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Improvement of pH and Reduction of Heavy Metal Concentrations in Acid Mine

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Abstract: The oxidation of sulfide mineral compounds mixed with water during mining activities produces acid mine drainage (AMD). Due to the low pH and high concentrations of metals, remediation is needed before AMD is allowed to flow into free water systems. Therefore, this study aims to quantify the effect of coal fly ash (CFA) and organic matters (OMs) application on the changes in pH and heavy metal concentrations of AMD. Three different organic matters, namely chicken manure, water hyacinth, and empty fruit bunch of oil palm (EFBOP), were added to reclaimed mining soils (RMSs) either single or in combination with coal fly-ash (CFA) in a batch reactor experiment. After incubation at 70% water holding capacity for 15 days, the mixtures of RMSs and treatments in the reactors were gradually introduced to AMD, and changes in pH were monitored over 336 hours. Furthermore, the removal of Fe, Al, and Mn in the treated AMD was also quantified. The results showed that the separate application of OMs and CFA increased pH from 3.18 to 5.04-5.43 and 6.94, respectively, while simultaneous application increased the pH from 3.18 to 7.62−7.70. Similarly, the removal of metals (Fe, Mn, and Al) was also significantly higher when OMs and CFA were added concurrently than separate addition. This study demonstrates that the application of OMs with CFA improves pH and reduces heavy metal concentrations in AMD.

Keywords: constructed wetland, passive treatment, adsorption, functional groups.

酸性礦山酸鹼度值的提高和重金屬濃度的降低

摘要：在採礦活動中與水混合的硫化物礦物化合物的氧化會產生酸性礦井排水。由於低酸碱度值和高金屬濃度，在允許酸性礦山排水流入自由水系統之前需要進行補救。因此，本研究旨在量化粉煤灰和有機物應用對酸性礦山排水的酸碱度值和重金屬濃度變化的影響。在間歇反應器實驗中，將三種不同的有機物質，即雞糞、水葫蘆和油棕空果串，單獨或與粉煤灰結合添加到再生採礦土壤中.在 70% 的持水量下孵育 15 天后，將反應器中的回收的採礦土壤和處理的混合物逐漸引入酸性礦山排水，並在 336 小時內監測酸鹼度值的變化。此外，還對處理過的酸性礦山排水中鐵、鋁和錳的去除進行了量化。結果表明，單獨施用有機物和煤粉煤灰分別使酸鹼度值從 3.18 增加到 5.04-5.43 和 6.94，而同時施用使酸鹼度值從 3.18 增加到 7.62-7.70。同樣，當同時添加有機物和煤粉煤灰時，金屬（鐵、鋁和錳）的去除率也明顯高於單獨添加。這項研究表明，有機物與煤粉煤灰的應用改善了酸性礦山排水中的酸鹼度值並降低了重金屬濃度。

关键词：人工濕地、被動處理、吸附、官能團。

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1. Introduction

Acid mine drainage produced from the oxidation of sulfide compounds causes environmental problems for water resources, threatening human health [1] due to the low pH and high concentration of heavy metals [2, 3]. Meanwhile, the flow of AMD from the management site in mining areas to open water systems poses serious problems to benthic invertebrates [4, 5] and fish communities [6, 7]. It also causes the disruption of physiological processes in rice fields which in turn decreases production [8]. Therefore, the management of AMD is necessary to meet environmental quality standards before its release into free waters.

A typical treatment for increasing pH and heavy metal precipitation of AMD is the application of lime [9, 10]. Although highly successful and easy to implement, the application of lime materials such as limestone is very expensive [11, 12]; therefore, this method is regarded as a non-economical viable option. In addition, limestone is considered a mineral resource; hence, long-term use and in high amounts potentially leads to environmental disturbances [13]. Constructed wetlands are an inexpensive AMD management and considered low-energy and less-operational requirements compared to limestone application [14, 15]. Several studies have shown the high efficiency of constructed wetlands to increase pH and reduce the concentrations of heavy metals in AMD [16, 17].

