y. Release properties of semi-volatile heavy metals in sewage sludge /coal co-incineration under O_2 /CO_2 atmosphere. Journal of Fuel Chemistry and Technology. **48** (5), 533, **2020**.
6. ZHAN T.L., ZHAN X.J., LIN W.A., LUO X.Y., CHEN Y.M. Field and laboratory investigation on geotechnical properties of sewage sludge disposed in a pit at Changan landfill, Chengdu, China. Engineering Geology. **170**, 24, **2014**.
7. SONG U., LEE E.J. Environmental and economical assessment of sewage sludge compost application on soil and plants in a landfill. Resources Conservation and Recycling. **54** (12), 1109, **2010**.
8. KRZYZANOWSKI F., LAURETTO M.D., NARDOCCI A.C., SATO M.I.Z., RAZZOLINI M.T.P. Assessing the probability of infection by Salmonella due to sewage sludge use in agriculture under several exposure scenarios for crops and soil ingestion. Science of the Total Environment. **568**, 66, **2016**.
9. SYED-HASSAN S.S.A., WANG Y., HU S., SU S., XIANG J. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. Renewable & Sustainable Energy Reviews. **80**, 888, **2017**.
10. ZHANG H., HU Q., WU Z., PAN H. An overview on utilization of municipal sludge as energy resources. Chemical Industry and Engineering Progress. **32** (5), 1145, **2013**.
11. LIANG Y., XU D.H., FENG P., HAO B.T., GUO Y., WANG S.Z., KLEMES J.J. Municipal sewage sludge incineration and its air pollution control. Journal of Cleaner Production. **295**, **2021**.
12. LIU H.M., WANG Y.C., ZHAO S.L., HU H.Y., CAO C.Y., LI A.J., YU Y., YAO H. Review on the current status of the co-combustion technology of organic solid waste (OSW) and coal in China. Energy & Fuels. **34** (12), 15448, **2020**.
13. XIAO H.P., LI K., ZHANG D.Q., TANG Z.H., NIU X.J., YI L.Z., ZHANG L., FU M.L. Environmental, energy, and economic impact assessment of sludge management alternatives based on incineration. Journal of Environmental Management,Volume **321**, **2022**.
14. HUANG W., LIN Y.H., LUO Z.F., WU J., ZHUANG G.X., WU X.W., ZHU L.S. Progress on Research and Technology of Sludge Blending Combustion in Coal-fired Power Plants. Journal of Shanghai University of Electric Power. **37** (1), 1, **2021**.
15. Guoneng Shenwan Chizhou Power Generation Company: Total sludge blending exceeds 25,000 tonnes. Available online: https://www.china5e.com/news/news-1129951-1.html (accessed on 6 May 2025).
16. VAMVUKA D., ALEXANDRAKIS S., PAPAGIANNIS I. Evaluation of municipal wastes as secondary fuels through co-combustion with woody biomass in a fluidized bed reactor. Journal of the Energy Institute. **93** (1), 272, **2020**.

17. WANG Y.L., JIA L., GUO J.R., WANG B.R., ZHANG L., XIANG J., JIN Y. Thermogravimetric analysis of co-combustion between municipal sewage sludge and coal slime: Combustion characteristics, interaction and kinetics. Thermochimica Acta. **706**, **2021**.
18. NIKKU M., DEB A., SERMYAGINA E., PURO L. Reactivity characterization of municipal solid waste and biomass. Fuel. **254**, **2019**.
19. CHEN J.C., XIE C.D., LIU J.Y., HE Y., XIE W.M., ZHANG X.C., CHANG K.L., KUO J.H., SUN J., ZHENG L., SUN S.Y., BUYUKADA M., EVRENDILEK F. Co-combustion of sewage sludge and coffee grounds under increased O_2/CO_2 atmospheres: Thermodynamic characteristics, kinetics and artificial neural network modeling. Bioresource Technology. **250**, 230, **2018**.
20. NIU S.B., CHEN M.Q., LI Y., SONG J.J. Co-combustion characteristics of municipal sewage sludge and bituminous coal. Journal of Thermal Analysis and Calorimetry. **131** (2), 1821, **2018**.
