Indonesian Journal of Environmental Management and Sustainability
e-ISSN:2598-6279 *p*-ISSN:2598-6260

Research Paper

Properties and Utilization of Fly Ash for Treating Acid Mine Drainage

Nurlela[1,4], Tuty Emilia Agustina[2,3]*, Susila Arita[2], David Bahrin[2], Muhrinsyah Fatimura[4], Rully Masriatini[4], Rianyza Gayatri[1]

[1]*Engineering Science Doctoral Program, Faculty of Engineering, Universitas Sriwijaya, Palembang, 30139, Indonesia*
[2]*Chemical Engineering Department, Faculty of Engineering, Universitas Sriwijaya, 30662, Indonesia*
[3]*Water and Wastewater Engineering Research Group, UPT Integrated Laboratory, Universitas Serasan, Muara Enim, South Sumatra, 31312, Indonesia*
[4]*Chemical Engineering Department, Faculty of Engineering, Universitas PGRI Palembang, Palembang, 30251, Indonesia*
***Corresponding author e-mail**: tuty_agustina@unsri.ac.id

Abstract

The combustion of coal in power plants (PLTU) generates fly ash containing silica dioxide (SiO_2) and alumina (Al_2O_3), which exhibit promising properties as adsorptive materials. Fly ash, typically regarded as an industrial by-product, has been widely explored for its application as an adsorbent in wastewater purification. One of the most challenging wastewaters is acid mine drainage, characterized by a strong acidity ($pH < 5$), residual contaminants, and elevated concentrations of heavy metal ions such as manganese (Mn) and iron (Fe). When released untreated, this effluent poses significant risks to both surface and groundwater quality in mining areas. This study focuses on the characterization and utilization of fly ash as an adsorbent to neutralize acidity and reduce Mn and Fe concentrations in acid mine drainage. The material was characterized using SEM-EDX and XRD techniques, followed by adsorption experiments. To enhance its properties, fly ash underwent physical activation through heating at 100 °C for 60 minutes. The activation process modified its structure, expanding pore volume and increasing surface area, thereby improving adsorption performance. The experimental results revealed significant differences in the properties of fly ash before and after activation. Activated fly ash effectively raised the pH of acid mine drainage to near-neutral conditions, while achieving removal efficiencies of 96.61% for Mn and 83.33% for Fe using 50 g of adsorbent. These findings highlight the potential of fly ash as a low-cost and effective material for acid mine drainage treatment, both for acidity control and heavy metal removal.

Keywords

Acid Mine Drainage, Adsorbent, Fly Ash, Heavy Metal Ions

Received: 12 September 2025, Accepted: 8 December 2025
https://doi.org/10.26554/ijems.2025.9.4.223-232

1. INTRODUCTION

Coal is one of the main sources of energy worldwide, with around 30-40% of its use allocated to electricity generation (Patel et al., 2022). The use of coal as an energy source is still considered cost-efficient. However, its Utilization also has the potential to pose risks and create new environmental problems around mining areas as well as steam power plants (PLTU) (Aigbe et al., 2021).

The process of burning or carbonizing coal in the furnace of a power plant produces a solid residue known as fly ash (Wang et al., 2021). The Utilization of fly ash is based on the characteristics of the elements contained in it, as well as the potential presence of heavy metals in it. The main components contained in fly ash include quartz (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3) (Chindaprasirt and Rattanasak, 2020). Fly ash is a highly alkaline waste, with a pH of more than 12, must be managed safely as it is classified as hazardous waste if disposed of carelessly (Kalombe et al., 2020). There are two types of fly ash commonly produced from coal combustion, F-type and C-type. Type F is mainly produced from burning anthracite and bituminous coal, which have high loss on ignition (LOI) and low lime content. In contrast, type C is derived from subbituminous and lignite coal, which has a higher calcium content and lower LOI compared to type F fly ash (Roulia et al., 2022).

In addition to producing fly ash from burning coal in the furnace, coal mining activities also produce mine wastewater. Mine wastewater mainly consists of sludge and acid mine drainage (AMD). Acid water from coal mines contains residues, is acidic, and contains iron (Fe) and manganese (Mn) heavy metal ions. If discharged directly into the environment, this waste has the potential to damage the environment, including polluting rivers around the mining area.

Acid mine drainage is formed by the oxidation of sulfide minerals, such as pyrite (FeS_2), exposed to the ground surface during the extraction of mining materials. This oxidation process occurs due to the interaction between pyrite, water and oxygen (Tavengwa, 2019). Oxidizing metal sulfides will form acids, resulting in acid mine drainage that is highly acidic, characterized by a low pH below 5, and contains metals with high solubility (Fadhilah et al., 2022). Improper treatment of acid mine drainage can damage the environment as it can contaminate streams through the sulfide oxidation process. The solution to this problem is to effectively treat acid mine drainage to prevent it from contaminating the surrounding environment (Keller et al., 2020).

One alternative to acid mine drainage treatment is through adsorption. Adsorption is one of the processes that can be used to remove contaminants from various types of wastewaters. Currently, adsorption is considered the most effective and economical method in reducing heavy metal pollution (Ehiomogue et al., 2022). In addition, this method is also simple, easy to implement, and more affordable (Patel et al., 2022). Fly ash-based adsorbents are also a major concern to scale up more effectively. Through this approach, fly ash has significant potential as a cheap and efficient adsorbent in wastewater treatment. This research aims to characterize and utilize fly ash as an adsorbent to neutralize pH and reduce the concentration of heavy metal ions such as Mn and Fe in acid mine drainage. Thus, fly ash not only has the potential to become waste that pollutes the environment, but can also be utilized to overcome environmental pollution problems (Mushtaq et al., 2019).

