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Research Article

# Changes in properties of reclaimed-mine soil, plant growth, and metal accumulation in plants with application of coal fly ash and empty fruit bunches of oil palm

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## Abstract

Reclaimed-mining soil (RMS) is characterized by low fertility, acidic pH, and high heavy metal contents. As a result, adding amendments becomes essential to support plant growth. Therefore, this research measured alterations in the characteristics of RMS, plant growth, and metal accumulation in plants with the co-application of coal fly ash (CFA) and empty fruit bunches of oil palm (EFBOP). In the first experiment, various levels of CFA (0, 75, and 150 Mg ha$^{-1}$) and EFBOP (0, 25, and 50 Mg ha$^{-1}$) were added to the RMS and then incubated at 70% water holding capacity for 45 days to determine their effect on changes in soil properties. In the second experiment, four treatments: control, CFA, EFBOP, and CFA+EFBOP were tested in the greenhouse to quantify their effects on the growth and metal accumulation of plants. Results of the study showed that the co-application of CFA and EFBOP significantly affected bulk density, pH, mineral nitrogen ($NH_4^+$ and $NO_3^-$), available phosphorus, and exchangeable Ca and Mg in RMS. CFA application increased exchangeable Al by 82-160%, while EFBOP resulted in a decrease of 24-119%. CEC decreased with CFA application and increased with the use of EFBOP. Plant growth increased with the co-application of CFA and EFBOP. The addition of CFA to soils results in increasing metal contents in plant tissue; however, the presence of EFBOP reduced the concentrations of metal in plant tissue. These results highlight the potential of CFA and EFBOP, which are industrial and agricultural wastes, as valuable soil amendments.

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## Introduction

Coal production in Indonesia is constantly increasing to meet energy needs, rising from 163 million tonnes in 2014 to 685 million tonnes in 2022 (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2023). In addition, the predominant method used for coal mining in Indonesia is the open-pit mining system. During this process, soil and rock overlying the mineral deposit are removed to access the ore. Once the mining activities are completed and the pit is no longer in use, the area needs to be reclaimed. Reclaimed-mining soil (RMS) is typically created by blending different materials, such as topsoil, subsoil, and organic matter, to recreate a soil profile that may support vegetation growth. However, several observations showed that RMS is frequently not suitable for vegetation growth (Vidal-Macua et al., 2020; Honscha et al., 2021).

RMSs located in Satui Sub-district, Tanah Bumbu Regency, South Kalimantan Province, Indonesia, is a former coal mining land with an open pit system that completed mining activities in 2016 (Figure 1). After the completion of the mine closure processes, the land has been reorganized, applied with organic matter and lime, and then planted with forestry and ground cover plants. RMSs in this site are characterized by relatively low organic carbon and nitrogen contents, a high soil bulk density, acidic soil pH, and low contents of exchangeable cations (Saidy et al., 2021). Although RMSs have physical, chemical, and biological soil properties that do not support plant growth, plants from the Cyperaceae family are able to grow on this land, especially on land that is a pile of over-burden layers (Novianti et al., 2017). Soil developed on this site is classified as Typic Dystrudepts on the basis of the Soil Taxonomy system (Saidy et al., 2020). The results of these studies suggest that improving soil fertility is essentially required for growing plants or other purposes in this soil.

Coal fly ash, also known as CFA, is produced by the burst of coal conducted in power plants containing various minerals as well as trace elements. Due to its high content of beneficial elements, including calcium, magnesium, and potassium (Gopinathan et al., 2022), CFA holds promise as a potential soil modifier for enhancing soil structure and nutrient availability (He et al., 2017; Panda and Biswal, 2018). CFA also contains a trace number of heavy metals, so soil amendment using CFA may result in metal translocation from soil to plants and lead to metal accumulation in plant tissue. On the other hand, empty fruit bunches of oil palm, or EFBOP, are agricultural residues produced as a byproduct of palm oil processing. This material is also used for amendment due to its high organic matter contents (Lim et al., 2015). When incorporated into soil, EFBOP typically enhances the nutrient cycling its elements, as well as augments water-retention capabilities (Moradi et al., 2015; Tao et al., 2017). EFBOP is also used as plant growth-promoting microorganisms (PGPM), which have the potential to enhance plant growth and is used to reduce the use of inorganic fertilizers (Mahmud and Chong, 2021). The use of both CFA and EFBOP is desired to enhance soil grade, increase crop productivity, as well as reduce the need for synthetic fertilizers.