21. SURYAWAN I., SEPTIARIVA I., WIDANARKO D., QONITAN F., SARWONO A., SARI M., PRAYOGO W., ARIFIANINGSIH N., SUHARDONO S., LIM J. Enhancing energy recovery from Wastewater Treatment Plant sludge through carbonization. Energy Nexus. **14** (100290), **2024**.
22. SURYAWAN I., LIM J., RAMADAN B., SEPTIARIVA I., SARI N., SARI M., ZAHRA N., QONITAN F., SARWONO A. Effect of sludge sewage quality on heating value: case study in Jakarta, Indonesia. Desalination and Water Treatment. **249**, 183, **2022**.
23. WANG Y.L., JIA L., GUO B.H., WANG B.R., ZHANG L., ZHENG X., XIANG J., JIN Y. N migration and transformation during the co-combustion of sewage sludge and coal slime. Waste Management. **145**, 83, **2022**.
24. LIN Y., LIAO Y.F., YU Z.S., FANG S.W., MA X.Q. The investigation of co-combustion of sewage sludge and oil shale using thermogravimetric analysis. Thermochimica Acta. **653**, 71, **2017**.
25. LIU J.Y., HUANG L.M., SUN G., CHEN J.C., ZHUANG S.W., CHANG K.L., XIE W.M., KUO J.H., HE Y., SUN S.Y., BUYUKADA M., EVRENDILEK F. Co-combustion of additives, water hyacinth and sewage sludge: Thermogravimetric, kinetic, gas and thermodynamic modeling analyses. Waste Management. **81**, 211, **2018**.
26. YE C., XING X., ZHANG X., CHEN T., ZHANG J. Co-combustion characteristics and kinetics of municipal sludge and rice husk hydrochar. The Chinese Journal of Process Engineering. **20** (3), 362, **2020**.
27. GUO S., HAN Y., WANG L.Y., CHE D.Y., LIU H.P., SUN B.Z. Synergistic effects of co-combustion of sewage sludge and corn stalk and the resulting gas emission characteristics. Iet Renewable Power Generation. **14** (9), 1596, **2020**.
28. WANG T., FU T.M., CHEN K., CHENG R.S., CHEN S., LIU J.X., MEI M., LI J.P., XUE Y.J. Co-combustion behavior of dyeing sludge and rice husk by using TG-MS: Thermal conversion, gas evolution, and kinetic analyses. Bioresource Technology. **311**, **2020**.
29. XU T., WANG C.B., HONG D.K., LI S., YUE S. The synergistic effect during co-combustion of municipal sludge and coal: Experimental and ReaxFF molecular dynamic study. Energy. **262**, **2023**.
30. MAGDZIARZ A., WILK M. Thermogravimetric study of biomass, sewage sludge and coal combustion. Energy Conversion and Management. **75**, 425, **2013**.
31. AKDAG A.S., ATAK O., ATIMTAY A.T., SANIN F.D. Co-combustion of sewage sludge from different treatment processes and a lignite coal in a laboratory scale combustor. Energy. **158**, 417, **2018**.
32. ZHUANG X., SONG Y., ZHAN H., YIN X., WU C. Synergistic effects in co-combusting of hydrochar derived from sewage sludge with different-rank coals. Journal of Fuel Chemistry and Technology. **46** (12), 1437, **2018**.
33. ZHANG Y.S., ZHANG L.H., DUAN F., JIANG X.X., SUN X.R., CHYANG C.S. Co-combustion characteristics of sewage sludge with different rank bituminous coals under the O_2/CO_2 atmosphere. Journal of Thermal Analysis and Calorimetry. **121** (2), 729, **2015**.
34. LI Y., JIN Y., NIE Y. Effects of sewage sludge on coal combustion using thermo-gravimetric kinetic analysis. China Environmental Science. **34** (3), 604, **2014**.
35. PARK J.M., KEEL S., YUN J., YUN J.H., LEE S.S. Thermogravimetric study for the co-combustion of coal and dried sewage sludge. Korean Journal of Chemical Engineering. **34** (8), 2204, **2017**.