The high efficiency of the constructed wetlands to improve the quality of AMD occurs through the precipitation of H^+ and heavy metals by the mechanisms of complexation, ion exchange, and adsorption [18, 19]. Mohammed and Babatunde [20] reported 89%, 91%, and 91% removal of Pb, Cr, and Cd from AMD using constructed wetlands. Meanwhile, the addition of OMs to the constructed wetlands leads to a higher metal removal [21, 22]. Waste and by-products from industrial activities such as rice husk, coal fly-ash, paper mill, steel mill, blast furnace slag also have high capabilities as materials for remediating AMD [13, 23]. This study shows the importance of sorbent materials in improving the capability of constructed wetlands in AMD management.

Coal fly ash (CFA) is a waste produced from the coal combustion of power plants and generally contains metal oxides; hence, it can neutralize the acidic pH of AMD. Furthermore, CFA application reportedly improves the quality of AMD [24, 25], where the degree of improvement is controlled by the amount applied CFA [28]. Organic matter was also applied for the remediation of AMD [21, 27]. Functional groups of OMs with negative charges react with positively charged hydrogen and heavy metals in AMD, increasing pH and decreasing heavy metal concentrations [28, 29]. Although several studies have been carried out to improve the quality of AMD with the application of coal fly-ash and OMs, there is no report on the combination of both OMs and CFA in remediating AMD. Therefore, this study aims to quantify the effect of CFA application in combination with OMs on changes in pH and heavy metal concentrations of AMD.

2. Materials and Methods

2.1. Sampling and Characterization of Soil, Organic Matters, and Coal Fly-Ash

This study used soils collected from reclaimed diamond mining areas in Desa Palam, Cempaka Sub-district, Banjarbaru Regency, Indonesia. The soil was sampled at a 0-30 cm depth using a soil auger at several sampling points adjacent to the ponds used for AMD management. Furthermore, the samples were homogenized after cleaning for plant debris, placed in plastic bags, transported to the laboratory for air-drying, grind to 2 mm, and then stored at 4 ºC before being used for the study. The soil sub-samples were then characterized for physical (particle size, bulk density, and particle density) and chemical (pH, organic C contents, N, P, K, Ca, Mg, Na, K, Al, Fe, Mn, and exchangeable cation capacity) properties using the standardized methods. The physical and chemical characteristics of soils used for this study are presented in Table 1. Meanwhile, AMD was sampled from a diamond washing plant in the Desa Palam, Cempaka Sub-district, Banjarbaru Regency, Indonesia.

The OMs for this study consisted of chicken manure, water hyacinth, and empty fruit bunches of oil palm (EFBOP). Chicken manure and water hyacinth (*Eichhornia crassipes*) were obtained from small-holder chicken farms and a river near the reclaimed diamond mining areas. At the same time, EFBOP was sampled from oil palm processing plant of the PT Perkebunan Nusantara XIII at the Desa Ambungan, Pelaihari Sub-district, Tanah Laut Regency, Indonesia. All OMs were ground to a-2 mm size after oven-dried at 60º C for 72 hours and then characterized for organic C [30], N content [31], hot water soluble C (carbohydrate) [32], as well as lignin [33], and ash contents [34].

The coal fly-ash was collected from the power plant of PT Total Power Indonesia (TPI) situated at Desa Kasiyau Raya, Kecamatan Murung Pudak, Tabalong Regency, South Kalimantan. The sample was air-dried, sieved to a-2 mm size, and then digested using a mixture of HNO_3 and $HClO_4$. The concentrations of cations including K, Na, Ca, Mg, Al, Fe, and Mn in the digested solution were determined by atomic absorption spectrophotometry (Shimadzu AA6300G). The characteristics of coal fly-ash in the study are presented in Table 2 in the Results section.