The activation process for making adsorbent can be through the physical, chemical, or combined physical-chemical methods. The physical activation method can be done with 100oC heating, which has been applied in the manufacture of activated carbon (Rafizan et al., 2022; Fajri and Takwanto, 2024). In other studies, the physical activation method has also been used with 100 °C-200 °C heating which is applied to the manufacture of bottom ash as an adsorbent (Pisceselia et al., 2023). Whereas in this study the use of physical activation method with 100 °C heating was examined in the manufacture of fly ash as adsorbent. This research lies in the optimization of physical activation conditions and its effectiveness compared to directly used of fly ash as an adsorbent. Unlike previous studies that generally use chemical activation, this study focuses on a simple and environmentally friendly physical activation method by heating at 100 °C for 60 minutes, which is more energy efficient and scalable for industrial applications. Fly ash is one of the wastes that has great potential to be used in the adsorption process. Therefore, this study advantage makes the adsorption method using fly ash the potential choice to neutralize acid mine drainage.

In contrast to previous studies that predominantly rely on chemical activation or high-temperature treatments, the novelty of this research lies in applying and optimizing a simple, low-energy physical activation method, heating fly ash at 100 °C for 60 minutes to enhance its adsorption performance for acid mine drainage treatment. This approach demonstrates that mild thermal activation is sufficient to improve the ability of fly ash to neutralize acidic pH and remove Mn and Fe ions, offering a more cost-effective, energy-efficient, and environmentally friendly strategy. By converting an abundant industrial waste into a functional adsorbent, this study provides a practical and scalable solution for mitigating mining-related water pollution.

2. EXPERIMENTAL SECTION

2.1 Materials

Prior to treatment, the acid mine drainage samples must first be characterized by measuring the pH value using a pH meter and determining the levels of Mn and Fe metal ions using the AAS (GBC Scientific Equipment) method. In addition, fly ash was also analyzed before and after the activation process using SEM-EDX (PhenomProX Desktop Scanning Electron Microscope) and XRD (SMARTLAB RIGAKU (Cu Source)) to identify its characteristics.

2.2 Methods

2.2.1 Fly Ash Adsorbent Activation

A total of 500 g of fly ash was weighed using a digital analytical balance. The sample was then placed in a stainless-steel tray and heated in a laboratory oven at 100 °C for 60 minutes. This thermal activation aims to remove moisture, reduce agglomeration, and enhance pore accessibility to improve adsorption performance. After heating, the fly ash was transferred immediately into a desiccator and allowed to cool to room temperature to prevent moisture reabsorption prior to use in the adsorption experiments.

2.2.2 Adsorption of Mn and Fe Metal Ions in Acid Mine Drainage using Fly Ash Adsorbent

A volume of 250 mL of acid mine drainage (AMD) was measured using a graduated cylinder and poured into a 500 mL beaker. Fly ash was added in varying mass of 10, 20, 30, 40, and 50 g to evaluate the effect of adsorbent dosage. The beakers were placed on a jar test apparatus and stirred at 100 rpm for 30 minutes at room temperature to ensure uniform mixing and adequate contact between the fly ash and AMD. Upon completion of mixing, the suspension was filtered using Whatman No. 41 filter paper to separate the solid adsorbent from the treated solution. The filtrate was then analyzed for pH, and the concentrations of Fe and Mn were quantified. The entire procedure was repeated using fly ash previously activated at 100 °C.

2.3 Adsorption Percentage Calculation

Adsorption percentage measures how much solute is successfully adsorbed by the adsorbent in an adsorption process.

It is calculated based on the ratio between the initial concentration (C_0) and the final concentration (C_e) of solute in the solution. Adsorption percentage can be calculated using the following equation (Agustina et al., 2017):

$$\%\text{Adsorption} = \frac{C_0 - C_e}{C_0} \times 100\% \quad (1)$$

Where: % Adsorption = Percentage of solute adsorbed, C_0 = Initial concentration of solute (before adsorption), in mg/L or ppm, and C_e = Final concentration of solute (after adsorption), in mg/L or ppm.

2.3.1 Jar Test Procedure and Fly Ash Analysis

Fly ash with mass variations of 10, 20, 30, 40, and 50 g were weighed. Each sample was then dissolved in 250 mL of acid mine drainage using a 500 mL beaker. The beaker glass was placed in a jar test device with a stirring speed of 100 rpm at room temperature for 30 minutes. This mixing speed provides sufficient agitation to suspend the fly ash particles while preventing excessive turbulence that could interfere with adsorption. After the process was complete, the mixture was separated by filtering it using a filter paper (Pisceselia et al., 2023). The pH of the acid mine drainage treated with fly ash adsorbent was measured using a pH meter, and the concentrations of Fe and Mn metal ions were analyzed using the AAS method.

Calibration of the pH meter should be done first using pH 4 buffer and adjust the device until it shows a value of 4 in the calibration process. After that, rinse the electrodes and dry them. Then, take measurements with pH 10 buffer and adjust the reading until it shows a value of 10 in the calibration process (Komala et al., 2024). After the calibration is complete, the calibrated electrode is inserted into the acid mine drainage sample container to measure its pH. Next, measure the pH of the acid mine drainage that has been mixed with fly ash adsorbent after undergoing the jar test process.

3. RESULTS AND DISCUSSION

3.1 Characterization of Fly Ash Adsorbent with SEM-EDX

The Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) method is applied to examine the structure and surface characteristics of materials, as well as to identify their elemental composition through X-ray spectroscopic analysis using an electron microscope (Dolic et al., 2021). Characterization using SEM produces micrographs that show the surface morphology of the sample, allowing observation of the shape and size of the particles (grains) (Mostafa et al., 2019).

A combined technique known as SEM-EDX analysis is used to analyze the surface of solid materials and their chemical composition simultaneously, providing detailed information regarding the composition and morphology of the material (Muksin et al., 2024). This analysis aims to identify changes in the chemical composition of fly ash adsorbent before and after activation.

The chemical composition of the fly ash adsorbent underwent significant changes before and after the activation process, as shown by the SEM-EDX analysis results in Figure 1(a) (before activation) and Figure 1(b) (after activation). Figure 1(a) shows the existence of oxygen, carbon, silicon, aluminum, iron, calcium, sodium, tellurium, magnesium, and potassium. However, after the activation process, only the elements of oxygen, carbon, silicon, iron, calcium, sodium, and magnesium were detected as shown in Figure 1(b).