36. SHAO Z.W., HUANG Y.J., ZHANG Q., LIU P.G., YAN Y.P. Co-combustion characteristics of sludge and bituminous coal in O_2/CO_2 atmosphere. Journal of Zhejiang University (Engineering Science). **48** (10), 1739, **2014**.
37. CHEN Y.C., GUI H.R., XIA Z.W., CHEN X., ZHENG L.G. Thermochemical and Toxic Element Behavior during Co-Combustion of Coal and Municipal Sludge. Molecules. **26** (14), **2021**.
38. WANG Z.Q., HONG C., XING Y., LI Y.F., FENG L.H., JIA M.M. Combustion behaviors and kinetics of sewage sludge blended with pulverized coal: With and without catalysts. Waste Management. **74**, 288, **2018**.
39. LEE D.G., LEE J.H., KIM G.M., JEONG J.S., KIM S.M., JEON C.H. The Initial ash deposition formation in horizontal combustion reactor for blending torrefied biomass wood pellets and coals. Renewable Energy. **226**, **2024**.
40. QI X.B., SONG G.L., SONG W.J., YANG S.B., LU Q.G. Combustion performance and slagging characteristics during co-combustion of Zhundong coal and sludge. Journal of the Energy Institute. **91** (3), 397, **2018**.
41. ZHAO Z.H., WANG R.K., WU J.H., YIN Q.Q., WANG C.B. Bottom ash characteristics and pollutant emission during the co-combustion of pulverized coal with high mass-percentage sewage sludge. Energy. **171**, 809, **2019**.
42. YANG Z.Z., ZHANG Y.Y., LIU L.L., WANG X.D., ZHANG Z.T. Environmental investigation on co-combustion of sewage sludge and coal gangue: SO_2, NO_x and trace elements emissions. Waste Management. **50**, 213, **2016**.
43. LIAO Y.F., MA X.Q. Thermogravimetric analysis of the co-combustion of coal and paper mill sludge. Applied Energy. **87** (11), 3526, **2010**.
44. VAMVUKA D., SALPIGIDOU N., KASTANAKI E., SFAKIOTAKIS S. Possibility of using paper sludge in co-firing applications. Fuel. **88** (4), 637, **2009**.
45. SADHWANI N., ADHIKARI S., EDEN M.R., WANG Z.H., BAKER R. Southern pines char gasification with CO_2-Kinetics and effect of alkali and alkaline earth metals. Fuel Processing Technology. **150**, 64, **2016**.
46. HOGNON C., DUPONT C., GRATEAU M., DELRUE F. Comparison of steam gasification reactivity of algal and lignocellulosic biomass: Influence of inorganic elements. Bioresource Technology. **164**, 347, **2014**.

47. WANG Y.L., JIA L., ZHANG L., ZHENG X., XIANG J., JIN Y. Effects of CaO-Fe_2O_3-$Fe_3(PO_4)_2$ in sewage sludge on combustion characteristics and kinetics of coal slime. Fuel. **322**, **2022**.
48. LI J.K., CHEN Y., ZHANG Y.Y., WU J., GUO C.X., JIN Y., WANG Y.L. Effects of alkali and alkaline earth metals on co-combustion of sewage sludge and coal slime: Combustion characteristics, interactions, and kinetics. Journal of Environmental Management. **356**, **2024**.
49. WANG Y.L., JIN Z.P., LI J.K., BAI T., CHEN Y. Heavy metals behavior of co-combustion ash from sewage sludge and coal slime: Temperature and mixing ratio dependence, interactions and speciation. Journal of Cleaner Production. **434**, **2024**.
50. WANG Y., JIA L., GUO B., LI J., BAI T., JIN Z., JIN Y. Investigation on the interaction mechanism during co-combustion of sewage sludge and coal slime: The effect of coal slime type and pretreatment method. The Science of the total environment. **927**, 172419, **2024**.
51. ZHAO L., WANG X., HUANG B., SUN Y., XUE Y., ZHANG H. Mechanistic study of nitrogen migration and transformation during sludge combustion process. Clean Coal Technology. **29** (10), 153, **2023**.