2.2. Laboratory Experiment

A laboratory experiment was conducted to examine the effect of coal fly-ash and OMs applications on the changes in pH and heavy metal removal of AMD using a batch reactor system. The experiment, employed a completely randomized design, consisted of 6 treatments: (1) control i.e., soil without OM and CFA (2) soil + chicken manure, (3) soil + water hyacinth, (4) soil + EFBOP, (5) soil + CFA, (6) soil + chicken manure + CFA, (7) soil + water hyacinth + CFA, and (8) soil + EFBOP + CFA, with 3 replications each. An amount of soil (2,000 g) was placed in a reactor with length: 35 cm x width: 15 cm, height: 9 cm to obtain a 4-cm depth of soil layer. Furthermore, according to the treatments, OMs (200 g) and CFA (200 g) were added and mixed homogeneously. Aquadest was added to soils in the reactor to obtain 60% of water holding capacity, and the mixtures of soil, OMs, and coal fly-ash were incubated at room temperature in the dark for 15 days. The water content of mixed soil, OMs, and CFA was maintained at 60% water holding capacity by adding Aqua Dest to compensate for water loss through evaporation during the incubation period. Sub-sampling was then carried out by collecting approximately 200g of soil, OM, and coal fly-ash mixtures from the reactors after the completion of incubation. The collected samples were then air-dried to determine pH [35], CEC [36], and specific surface areas (Nova 4200 Analyzer, Boynton Beach, USA).

After the incubation period, AMD was slowly released to each reactor until the level reached an average of 3 cm from the top of the soil. The pH measurement for each reactor was conducted at 6, 12, 24, 48, 72, 144, 216, and 336 hours after the AMD flowed into the reactors using a pH meter (Hanna HI98190). Meanwhile, Fe, Al, and Mn were measured by removing 100 ml of treated AMD from each reactor through the outlet at the end of the study and then filtered through a 0.45 µm syringe filter (MF-Millipore® Membrane Filter). The heavy metal concentrations in the treated AMD were determined using atomic absorption spectrophotometry (Shimadzu AA6300G).

2.3. Statistical Analysis

Analysis of variance was carried out to quantify the effect of treatments on changes in the pH and the heavy metals (Al, Fe, and Mn) concentration in AMD. The data were initially quantified for homogeneity and normality using Bartlett and Shapiro–Wilk test, respectively. Treatments that significantly affect the observed variables were then analyzed using the least significant difference (LSD) test at $P < 0.05$. All statistical analyses were conducted using the statistical package of GenStat 12 [37].

3. Results and Discussion

3.1. Characteristics of Soil, Coal Fly-Ash, and Organic Matters

The soil used for this study had a clay texture, with a high bulk density (1.34 g cm^{-3}) as commonly observed in reclaimed-mining soils. This soil had a high level of acidity with a pH of 3.23 (Table 1), low organic carbon (C), and nitrogen (N) contents, as well as moderate cation exchangeable capacity (CEC) and relatively low exchangeable bases (Na, K, Mg and Ca) (Table 1). Meanwhile, the CFA used for this study was characterized by relatively neutral pH (7.98) with significantly low organic C and N contents. In addition, the Ca and Mg concentrations were relatively high, reached to 1.57 g kg^{-1} and 1.48 g kg^{-1}, respectively (Table 1).

Table 1 Characteristics of the soil and coal fly-ash. Numbers in the parenthesis represent the standard deviation of the mean (n = 3)

Characteristics	Soil	Coal Fly-Ash
Texture		
- Sand (%)	35.65 (4.65)	-
- Silt (%)	23.87 (2.11)	-
- Clay (%)	40.48 (3.54)	-
Bulk density (g cm^{-3})	1.34 (0.16)	1.66 (0.18)
Particle density (g cm^{-3})	1.81 (0.09)	2.14 (0.11)
pH (H_2O)	3.23 (0.07)	7.98 (0.12)
Organic C (g kg^{-1})	15.76 (0.96)	1.65 (0.06)
N (g kg^{-1})	2.54 (0.07)	0.16 (0.04)
P (g kg^{-1})	6.54 (0.09)	0.14 (0.06)
Na (mg kg^{-1})	2.12 (0.67)	435.87 (9.65)
K (mg kg^{-1})	1.98 (0.43)	587.34 (8.97)
Ca (mg kg^{-1})	2.65 (0.49)	1567.67 (9.67)
Mg (mg kg^{-1})	4.65 (0.43)	1476.54 (9.66)
Al (mg kg^{-1})	12.54 (0.98)	765.45 (8.87)
Fe (mg kg^{-1})	8.98 (0.67)	476.76 (7.76)
Mn (mg kg^{-1})	7.54 (0.23)	143.54 (5.66)
CEC (cmol kg^{-1})	20.54 (1.54)	-