Application of CFA enhances soil characteristics, leading to an increase in crop production. The mechanisms for this improvement occur through (i) the presence of elements in CFA modifies the chemical properties of soil, which in turn provides nutrients for plant growth, (ii) the constituent particles provide a reactive surface that stimulates chemical reactions, ultimately increasing nutrient and water retention, (iii) alteration in the physical properties of soil to improve conditions for root growth (He et al., 2017; Gopinathan et al., 2022). Meanwhile, EFBOP improves bulk density, water-holding capacity, retention, porosity, pH, as well as nutrient availability (Carron et al., 2015; Fahrunsyah et al., 2019). Although many investigations were conducted on the individual impact of EFBOP and CFA on soil characteristics and plant growth, information on the impact of co-application is still very limited. This research aimed to quantify changes in characteristics of reclaimed-mining soils, plant growth, and metal contents in plant tissue as influenced by co-application of CFA and EFBOP.

## Materials and Methods

### *Sampling and characterization of soil, CFA, and EFBOP*

The soil sample was taken from reclaimed coal mining areas in Mulia Village, Satui Sub-district, Tanah Bumbu Regency, South Kalimantan Province, Indonesia (Figure 1) at 0-30 cm depth, homogenized into one sample, and then air-dried. Some were used to determine soil characteristics, while the remaining were stored at 4°C for subsequent incubation study in the laboratory. The soil used for the study has a clay texture with a bulk density of 1.57 kg $m^{-3}$, and the soil reaction is acidic. The soil also has relatively low organic C and total N content. Details of soil characteristics used for this study are displayed in Table 1.

CFA was collected from the dumping area of the PLTU Asam-Asam power plant in Asam-Asam Village, Jorong District, Tanah Laut Regency, Indonesia. Afterward, the samples were allowed to naturally dry and subsequently filtered through a 2 mm sieve, reserved at 4°C for future applications, and a portion was utilized for characterizing CFA. The CFA used in this study has an alkaline pH, with a relatively high bulk density, and very low organic C and total nitrogen contents. The content of base cations (Ca, Mg, Na, and K) in CFA is very high. Comprehensive attributes of the CFA employed in this experiment are outlined in Table 1. The EFBOP was obtained from the palm oil factory of the Perkebunan Nusantara XIII at Ambungan Village, Pelaihari District, Tanah Laut Regency, Indonesia. The specimens drying was accomplished for 72 hours in an oven with a temperature of 60°C and finely crushed to a size of 0.5 mm; some were stored at 4°C for incubation study, while the remaining were characterized using standardized laboratory methods. The EFBOP used in this study contains high organic C, but has a low total

N content, resulting in a relatively high C/N ratio. The lignin content (a carbon compound that is relatively resistant to microbial decomposition) of EFBOP is also higher than the carbohydrate contents (a carbon compound that is easily decomposed). The properties of the EFBOP are presented in Table 2.