52. LI Y.D., YANG D., QU M.F., SUO L.H., SUN W.B. Experimental investigation on co-combustion kinetics and gas emission law of sewage sludge-bituminous coal. International Journal of Energy Research. **42** (13), 4097, **2018**.
53. ZHANG S.R., JIANG X.G., LV G.J., WU L., LI W., WANG Y.F., FANG C.Q., JIN Y.Q., YAN J.H. Co-combustion of Shenmu coal and pickling sludge in a pilot scale drop-tube furnace: Pollutants emissions in flue gas and fly ash. Fuel Processing Technology. **184**, 57, **2019**.
54. LI J.P., HU J.Q., WANG T., GAN J.H., XIE J.P., SHUI Y.H., LIU J.X., XUE Y.J. Thermogravimetric analysis of the co-combustion of residual petrochemical sludge and municipal sewage sludge. Thermochimica Acta. **673**, 60, **2019**.
55. SHIMIZU T., TOYONO M. Emissions of NO_x and N_2O during co-combustion of dried sewage sludge with coal in a circulating fluidized bed combustor. Fuel. **86** (15), 2308, **2007**.
56. ZHANG Q., LIU H., ZHANG X.J., XING H.X., HU H.Y., YAO H. Novel utilization of conditioner CaO for gas pollutants control during co-combustion of sludge and coal. Fuel. **206**, 541, **2017**.
57. WANG Y.D., HUANG Y., MCILVEEN-WRIGHT D., MCMULLAN J., HEWITT N., EAMES P., REZVANI S. A techno-economic analysis of the application of continuous staged-combustion and flameless oxidation to the combustor design in gas turbines. Fuel Processing Technology. **87** (8), 727, **2006**.
58. HOUSHFAR E., SKREIBERG O., LOVÅS T., TODOROVIC D., SORUM L. Effect of Excess Air Ratio and Temperature on NO_x Emission from Grate Combustion of Biomass in the Staged Air Combustion Scenario. Energy & Fuels. **25** (10), 4643, **2011**.
59. HOUSHFAR E., LOVÅS T., SKREIBERG O. Experimental investigation on NO_x reduction by primary measures in biomass combustion: straw, peat, sewage sludge, forest residues and wood pellets. Energies. **5** (2), 270, **2012**.
60. SHIM S.H., JEONG S.H., LEE S.S. Low-nitrogen oxides combustion of dried sludge using a pilot-scale cyclone combustor with recirculation. Journal of the Air & Waste Management Association. **65** (4), 413, **2015**.
61. TONG M., FENG Y., LUO Y. Study on co-combustion characteristics and pollutants emission of municipal sludge and coal. Environment Engineering. **36** (3), 133, **2018**.
62. SHEN X., JIN Y., LI J.K., YE L., YANG H.R., WANG Y.L. Co-pyrolysis behavior of sewage sludge and coal slurry: Pyrolysis characteristics, interaction mechanisms, and gas emissions. Journal of Environmental Management, **2025**, 379,124926.
63. XU X., ZHONG W., CHEN X., ZHOU G., XU Y. Co-combustion kinetics and pollutant emission characteristics of sludge and coal slime. Journal of Southeast University. Natural Science Edition. **52** (1), 25, **2022**.
64. MA M.Y., LIANG Y., XU D.H., SUN S.Y., ZHAO J., WANG S.Z. Gas emission characteristics of sewage sludge co-combustion with coal: Effect of oxygen atmosphere and feedstock mixing ratio. Fuel. **322**, **2022**.
65. CHEN J.J., SUN Y.Q., ZHANG Z.T. Evolution of trace elements and polluting gases toward clean co-combustion of coal and sewage sludge. Fuel. **280**, **2020**.
66. FRAISSLER G., JÖLLER M., MATTENBERGER H., BRUNNER T., OBERNBERGER I. Thermodynamic equilibrium calculations concerning the removal of heavy metals from sewage sludge ash by chlorination. Chemical Engineering and Processing-Process Intensification. **48** (1), 152, **2009**.