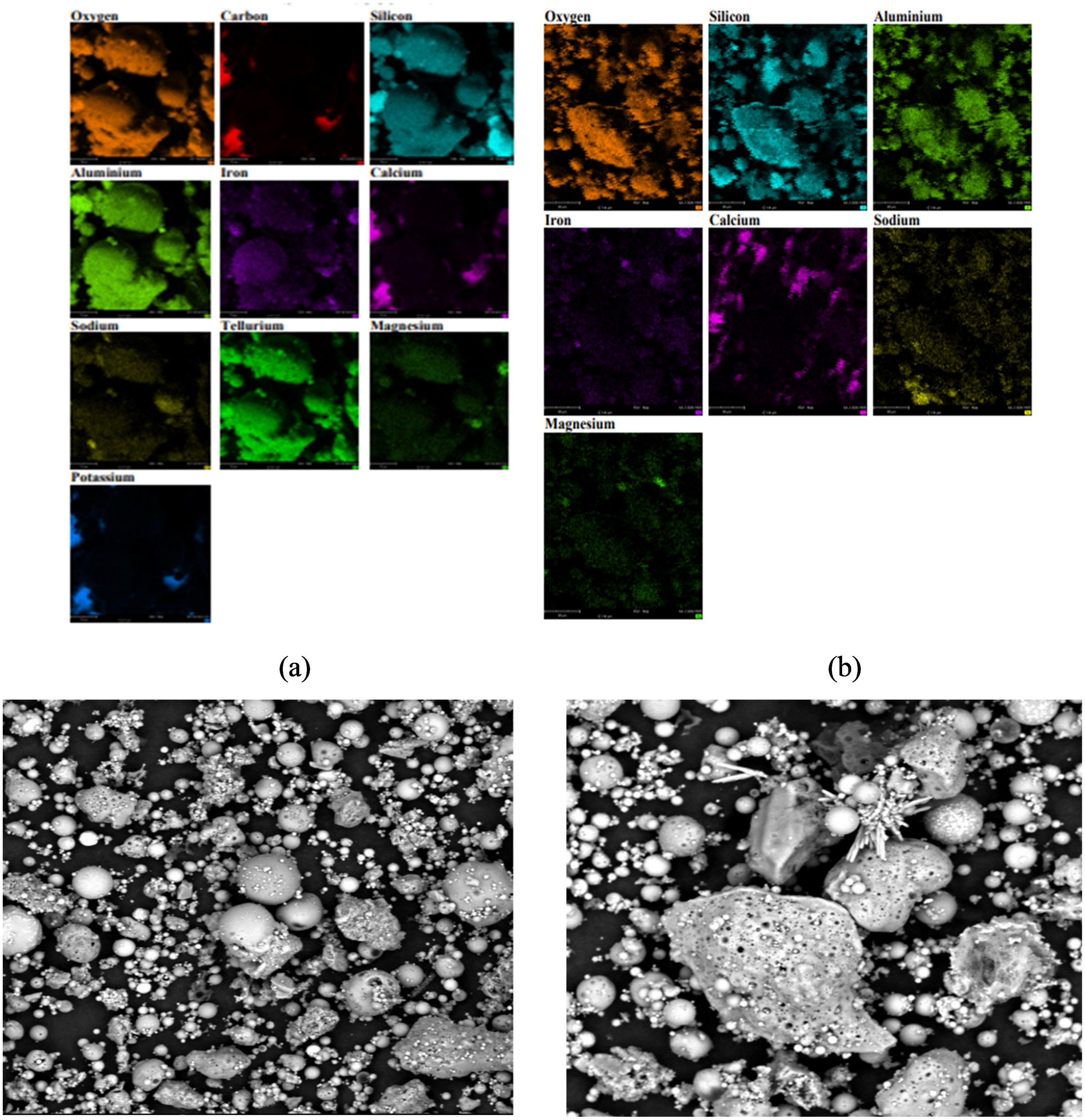
According to the SEM-EDX analysis results listed in Table 1, the chemical elements on the fly ash adsorbent, such as oxygen, silica, aluminium, iron, calcium, sodium, and magnesium, remained before and after activation. However, the elements carbon, potassium, titanium, and sulphur were not detected after activation. The analysis also showed that physical activation increased the atomic concentration as well as the weight concentration of oxygen, silica, aluminium, iron, calcium, sodium, and magnesium. In addition, there was an increase in the composition of silica dioxide (SiO_2) and alumina (Al_2O_3) after activation, as shown in Table 1.

The surface morphological analysis of the fly ash adsorbent using SEM showed significant changes before and after the heating process. Figure 1(c) (before heating) demonstrates the pores of the particles are not fully open. The particles have various shapes, including spherical, irregular, and some of them may be shaped like solid spheres. In general, the surface of the particles looks relatively smooth, although there are some particles that exhibit surface irregularities. The activation process seems to increase the porosity of the particles where there are more open pores or empty spaces. Some particles show a hollower structure or have a rougher surface. Some particles shapes were changed, possibly as a result of the activation process changing the internal or external structure of the particles, as shown in Figure 1(d) (after heating). Figures 1(c) and 1(d) show the SEM results before and after activation of fly ash, respectively.

This morphological analysis shows that activation has successfully changed the structure and surface of fly ash. These changes are likely to affect the properties of fly ash, such as reactivity and adsorption ability. These morphological changes are indicative of the changes that occur as a result of activation.