Empty fruit bunches of oil palm (EFBOP) contained the highest organic C content compared to other OMs but had a low total N. In contrast, chicken manure had relatively high organic C and total N; therefore, the C/N ratio (w/w), calculated based on total dry organic matter, was lower in chicken manure (7.59) compared to EFBOP (22.49). Water hyacinth had low organic C and total N contents; therefore, the C/N ratio ranged between chicken manure and EFBOP. The highest hot water-soluble C was observed in chicken manure, while water hyacinth and EFBOB were the lowest (Table 2). The lignin content in the three OMs ranged from the lowest in chicken manure (17 g kg^{-1}) to the highest in EFBOP (74 g kg^{-1}). Differences in these characteristics suggest that OMs used in this study have different chemical compositions.

Table 2 Chemical characteristics of organic matter. Numbers in the parenthesis represent the standard deviation of the mean (n = 3)

Chemical Characteristics	Chicken Manure	Water Hyacinth	Empty Fruit Bunches of Oil Palm
Organic C (g kg^{-1})	412.65 (3.45)	286.37 (5.64)	489.35 (9.56)
Total N (g kg^{-1})	54.34 (2.34)	18.76 (1.56)	21.76 (0.54)
Hot water-soluble C (g kg^{-1})	118.74 (1.34)	25.43 (0.87)	27.76 (1.24)
Lignin (g kg^{-1})	16.54 (0.87)	39.76 (1.23)	73.76 (0.87)
Ash contents (g kg^{-1})	12.36 (0.56)	28.45 (0.98)	23.76 (0.98)
C/N ratio	7.59 (1.21)	15.26 (0.88)	22.49 (0.98)

3.2. Changes in pH of Acid Mine Drainage due to Organic Matter and Coal Fly-Ash Applications

The study showed that the application of OMs and CFA increased the pH, depending on the types of applied OMs. The increase in pH with the addition of chicken manure started 6 hours after reaction, gradually increased after 48 hours, and then remained unchanged until the end of the observation (14 days) (Fig. 1A). The application of CFA and the combination of chicken manure–CFA increased the pH after 6 hours of reaction, and this effect persisted until the end of the experiment. A similar trend was also shown in water hyacinth and EFBOP, either applied separately or combined with coal fly-ash (Figs 1B and 1C). The effect of these treatments on changes in the pH of AMD was unchanged until the end of the experiment (14 days) (Fig. 1B and 1C). On the other hand, AMD pH in untreated soil (control) for 14 days of observation was relatively constant (2.67–3.18).

Changes in pH of AMD treated with the application of OMs have also been reported in several previous studies, although with different reaction times. In a study that used an anaerobic bioreactor with glucose as a source of OM, an increase in pH from 4.3 to 6.1 was observed on day 5 after adding AMD into the reactors [38]. Furthermore, Noor, Arifin, Priatmadi, and Saidy [39] drained AMD through a compartment containing EFBOP as an OM source and reported a significant increase in AMD pH one week after the reaction. This discrepancy in the reaction time to an increasing pH of treated AMD is attributed to differences in the incubation period. Most studies employed a relatively short incubation period before introducing the AMD into the reactors. In contrast, a 2-week incubation period was used in this study to allow proper decomposition of the OMs.

The application of OM increased the pH from 3.18 to 5.04–5.43 (89−104%), depending on the types of added OMs (Fig. 2). Adding OMs to increase the pH of AMD is related to the reaction between negatively charged functional groups from OMs and positively charged hydrogen ions from AMD. The neutralization of the H^+ ions by these functional groups leads to a decrease in the number of H^+ ions in AMD, increasing the pH. A previous study reported that adding OMs to reclaimed-mining soils increases the total functional groups by 365−696%, depending on the types and amounts of added OMs [18]. This study demonstrates the importance of the functional groups produced from OM decomposition in remediating acidic AMD.