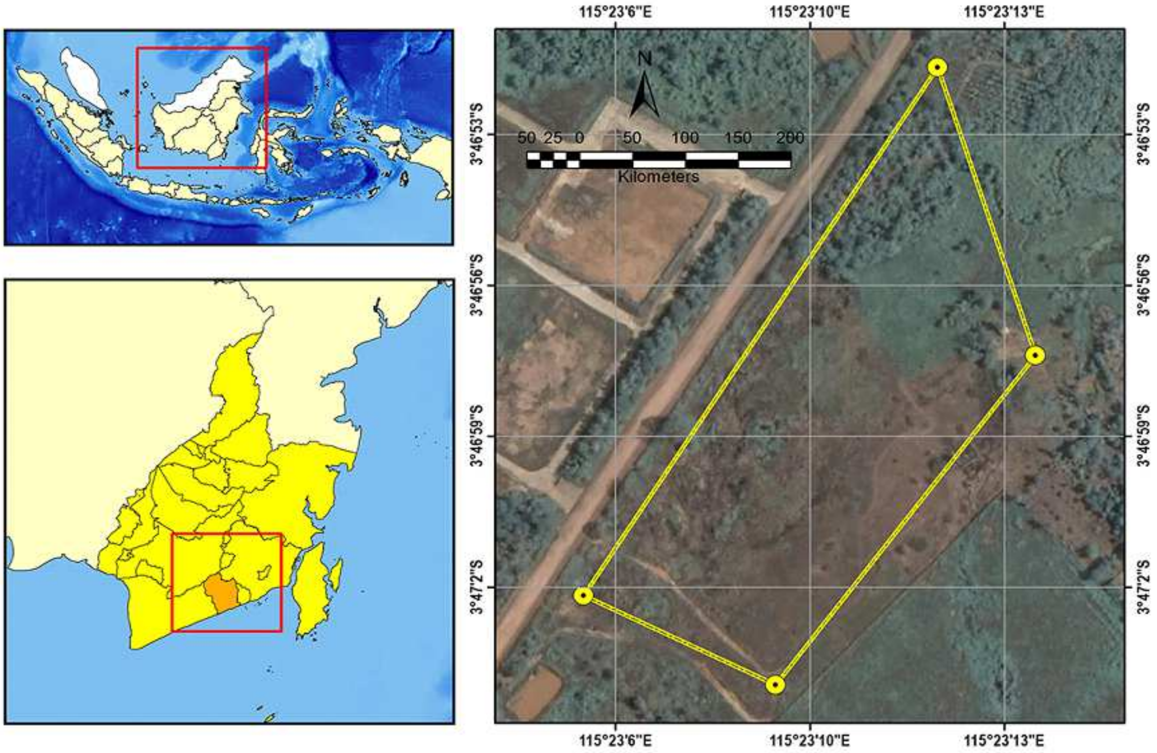

Figure 1. Study site of reclaimed mining soils.

### *Incubation experiment*

Measuring the effect of CFA and EFBOP on the characteristics of RMS was performed by an incubation study in the laboratory conducted using a completely randomized two-factorial experimental procedure. The first factor consisted of the quantities of CFA (CA), specifically 0, 75, and 150 Mg ha$^{-1}$, while the second was the amounts of EFBOP (EB) comprised of 0, 25, and 50 Mg ha$^{-1}$. In the experiment, each treatment consisted of three replicates. Approximately 1,000 g of RMS was positioned within an incubation container with dimensions of 100 cm in diameter and 15.0 cm in height. Subsequently, CFA and EFBOP were introduced and thoroughly homogenized following the prescribed treatments. Afterward, distilled water was added to achieve 70% of the water holding capacity.

The incubation container with CFA, soil, and EFBOP was placed in the dark for a period of 45 days, with continuous maintenance of water content at 70% of the water-holding capacity. This was achieved by precise watering every three days. As many as 27 tubes were assembled and incubated, denoting the combination of three CFA levels, three EFBOP levels, and three replicates. Several soil characteristics were measured after the completion of the incubation period. Measuring bulk density was carried out using a ring sampler technique (Blake and Hartge, 1986), while the pH measurement was performed with the electrode glass method (McLean, 1982). Nitrogen mineral ($NH_4^+$ and $NO_3^-$) was quantified following the procedure outlined in Bundy and Meisinger (1994). Furthermore, available P was extracted using a P-Bray I solution, and its concentration was determined through the molybdate-ascorbic acid procedure (Jackson, 1967). Extraction of exchangeable Ca and Mg was accomplished with ammonium acetate 1.0 N with pH 7.0, while exchangeable Al was extracted using KCl 1.0 N. The contents of Ca, Mg, and Al in the extracted solution were quantified using an atomic adsorption spectrophotometer (Barnhisel and Bertsch, 1982; Lanyon and Heald, 1982). Meanwhile, the CEC measurement of the amended soils was carried out using the ammonium acetate (pH 7.0) technique (Rhoades, 1982).