3.2 Characterization of Fly Ash Adsorbent with XRD

X-Ray Diffraction (XRD) is an analytical method used to identify and characterize the crystal structure of solid materials (Putri et al., 2024). The XRD was used to qualitatively identify the crystalline phase of fly ash (Alterary and Marei, 2021). Characterization using XRD aims to identify the



(a) (b)

(c) (d)

Figure 1. (a) Elemental Constituents of Fly Ash Adsorbent Before Activation; (b) Elemental Constituents of Fly Ash Adsorbent After 100 °C Activation; (c) Surface Morphology of Fly Ash Before Activation (SEM Magnification of 2000×); (d) Surface Morphology of Fly Ash After Activation (SEM Magnification of 2000×)

Table 1. Chemical Composition of Fly Ash Adsorbent Before and After Activation

Element Symbol	Before Activation		After Activation	
	Atomic Concentration	Weight Concentration	Atomic Concentration	Weight Concentration
O	48.76	47.30	69.89	55.82
C	36.80	26.80	-	-
Si	6.54	11.13	15.86	22.24
Al	5.86	9.59	9.73	13.11
Fe	0.58	1.97	1.38	3.86
Ca	0.53	1.28	1.57	3.13
Na	0.43	0.59	1.03	1.18
Mg	0.22	0.33	0.54	0.65
K	0.09	0.21	-	-
Ti	0.06	0.17	-	-
S	0.08	0.16	-	-

main peaks of fly ash adsorbent (Mokrzycki et al., 2022). The analysis was carried out by comparing the peaks in the XRD patterns of fly ash adsorbents before and after heating, which are shown in Figure 2.

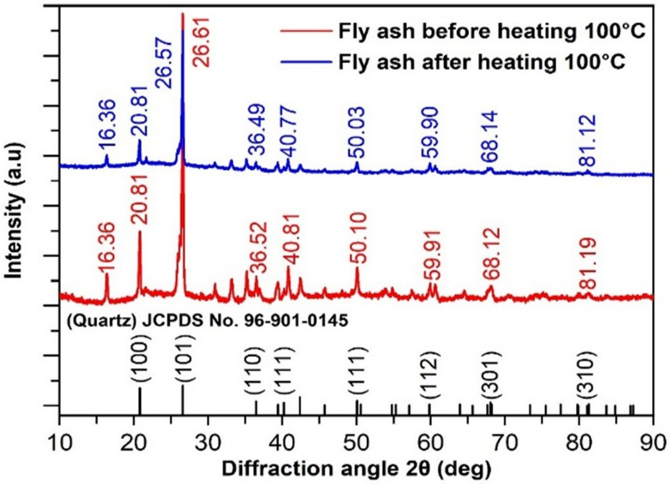


Figure 2. Comparison of Fly Ash Diffraction Before and After 100 °C heating

Identify the phase formed at each peak in the XRD graph of the fly ash, were carried out based on Figure 2. Based on the information provided, it shows the quartz phase. The phase identification for each peak shown in Figure 2: 16.36° (2θ): (100), 20.81° (2θ) :(101) which is characteristic of quartz. For 26.57° and 26.61° (2θ): These are very strong peaks, corresponding to the (101) plane of quartz. This peak is the main characteristic of crystalline quartz. 36.49° and 36.52° (2θ) :(110), 40.77° and 40.81° (2θ) :(111), 50.03° and 50.10° (2θ) :(111), 59.90° and 59.91° (2θ) :(112), 68.12° and 68.14° (2θ) :(301), 81.12° and 81.19° (2θ) :(310) are quartz (Alterary and Marei, 2021).

The peak at a diffraction angle (2θ) of about 26.57° (corresponding to (101) quartz) is very sharp and intense in both samples, indicating the dominant presence of crystalline quartz. In general, the diffraction patterns between fly ash before and after heating at 100 °C look very similar. This indicates that heating at 100 °C did not cause significant changes in the crystalline phase or structure of quartz in the fly ash. The intensity of the peaks differs slightly between the two samples, caused by small changes in crystal size or orientation after heating.

3.3 Effect of Fly Ash Adsorbent Mass on pH in Acid Mine Drainage

The use of fly ash as an adsorbent as in the research conducted by Zhou et al. (2019) using fly ash pellets as adsorbents for phosphorus and heavy metals (Mushtaq et al., 2019), which applying coal fly ash in wastewater treatment. Fly Ash also has potential as an adsorbent in treating wastewater in the pulp and paper industry (Arita et al., 2022). The utilization and management of coal fly ash, which is an industrial waste, is directed towards wastewater treatment applications as a waste recycling effort to overcome the problem of water scarcity (Patel et al., 2022). Fly ash serves as a suitable adsorption material for various applications (Wang et al., 2021). Coal fly ash (CFA)-based adsorbents are an efficient and economical alternative for removing pollutants from water and gas (Mostafa et al., 2019).

Fly ash can also increase the pH of acid mine drainage such as research conducted by Keller et al. (2020) where the initial pH was 1.9, and after adsorption with fly ash, the pH becomes 6. In this research, the initial pH of acid mine drainage was below 5, which was around 3.5, then the pH increased significantly after being adsorbed using fly ash, as shown in Figure 3.

Under initial conditions without the addition of fly ash adsorbent (0 g), the initial pH was 3.5, reflecting the strong characteristics of acid mine drainage. When the adsorbent mass was increased to 10 g, the pH increased sharply to 8.3, indicating a highly effective neutralization process at the

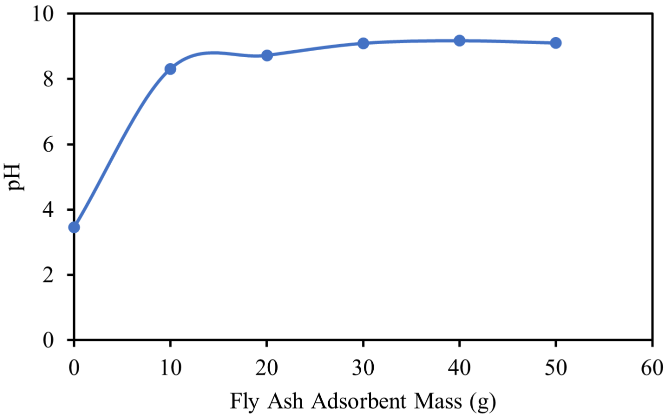


Figure 3. Effect of Fly Ash Adsorbent Mass on pH

initial dose. After the adsorbent mass exceeded the range of 10-20 g, the pH increase slowed down and tended to approach a plateau (the pH increases still occurred but slowed down); adding mass up to 50 g only resulted in a minor increase in pH (around 9-9.1). This pattern indicates an effective (optimum) dose in the range of 10–20 g, where neutralization efficiency is highest before alkalinity equilibrium is reached (Aigbe et al., 2021).