Coal-fly ash application increased the pH of AMD from 3.18 to 6.94 (160%) and produced greater results than OM application. The application of OMs in combination with coal fly-ash led to the biggest improvement in the pH, which increased from 3.18 to 7.62–7.79 (186−192%) (Fig. 2). The increase in pH of AMD in response to coal fly-ash application was also found in the previous studies. Mahedi, Dayioglu, Cetin, and Jones [40] observed an increase in pH of AMD after flowing to a column containing coal fly ash. Moreover, the application of CFA produces alkalinity and neutralizes H^+ ions of AMD [41]. The CFA used in this study contained high amounts of Ca and Mg (Table 1); hence, after applying to AMD, it dissociates and increases the pH, coinciding with Gitari, Petrik, and Akinyemi [26], who observed the pH of mixed CFA–AMD and reported a strong buffering zone at pH 6.2–6.8 due to the dissolution and hydrolysis of basic oxides such as MgO and CaO contained in the CFA. The effect of coal fly-ash in increasing pH of AMD is controlled by the amounts of alkaline components such as CaO and MgO. The dissolution of these components leads to hydroxyl ions, which neutralize acidic AMD [24]. These results demonstrate the potential of CFA in neutralizing and increasing the pH of AMD.

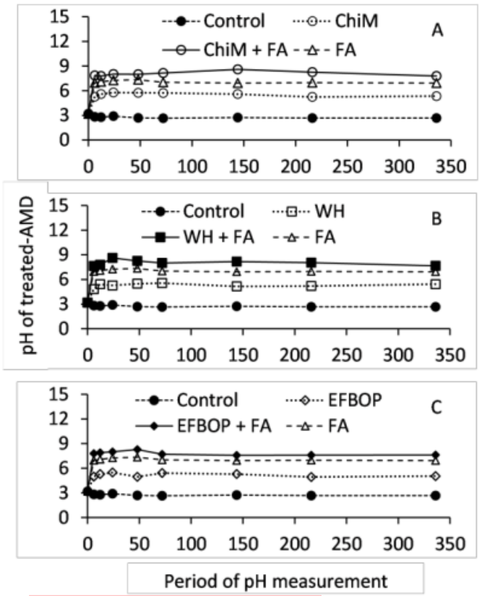

Fig. 1 Changes in pH of acid mine drainage after the application of chicken manure (ChiM) (A), water hyacinth (WH) (B); empty fruit bunch of oil palm (EFBOP) (C) in combination with coal-fly-ash (FA) observed at 336 hours (14 days) after application

The effect of coal fly-ash in increasing pH of AMD is controlled by the amounts of alkaline components such as CaO and MgO. The dissolution of these components leads to hydroxyl ions, which neutralize acidic AMD [26]. The pH of CFA in AMD varies based on the sulfuric contents of the parent coal [46]. Coal fly ash obtained from anthracite generally contains high sulfur and generates acidic fly ashes [47], while lignite coals contain low sulfur but have high Ca and generate alkaline fly ashes [48]. Qureshi, Jia, Maurice, and Öhlander [49] showed that the acid neutralization potential varies from 20 kg $CaCO_3$ Mg^{-1} for CFA obtained from lignite coals to 25 kg $CaCO_3$ Mg^{-1} for bituminous coals. These results demonstrate the potential of CFA in neutralizing and increasing the pH of AMD.

3.3. Removal of Fe, Al, and Mn due to Organic Matter and Coal Fly-Ash Applications

The application of OMs and CFA decreased the Fe, Mn, and Al concentrations of AMD. The application of OMs led to a reduction in Fe ranging from 47-71% compared to AMD without treatment (control), depending on the types of added OMs (Fig. 3A). The Fe concentration of AMD was decreased by 65% after CFA application (Fig. 3A). A significant reduction from 94-97% was observed when OMs and CFA were applied concurrently in the reactors (Fig. 3A). The Mn concentration in AMD reduced from 35 mg L^{-1} to 5–10 mg L^{-1} with OM application and 10 mg L^{-1} with CFA (Fig. 3B), while the combination of both decreased the concentration from 35 mg L^{-1} to 3–5 mg L^{-1} (Fig. 3B). Furthermore, the concentration of Al in the AMD also decreased with the application of OMs and CFA, although the degree of reduction was not as large as Fe and Mn. The concentrations of Al in the AMD decreased by 35–50% with OM application and 59% with CFA (Fig. 3C), while the combination of both decreased Al concentration by 70-81% (Fig. 3C).