### *Greenhouse experiment*

This greenhouse experiment aimed to quantify the effect of CFA and EFBOP application on plant growth and the accumulation of metals in plant tissue. Four treatments: (1) soil without treatments – control ($EB_0CA_0$), (2) soil + 50 Mg ha$^{-1}$ EFBOP + 0 Mg ha$^{-1}$ CFA ($EB_{50}CA_0$), (3) soil + 0 Mg ha$^{-1}$ EFBOP + 150 Mg ha$^{-1}$ CFA ($EB_0CA_{150}$), and (4) soil + 50 Mg ha$^{-1}$ EFBOP + 150 Mg ha$^{-1}$ CA ($EB_{50}CA_{150}$) were arranged in a completely randomized design with four replicates. A 10 kg of soil was placed in an experimental pot (diameter of 20 cm and height of 40 cm), and then EFBOP and CFA, according to the treatments, were mixed homogenously in the pot. Free-ion water was added to the admixture of soil-EFBOB/CFA in the pots to achieve 70% water-holding capacity, and then the pots were incubated in the greenhouse for 15 days.

Table 1. Characteristics of soil and CFA. Numbers after ± are the standard deviation of the mean (n=3).

| **Characteristics** | **Soil** | **Coal fly ash** |
|---|---|---|
| Texture[a] | | |
| - Sand (%) | 23.45 ± 3.45 | - |
| - Silt (%) | 23.90 ± 2.56 | - |
| - Clay (%) | 52.65 ± 3.45 | - |
| Bulk density[b] (kg $m^{-3}$) | 1.57 ± 0.07 | 1.89 ± 0.08 |
| pH ($H_2O$)[c] | 4.95 ± 0.13 | 7.23 ± 0.65 |
| Organic carbon[d] (g $kg^{-1}$) | 15.74 ± 1.42 | 5.65 ± 0.87 |
| Total nitrogen[e] (g $kg^{-1}$) | 0.72 ± 0.06 | 0.34 ± 0.05 |
| Total phosphorus[f] (g $kg^{-1}$) | 9.80 ± 1.12 | 3.98 ± 0.23 |
| Calcium[g] (mg $kg^{-1}$) | 5.45 ± 0.43 | 876.45 ± 9.78 |
| Magnesium[g] (mg $kg^{-1}$) | 6.34 ± 0.89 | 348.65 ± 8.99 |
| Sodium[g] (mg $kg^{-1}$) | 2.43 ± 0.86 | 143.76 ± 6.89 |
| Potassium[g] (mg $kg^{-1}$) | 3.45 ± 0.76 | 287.65 ± 7.65 |
| Aluminium[g] (mg $kg^{-1}$) | 7.23 ± 0.87 | 435.45 ± 7.98 |
| Iron[g] (mg $kg^{-1}$) | 3.34 ± 0.65 | 287.44 ± 8.87 |
| Cation exchange capacity[h] (cmol $kg^{-1}$) | 22.67 ± 4.45 | - |
| Manganese[i] (mg $kg^{-1}$) | - | 145.32 ± 4.87 |
| Chromium[i] (mg $kg^{-1}$) | - | 125.65 ± 5.93 |
| Lead[i] (mg $kg^{-1}$) | - | 86.34 ± 4.56 |
| Cobalt[i] (cmol $kg^{-1}$) | - | 75.87 ± 7.98 |

[a]Methods of sieving and sedimentation (Corey, 1986); [b]Method of soil core sampling (Blake and Hartge, 1986); [c]Method of electrode glass (1 : 5, soil : water) (McLean, 1982); [d]Method of wet oxidation by dichromate-sulphuric acid (Nelson and Sommers, 1996); [e]Method of Kjeldahl (Bremer and Mulvaney, 1982); [f]Soil and coal fly ash digested using 60% $HClO_4$ and then measurement at 660 nm (Olsen and Sommers, 1982); [g]Soil and coal fly ash digested using the mixture of $HNO_3$ and $HClO_4$ and the concentration of base cations in the digested solution were quantified using an atomic absorption spectrophotometer (Barnhisel and Bertsch, 1982; Knudsen and Peterson, 1982; Lanyon and Heald, 1982; Olson and Ellis, 1982); [h]Method of ammonium acetate (pH 7.0) (Rhoades, 1982). [i]Metal contents in CFA were quantified using an atomic absorption spectrophotometer following the digestion of CFA by tri-acid mixture (10 : 1 : 4 = $HNO_3$ : $H_2SO_4$ : $HClO_4$ acids) (Baker and Amacher, 1982; Burau, 1982; Reisenauser, 1982).