The phenomenon of a significant increase in pH upon initial dosage addition is caused by the basic oxide content in fly ash, particularly CaO, MgO, and calcium-aluminosilicate, which react with hydrogen ions (H^+) in acidic water to form hydroxide ions (OH^-). This mechanism is the dominant mechanism in the neutralization of acidic mine drainage and has been explained by various studies. According to Keller et al. (2020), fly ash has a high neutralization capacity due to the hydration reaction of basic oxides, which produces $Ca(OH)_2$ that then neutralises the acidity. Zhou et al. (2019) also confirmed that fly ash-based materials rich in alkali minerals are capable of increasing pH and adsorbing dissolved metals.

In addition to neutralization reactions, the increase in pH is also enhanced by surface adsorption, ion exchange, and metal precipitation at alkaline pH. When the pH rises above 5-6, metal ions such as Fe^{3+}, Al^{3+}, and Mn^{2+} begin to form insoluble hydroxides (e.g. $Fe(OH)_3$ and $Al(OH)_3$). This process reduces the concentration of metal ions that can undergo hydrolysis, thereby preventing the production of H^+. Similar findings were reported by Anupam et al. (2022), who showed that an increase in pH due to fly ash was followed by metal precipitation, causing the pH to stabilize.

Overall, the pattern shown is very consistent with previous literature. Fly ash has been proven to be effective as a neutralising material and adsorbent for reducing heavy metals in acid mine water. Therefore, these results reinforce the potential of fly ash as a cheap, abundant, and environmentally friendly alternative adsorbent for acid mine drainage treatment. Coal fly ash (CFA)-based adsorbents are an efficient and economical alternative for removing pollutants from water and gas (Mostafa et al., 2019).

The results of this study demonstrate that fly ash is highly effective in increasing the pH of acid mine drainage (AMD). The initial AMD pH of approximately 3.45 increased to near-neutral values following treatment, and the magnitude of pH elevation increased proportionally with the mass of fly ash applied, as shown in Figure 3. This trend is consistent with observations reported by Jones and Cetin (2017); Priatmadi et al. (2022) who indicated that applying coal fly ash at a dosage of 50 Mg ha^{-1} effectively elevated the pH of acid mine drainage compared to the untreated control. This pH increase is likely due to the dissolution of CaO and MgO present in the fly ash, which release OH^- ions that subsequently neutralize the acidity of the mine drainage (Jones and Cetin, 2017). The increase in pH can be primarily attributed to the dissolution of basic oxides such as CaO and MgO present in the fly ash. Upon hydration, these oxides release OH^- ions, which neutralize the acidity of AMD. Additional buffering is provided by carbonate minerals within fly ash, which react with H^+ and contribute to a more stable pH increase. As pH rises, hydrolysis and precipitation of metal ions (Fe^{3+}, Al^{3+}, Mn^{2+}) further reduce acidity while simultaneously lowering dissolved metal concentrations. These processes, combined with adsorption onto aluminosilicate surfaces, enhance overall AMD treatment performance.

3.4 Effect of Fly Ash Adsorbent Mass on Mn and Fe Metal Ions Sorption in Acid Mine Drainage

The adsorption performance of fly ash toward Mn and Fe ions increased substantially with addition of 10 g of adsorbent, as illustrated in Figure 4. With a volume of 250 mL of acid mine 10 g, the adsorption percentage of Mn metal was recorded at 84.41%, while Fe metal reached 83.33%. At an adsorbent weight of 20 g, the percentage of Mn metal adsorption increased to 93.80%. Furthermore, with the addition of adsorbent up to 50 g, the removal of heavy metal ions Mn and Fe reached 96.61% and 83.33%, respectively.

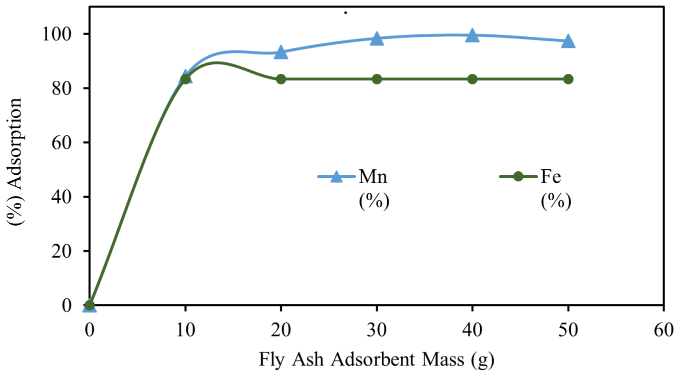


Figure 4. Effect of Fly Ash Adsorbent Mass on Adsorption Percentage

Once the mass reached 10–20 g, the curve began to flatten, indicating that most of the metal ions had interacted with the active sites, bringing the system close to saturation capacity. Adding mass up to 50 g only increased adsorption slightly because the concentration of metal ions in the solution was already limited and the adsorbent had reached equilibrium (Aigbe et al., 2021; Pratama et al., 2022).

This phenomenon is influenced by adsorption mechanisms involving electrostatic interactions, ion exchange, and metal hydroxide precipitation due to an increase in pH caused by fly ash alkalinity. At high adsorbent masses, additional effectiveness decreases because particle accumulation slows down intra-porous diffusion, so adsorption performance does not increase significantly. The efficiency of Mn is slightly higher than that of Fe, presumably due to the smaller size of Mn^{2+} ions and their easier adsorption onto the silica–alumina structure of fly ash (Zhang et al., 2022).

The difference in efficiency between Mn and Fe is related to the chemical properties of the ions and the removal mechanism. Mn^{2+} ions are more easily adsorbed and precipitated at higher pH conditions, so that an increase in pH due to the reaction of basic oxides (especially CaO and MgO) in fly ash accelerates the precipitation of $Mn(OH)_2$. Conversely, Fe^{3+} tends to precipitate at lower pH as $Fe(OH)_3$, so that ion competition mechanisms can reduce comparative adsorption efficiency. The plateau phenomenon in both metals indicates the achievement of adsorption–precipitation equilibrium, as reported by Aigbe et al. (2021) and Anupam et al. (2022). These findings are consistent with reports Keller et al. (2020)) and Wang et al. (2021), which states that fly ash is an effective adsorbent for removing metals from acid mine water through a combined mechanism of surface adsorption, ion exchange, and hydroxide precipitation.