Increased Fe, Al, and Mn adsorption from AMD onto soils with the addition of OMs is attributed to the increasing negative charges of the soil. The sorption of metals onto mineral surfaces is controlled by the negative charges of minerals [42, 43]. In this study, the increase in negative charges of soils was indicated by the increasing cation exchangeable capacity (CEC) with the application of OMs (Table 3). The CEC of reclaimed-mining soils increased from 20.39 kmol kg^{-1} to 26.40–36.52 kmol kg^{-1}, depending on the types of applied OMs (Table 3). The application of OMs to soil increases the number of negative charges through the decomposition of applied OMs which releases carboxyl and phenolic groups. A previous study showed that applying different types and amounts of OMs such as EFBOP, chicken manure, and water hyacinth increased the carboxylic and total functional groups [18], improving the interaction between negative charges of OMs and positive charges of metals in the AMD, which in turn enhances the removal of heavy metals.

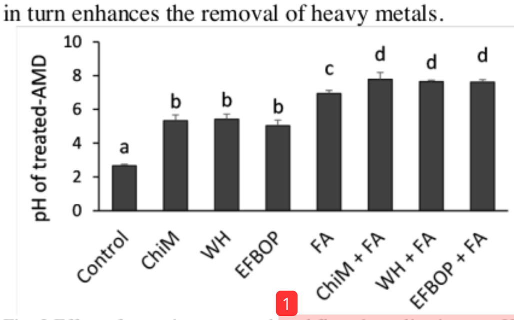

Fig. 2 Effect of organic matter and coal fly-ash application on pH of acid mine drainage after 14 days. ChiM - chicken manure, WH - water hyacinth, EFBOP - empty fruit bunches of oil palm, FA - coal fly-ash. Vertical lines above the bars represent the standard deviation of the mean (n = 3). Similar letters above the bar indicate the similar effect of the treatments based on the least significant difference (LSD) test at $P < 0.05$

The role of OMs in increasing the removal rate of heavy metals from AMD has also been reported in previous studies. Interaction between natural OM and AMD reportedly causes the accumulation of metals by natural OM [27]. The addition of OM improves the neutralization process of AMD in the removal of heavy metals through the aggregation of OM–metal complexes [44]. These results indicate the importance of OM in the removal of heavy metals from AMD. The application of coal fly ash to soils; either separately or in combination with OM, the removal of Al, Fe, and Mn also increased, consistent with previous studies that reported an increase in the removal of heavy metals with coal fly-ash application [41, 45]. The use of coal fly-ash is also effective for the removal of heavy metals from aqueous solutions, such as nickel (II) and copper (II), zinc (II), and aluminum and iron [41].

The effect of CFA on the sorption of heavy metals in AMD occurred through an increase in the specific surface areas (SSA) of soils up to 107% compared to soils without CFA application (Table 3). The increase in the SSA of soils with CFA application is attributed to the presence of iron and aluminum oxides. A previous study reported that CFA increases the sites (specific surface areas) for heavy metals sorption provided by the high density of reactive surface functional groups associated with the oxides [46]. An increase in the reactive sites of soils with CFA application enhances the removal of heavy metals from AMD.