67. LIU J.Y., ZENG J.J., SUN S.Y., HUANG S.S., KUO J.H., CHEN N.W. Combined effects of $FeCl_3$ and CaO conditioning on SO_2, HCl and heavy metals emissions during the DDSS incineration. Chemical Engineering Journal. **299**, 449, **2016**.
68. ALISHER M., SHAH D., IZQUIERDO M., YBRAY S., SARBASSOV Y. Synergistic effects of Cl-donors on heavy metal removal during sewage sludge incineration. Case Studies in Chemical and Environmental Engineering. **10**, 100876, **2024**.
69. SEKINE Y., SAKAJIN K., KIKUCHI E., MATSUKATA M. Release behavior of trace elements from coal during high-temperature processing. Powder Technology. **180** (1-2), 210, **2008**.
70. LIU X., JIANG L.X., ZHAO C.G., ZHANG K., LI Q., LI J.J., DUAN W.B. Migration and transformation characteristics of arsenic, selenium and lead during co-combustion of sewage sludge with coal slime. Clean Coal Technology. **1** (1-9), **2023**.
71. LIU J.Y., FU J.W., NING X., SUN S.Y., WANG Y.J., XIE W.M., HUANG S.S., ZHONG S. An experimental and thermodynamic equilibrium investigation of the Pb, Zn, Cr, Cu, Mn and Ni partitioning during sewage sludge incineration. Journal of Environmental Sciences. **35**, 43, **2015**.
72. WANG Z.Y. Dioxins Generation and Control of Sludge Co-combustion with Coal and Direct Incineration. Power System Engineering. **40**, 13, **2024**.
73. MA H.T., DU N., LIN X.Y., LIU C.F., ZHANG J.Y., MIAO Z.Z. Inhibition of element sulfur and calcium oxide on the formation of PCDD/Fs during co-combustion experiment of municipal solid waste. Science of the Total Environment. **633**, 1263, **2018**.
74. YAN M., LI X.D., YANG J., CHEN T., LU S.Y., BUEKENS A.G., OLIE K., YAN J.H. Sludge as dioxins suppressant in hospital waste incineration. Waste Management. **32** (7), 1453, **2012**.
75. KASAI E., KUZUHARA S., GOTO H., MURAKAMI T. Reduction in dioxin emissions by the addition of urea as aqueous solution to high-temperature combustion gas. Isij International. **48** (9), 1305, **2008**.

76. WANG Y., JIN Z., LI J., BAI T., CHEN Y. Heavy metals behavior of co-combustion ash from sewage sludge and coal slime: Temperature and mixing ratio dependence, interactions and speciation. Journal of Cleaner Production. **434**, **2024**.
77. QU Z., WEI X., CHEN W., WANG F., WANG Y., LONG J. Co-Combustion Characteristics of Municipal Sewage Sludge and Coal in a Lab-Scale Fluidized Bed Furnace. Energies. **16** (5), 2374, **2023**.
78. ELBL P., SITEK T., LACHMAN J., LISY M., BALÁS M., POSPISIL J. Sewage sludge and wood sawdust co-firing: Gaseous emissions and particulate matter size distribution. Energy. **256**, **2022**.
79. LI J., XU F., HE Z.H. Orthogonal experimental study to optimise the combustion conditions of blended municipal sludge and cotton stalks. Applied Chemical Industry. **53**, 1624, **2024**.
80. SHI Y.J., WANG H.M., XU K.Q., XIAO X. Study on mixed combustion characteristics of sewage sludge and camellia oleifera shell. Thermal Power Generation. **53**, 39, **2024**.
81. FANG S.W., LIN Y., DING L.X., CHEN S. The co-combustion characteristics and kinetic behavior of paper sludge and coal. Journal of Thermal Science and Technology. **22**, 583, **2023**.
82. CHEN L.F., ZHU L.J., LI F.Q., ZHU Q.Z. Simulation Study of the Effect of Sludge Blending Method on the Combustion of Coal-fired Boilers. Journal of Engineering for Thermal Energy and Power. **39**, 122, **2023**.