From this data, it can be concluded that the variation of fly ash adsorbent weight or mass has a significant influence on the adsorption of Mn and Fe metal ions in acid mine drainage. The greater the amount of adsorbent used, the higher the adsorption percentage obtained. These results clearly demonstrate that adsorbent mass plays a critical role in enhancing metal ion adsorption, where larger amounts of fly ash provide more active sites, greater surface area, and higher availability of reactive functional groups for metal binding. The increasing removal trend with higher dosage is consistent with the findings of Goyal et al. (2019). Similar data also found that the fly ash exhibited adsorption efficiencies of 82.95% for iron (Fe), 93.4% for manganese (Mn) (Pratama et al., 2023).

Fly ash (FA) serves as an effective and low-cost adsorbent for heavy metals and dyes due to its favorable surface structure, charge characteristics, and morphology. Consequently, FA, whether used on its own or combined with photocatalytic materials, functions as a versatile substrate capable of simultaneously removing both contaminants, as reported by Aigbe et al. (2021). The strong adsorption capability of fly ash can be attributed to its physicochemical characteristics, including its porous structure, heterogeneous surface morphology, and negatively charged aluminosilicate matrix. These features facilitate electrostatic attraction, surface complexation, and ion exchange interactions with dissolved metal ions. Additionally, previous research has highlighted that fly ash can act as a low-cost yet highly effective adsorbent for various pollutants due to its structural properties and surface charge behavior, and its performance can be further enhanced when combined with photocatalytic or other functional materials (Aigbe et al., 2021). Moreover, fly ash possessed a high degree of porosity, allowing volatile heavy metals such as Pb and Hg to become readily concentrated on its surface (Tian et al., 2015). Overall, the experimental results confirm that increasing fly ash dosage significantly improves Mn and Fe removal efficiency, reinforcing its potential as a practical adsorbent for treating acid mine drainage.

3.5 Adsorption Percentage of Fly Ash Adsorbent After 100 °C Activation

The percentage of Mn metal adsorption using adsorbent mass variations of 10-50 g is shown in Figure 5. At an initial dose of 10 g, Mn removal reached 93.18%, indicating a strong affinity of the adsorbent for Mn even at relatively low mass. Increasing the dose to 30 g resulted in a slight improvement to 94.93%, while further additions to 40 g and 50 g yielded removal efficiencies of 94.54% and 94.70%, respectively. These results show that although the addition of fly ash enhances Mn adsorption, the effect becomes marginal beyond 10–20 g, with removal efficiency stabilizing at approximately 94%. This result suggests that most available Mn ions in the solution had already been adsorbed at lower doses, and further increases in adsorbent mass did not provide additional benefit due to saturation of available binding sites relative to the metal concentration. This finding is in accordance with previous study, on average, activated fly ash has been shown to remove up to 95.15% of manganese (Mn), achieving an overall adsorption efficiency of 87.95% (Pratama et al., 2023). Several studies have also explored the use of modified fly ash as an adsorbent, highlighting its potential as a cradle-to-cradle approach for addressing mining-related waste challenges. Such high removal performance can be attributed to the porous structure, reactive aluminosilicate surface, and favorable charge characteristics of fly ash, which collectively facilitate surface complexation and ion exchange with Mn ions. Furthermore, recent studies have explored modified and engineered fly ash materials as sustainable adsorbents, highlighting their potential to simultaneously address waste generation and AMD treatment challenges (Madzivire et al., 2019).

The experimental results show an initial increase in Mn ion removal efficiency when the fly ash adsorbent mass is increased from 10 g (93.18%) to 30 g (94.93%), while a further increase to 40–50 g only results in marginal changes (94.54–94.70%). This pattern of rapid increase at initial

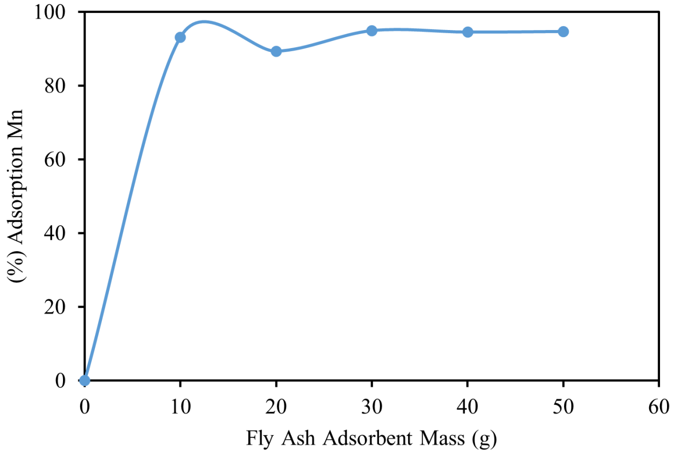


Figure 5. Effect of Fly Ash Adsorbent Mass (After 100 °C Activation) on Mn Adsorption Percentage

doses followed by a plateau is consistent with the dose-response behavior in many adsorption systems, where an increase in the number of effective active sites leads to surface equilibrium and saturation conditions (Raji et al., 2023; Hussain et al., 2022).

The stable removal rates close to 94% across the tested mass range indicates a dual mechanism contribution: surface adsorption and chemical processes in solution such as precipitation/co-precipitation. Fly ash contains oxides (Ca, Mg, Al) and silicate fractions that are alkaline in nature, thereby increasing the local pH, triggering the formation of Mn hydroxide and facilitating co-precipitation with other metal hydroxides, this mechanism has been described in studies on the use of fly ash for acid mine water treatment. In addition, thermal activation (heating) of fly ash can increase porosity and specific surface area, thereby increasing adsorption capacity, but mild activation effects (e.g. 100 °C) often only provide moderate improvements compared to higher activation (Hussain et al., 2022; Ridhowan et al., 2021).