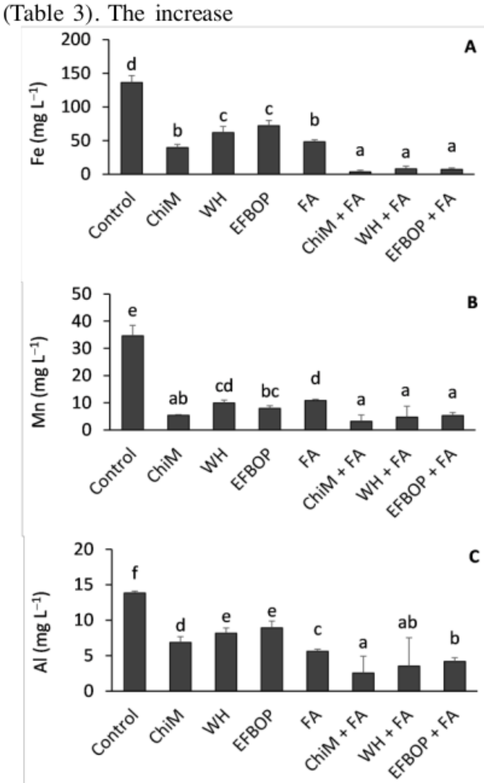

Fig. 3 Effect of organic matter and coal fly-ash applications on iron (Fe) (A), manganese (Mn), and aluminum (Al) (C) of acid mine drainage after 14 days. ChiM - chicken manure, WH - water hyacinth, EFBOP - empty fruit bunches of oil palm, FA - coal fly-ash. Vertical lines above the bars represent the standard deviation of the mean (n = 3). Similar letters above the bar indicate the similar effect of the treatments based on the least significant difference (LSD) test at P < 0.05

Table 3 Changes in soil characteristics due to the application of organic matter and coal fly-ash

Treatment	pH H_2O	Cation Exchangeable Capacity (cmol kg^{-1})	Specific Surface Areas (m^2 g^{-1})
Control	2.90 (0.23)* a**	20.39 (1.98) a	12.61 (0.34) a
ChiM	4.68 (0.78) c	36.52 (2.12) e	12.33 (1.43) a
WH	3.73 (0.88) b	30.38 (2.32) d	13.01 (3.21) a
EFBOP	3.38 (0.23) b	26.40 (1.21) c	13.32 (2.34) a
FA	7.64 (0.54) d	23.39 (0.98) b	26.11 (2.31) b
ChiM + FA	8.58 (0.33) f	42.35 (2.12) f	24.65 (2.12) b
WH + FA	8.62 (0.23) f	36.42 (1.92) e	25.95 (1.90) b
EFBOP + FA	8.19 (0.33) e	29.32 (1.43) d	24.73 (2.12) b

Notes: * Numbers in the parenthesis represent the standard deviation of the mean (n = 3)
** Similar letter following the parenthesis indicates the similar effect of the treatment based on the least significant difference (LSD) test at *P* < 0.05
ChiM - chicken manure, WH - water hyacinth, EFBOP - empty fruit bunches of oil palm, FA - coal fly-ash

This study suggests that CFA is suitable substitute for liming materials in increasing the pH and reducing the concentrations of heavy metals of AMD. Therefore, utilizing industrial waste such as CFA might reduce the costs of remediating AMD in the mining industry. The application of CFA and OMs found around the mining sites profoundly affects remediating AMD and reducing management costs.

4. Conclusion

Results of the study showed that the application of organic matters to reclaimed-mining soils, which is then drained by acid mine drainage, increases the pH of AMD 89−104% higher than without OM application. The removal of heavy metals including Fe, Al, and Mn also increases significantly with the application of organic matter. Reducing acidity and heavy metals of acid mine drainage are attributed to soil organic matter's decomposition processes producing functional groups (carboxyl groups) that neutralize H^+ ions of acid mine drainage and bind positive metal charges. Furthermore, coal fly-ash appears to contain high amounts of calcium and magnesium, which form hydroxyl ions following application to the soils. Therefore, the application of coal fly-ash leads to the neutralization of acidic AMD, thereby leading to a 160% higher pH than the control. The application of coal fly-ash also increases surface areas of soil−coal fly ash mixtures, which improves the removal of Al, Fe, and Mn. The most profound effect on improving acid mine drainage quality is observed with the application of combined-organic matter and coal fly-ash. This study confirms the results of previous studies that organic matter must be coupled with coal fly-ash to obtain maximum results in the AMD remediation. This result implies that waste materials from the industry as a substitute for limestone are not only potential in AMD management but may also increase mining industry profits from chemical cost savings.

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