The phenomenon of particle aggregation and mass transfer limitations (film diffusion/intraparticle diffusion) can reduce the effective surface area, so that adding mass no longer has a significant effect on the percentage of removal. The hydrodynamic conditions of the system (fixed solution volume, contact time, stirring speed) and the initial ion concentration are determining factors in whether increasing the mass will provide practical benefits. Based on the efficiency vs. cost relationship and the potential for side deposit formation, these data suggest that increasing the mass beyond a point of approximately 30 g under these experimental conditions is not economical; optimization approaches (e.g. surface modification, appropriate thermal activation, or improved hydrodynamic contact) are more promising than simply adding more adsorbent mass. These findings and interpretations are consistent with recent reviews and experimental studies on heavy metal adsorption using fly ash and modified materials (Raji et al., 2023). Overall, the results confirm that fly ash is a highly effective adsorbent for Mn removal, and that optimal performance can be achieved at relatively low dosages.

4. CONCLUSIONS

In the fly ash adsorbent before activation, the carbon content was found to be higher, but after activation, the percentage of silica content increased. The addition of fly ash as an adsorbent to acid mine drainage serves to increase the pH of acid mine drainage, which was initially 3.45, to reach 8.31 as the mass of fly ash adsorbent increases. The use of 50 g of fly ash as an adsorbent showed that the removal of Mn and Fe heavy metal ions reached 96.61% and 83.33%, respectively. By using the fly ash adsorbent which activated at 100 °C, the adsorption of Mn ions between 30-50 g achieved the adsorption percentage of around 94%. This study provides valuable insight into the effectiveness of fly ash in increasing pH and reducing heavy metal ion content in acid mine drainage treatment. The utilization of fly ash adsorbent for the treatment of acid mine drainage in this study can fulfil the environmental quality standard of acid mine drainage for pH, Fe, and Mn heavy metal ions.

5. ACKNOWLEDGEMENT

The research/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2023. SP DIPA-023.17.2.677515/2023. On November 30, 2022. In accordance with the Rector's Decree Number: 0187/UN9.3.1/SK/2023, on April 18, 2023. The authors also thank the Universitas PGRI Palembang for the financial support in this research through Dissertation Grant.

REFERENCES

Agustina, T. E., T. Aprianti, and S. Miskah (2017). Treatment of Wastewater Containing Hexavalent Chromium Using Zeolite Ceramic Adsorbent in Adsorption Column. *International Journal on Advanced Science, Engineering and Information Technology*, **7**(2); 566–572

Aigbe, U. O., K. E. Ukhurebor, R. B. Onyancha, O. A. Osibote, H. Darmokoesoemo, and H. S. Kusuma (2021). Fly Ash-Based Adsorbent for Adsorption of Heavy Metals and Dyes from Aqueous Solution: A Review. *Journal of Materials Research and Technology*, **14**; 2751–2774

Alterary, S. S. and N. H. Marei (2021). Fly Ash Properties, Characterization, and Applications: A Review. *Journal of King Saud University - Science*, **33**(6); 101536

Anupam, N. B. S., A. Anindita, and D. P. Singh (2022). Coal Fly Ash: An Emerging Material for Water Remediation. *International Journal of Coal Science & Technology*, **9**(1); 1–25

Arita, S., D. Kristianti, and L. Nurul (2022). Effectiveness of Biomass-Based Fly Ash in Pulp and Paper Liquid

Waste Treatment. *South African Journal of Chemical Engineering*, **41**; 79–84

Chindaprasirt, P. and U. Rattanasak (2020). Synthesis of Porous Alkali-Activated Materials for High-Acidic Wastewater Treatment. *Journal of Water Process Engineering*, **33**; 101118

Dolic, M., M. Karanac, D. Radovanovic, A. Umicevic, A. Kapidzic, Z. Velickovic, A. Marinkovic, and Z. Kamberovic (2021). Closing the Loop: As(V) Adsorption onto Goethite Impregnated Coal-Combustion Fly Ash as Integral Building Materials. *Journal of Cleaner Production*, **303**; 126924

Ehiomogue, P., I. I. Ahuchaogu, and I. E. Ahaneku (2022). Review of Adsorption Isotherms Models. *Acta Technica Corviniensis - Bulletin of Engineering*, **14**(4); 87–96

Fadhilah, F. Ramadhan, and R. Har (2022). Treatment of Acid Mine Drainage Using Fly Ash, Bottom Ash, and Lime Mixed. *JIPF (Jurnal Ilmu Pendidikan Fisika)*, **7**(2); 168–177

Fajri, D. P. F. and A. Takwanto (2024). Proses Aktivasi Arang dari Tempurung Kelapa Menggunakan Aktivasi Fisika dengan Microwave dan Variasi Waktu. *Distilat: Jurnal Teknologi Separasi*, **10**(2); 476–484

Goyal, M. K., A. Dwivedi, and D. Sharma (2019). Fly Ash as an Adsorbent for Removal of Heavy Metal: A Review. *International Journal of Research and Analytical Reviews (IJRAR)*, **6**(1); 835–851

Hussain, Z., H. Zhang, N. Chang, and H. Wang (2022). Synthesis of Porous Materials by the Modification of Coal Fly Ash and Its Environmentally Friendly Use for the Removal of Heavy Metals from Wastewater. *Frontiers in Environmental Science*, **10**; 1085326

Jones, S. N. and B. Cetin (2017). Evaluation of Waste Materials for Acid Mine Drainage Remediation. *Fuel*, **188**; 294–309

Kalombe, R. M., T. V. Ojumu, V. N. Katambwe, M. Nzadi, D. Bent, G. Nieuwouldt, G. Madzivire, J. Kevern, and L. F. Petrik (2020). Treatment of Acid Mine Drainage with Coal Fly Ash in a Jet Loop Reactor Pilot Plant. *Minerals Engineering*, **159**; 106611

Keller, V., S. Stopic, X. Buhle, and B. Friedrich (2020). Effectiveness of Fly Ash and Red Mud as Strategies for Sustainable Acid Mine Drainage Management. *Minerals*, **10**(12); 1128

Komala, R., Subroto, Sisnayati, H. Dwipayana, and Nurlela (2024). Comparison of Alum and Poly Aluminum Chloride Coagulant Performance on Turbidity and pH of Lematang Enim PDAM Raw Water. *Sainmatika: Jurnal Ilmiah Matematika dan Ilmu Pengetahuan Alam*, **21**(1); 30–38

Madzivire, G., R. M. Maleka, M. Tekere, and L. F. Petrik (2019). Cradle to Cradle Solution to Problematic Waste Materials from Mine and Coal Power Station: Acid Mine Drainage, Coal Fly Ash and Carbon Dioxide. *Journal of Water Process Engineering*, **30**; 100474

Mokrzycki, J., M. Fedyna, M. Marzec, J. Szerement, A. Klimek, T. Bajda, and M. Mierzwa-Hersztek (2022). Copper Ion-Exchanged Zeolite X from Fly Ash as an Efficient Adsorbent of Phosphate Ions from Aqueous Solutions. *Journal of Environmental Chemical Engineering*, **10**(4); 108567

Mostafa, S. S., H. G. Asl, H. Javadian, M. Khavarpour, C. Belviso, M. Taghavi, M. Maghsudi, and C. Ash (2019). Porous Adsorbents Derived from Coal Fly Ash as Cost-Effective and Environmentally-Friendly Sources of Aluminosilicate for Sequestration of Aqueous and Gaseous Pollutants: A Review. *Journal of Cleaner Production*, **208**; 1131–1147

Muksin, C., F. Mulana, N. Nasrullah, A. Azwar, and A. Chintia (2024). Enhancing Diatomaceous Earth Characteristics for Adsorption of Heavy Metals from Acid Mine Drainage: The Impact of Dual Modifications. *Journal of Chemical Engineering and Environment*, **19**(1); 10–17

Mushtaq, F., M. Zahid, I. A. Bhatti, S. Nasir, and T. Hussain (2019). Possible Applications of Coal Fly Ash in Wastewater Treatment. *Journal of Environmental Management*, **240**; 27–46

Patel, M. G., P. G. Marakana, A. Dey, B. Saini, and H. Chokshi (2022). Coal Fly Ash Derived Adsorbent for Enhancing Waste Water Treatment. *Materials Today: Proceedings*, **57**; 1630–1634

Pisceselia, D. F., S. Arita, and T. E. Agustina (2023). Pulp and Paper Wastewater Treatment with Bottom Ash Using Jar Test. *Journal of Ecological Engineering*, **24**(1); 188–194

Pratama, F. A., H. Rizki, N. Rohman, and F. B. Pangestu (2023). Analysis the Effectiveness of Coal Fly-Ash as Adsorbent in Neutralizing Heavy Metal Content in Acid Mine Drainage, Case Study at “Post-Mining Land X”. *Jurnal Teknik Patra Akademika*, **14**(1); 30–36

Pratama, H., E. Nursanto, R. Ernawati, and M. Giatman (2022). Adsorption of Heavy Metals Fe and Mn in Acid Mine Drainage from Coal Mining Waste Using Calcium Oxide and Fly Ash. *Jurnal Pertambangan*, **22**(2); 107–116

Priatmadi, B. J., M. Septiana, R. Mulyawan, and A. R. Saidy (2022). Increases in pH of Acid Mine Drainage with Coal Fly-Ash Application. *IOP Conference Series: Earth and Environmental Science*, **976**(1); 012020

Putri, R., F. Goembira, M. Ulfah, M. Andrifar, and R. Yuliarningsih (2024). Synthesis of Zeolite from Fly Ash and Bottom Ash and Application for Biodiesel Transesterification. *Journal of Chemical Engineering and Environment*, **19**(1); 45–53

Rafizan, S., H. Marsad, R. I. Ergantara, and D. Ayu (2022). Salinitas Air Sumur Di Kelurahan Lempasing. *Jurnal Analis Farmasi*, **7**(1); 42–50

Raji, Z., A. Karim, A. Karam, and S. Khalloufi (2023). Adsorption of Heavy Metals: Mechanisms, Kinetics, and Applications of Various Adsorbents in Wastewater Remediation—A Review. *Reviews in Environmental Science and Bio/Technology*, **22**; 775–805

Ridhowan, T., E. S. Yusmartini, and D. Kharismadewi (2021). Optimization of Coal Fly Ash Heating Temperature as an Adsorbent to Improve Acid Mine Water Quality. *Indonesian Journal of Fundamental and Applied Chemistry*, **6**(3); 96–103

Roulia, M., D. Alexopoulos, G. Itskos, and C. Vasilatos (2022). Lignite Fly Ash Utilization for Acid Mine Drainage Neutralization. *Cleaner Materials*, **4**; 100142

Tavengwa, T. (2019). Synthesis of Di-Carboxylic Acid Functionalized Zeolites from Coal Fly Ash for Cd(II) Removal from Acid Mine Drainage Using Column Studies Approach. *Journal of Environmental Chemical Engineering*, **7**(5); 103473

Tian, Z., B. Zhang, C. He, R. Tang, H. Zhao, and F. Li (2015). The Physiochemical Properties and Heavy Metal Pollution of Fly Ash from Municipal Solid Waste Incineration. *Process Safety and Environmental Protection*, **98**; 333–341

Wang, C., G. Xu, X. Gu, Y. Gao, and P. Zhao (2021). High Value-Added Applications of Coal Fly Ash in the Form of Porous Materials: A Review. *Ceramics International*, **47**(16); 22302–22315

Zhang, D., R. Cao, Y. Song, Y. Wang, P. Zhang, Y. Wang, F. Xiao, S. Wang, and Y. Jia (2022). Molecular Structures of Dissolved and Colloidal As(V)–Fe(III) Complexes and Their Roles in the Mobilization of As(V) under Strongly Acidic Conditions. *Journal of Hazardous Materials*, **430**; 128266

Zhou, H., R. Bhattarai, Y. Li, S. Li, and Y. Fan (2019). Utilization of Coal Fly and Bottom Ash Pellet for Phosphorus Adsorption: Sustainable Management and Evaluation. *Resources, Conservation & Recycling*, **149**; 372–380