Following the completion of the incubation period, three maize seeds were planted in each experimental pot. Plant growth parameters: plant height and plant dried weight were observed at 60 days after planting. Plant height was measured using a metric scale from the base of the plant at ground level to the highest part of the leaf. All parts of the plant above the ground (2-3 cm above ground) were then cut, washed with tap water, oven at 70°C for 48 hours, and then weighed immediately for plant-dried weight measurement. Maize shoots were then ground to powder for quantification of phosphorous, nitrogen, and metal contents in plant tissue. Powdered maize shoots were digested using 60% concentrated $HNO_3$, and the concentration of phosphorous in the digested solution was determined using the ascorbic acid-molybdate method (Caradus and Snaydon, 1987). Nitrogen contents of maize shoots were quantified using the Kjeldahl method (Hafez and Mikkelsen, 1981), while the contents of Mn, Co, Co, and Pb were measured using an atomic absorption spectrophotometer following the digestion of maize shoots in tri-acid mixture (10 : 1 : 4 = $HNO_3$ : $H_2SO_4$ : $HClO_4$ acids) (Baker and Amacher, 1982; Burau, 1982; Reisenauser, 1982).

Table 2. Chemical characteristics of EFBOP. The numbers after ± are the standard deviation of the mean (n=3).

| **Chemical Characteristics** | **Values** |
|---|---|
| Organic[a] (g $kg^{-1}$) | 399.35 ± 9.56 |
| Total N[b] (g $kg^{-1}$) | 21.63 ± 1.44 |
| Carbohydrates[c] (g $kg^{-1}$) | 31.87 ± 2.54 |
| Lignin[d] (g $kg^{-1}$) | 84.65 ± 3.87 |
| C/N ratio | 18.46 ± 1.56 |

[a]Method of wet oxidation by dichromate-sulphuric acid (Nelson and Sommers, 1996); [b]Method of Kjeldahl (Bremer and Mulvaney, 1982); [c]Method of anthrone-sulfuric acid (Grandy et al., 2000); [d]Method of sodium hydroxide (Chesson, 1981).

### *Statistical analysis*

In this research, analysis of variance (ANOVA) tested the impact of simultaneous CFA and EFBOP applications on RMS attributes. Before conducting the

ANOVA, the Bartlett and Shapiro-Wilk tests were performed to confirm that all data exhibited uniform variance and a normal distribution. Afterward, the least significant difference (LSD) test was employed at a significance rate of $p<0.05$ for treatments that exhibited noteworthy impacts on the observed variables. This research used GenStat 12th Edition for statistical analyses.

## Results and Discussion

### *Changes in soil characteristics as influenced by CFA and EFBOP application*

Several soil properties, including bulk density, pH, the concentration of mineral N ($NH_4^+$ and $NO_3^-$), available P, exchangeable Ca, and Mg, were significantly affected by CFA and EFBOP co-application (Figure 2). The bulk density decreased from 1.58 kg $m^{-3}$ to 1.15-1.55 kg $m^{-3}$, primarily due to CFA, which had a larger particle size than silt and clay particles. CFA generally contains at least 70% of coarse-grain particles of 0.075 mm (Kaur and Goyal, 2015), while the diameter of silt and clay particles scales from 0.002 to 0.05 mm and 0.002 mm. Therefore, when CFA was added in sufficiently large quantities, it loosened the added soil, resulting in a decline in bulk density. This result was consistent with the lower bulk density of sandy and loamy soils obtained following the application of 108 Mg $ha^{-1}$ CFA compared to the control (Yunusa et al., 2011). Dwibedi et al. (2023) explained that applying CFA up to 80% significantly reduced the bulk density.

The co-application of CFA and EFBOP increased soil pH from 4.33 in the control to a range of 4.48 to 6.23 with the addition of various treatment combinations (Figure 2B). EFBOP contributes to increasing the pH through the mechanism of binding cations that serve as a source of acidity, including Fe and Al. These cations donate $H^+$ ions in the soil through the hydrolysis process, changing from $Al^{3+}$ to $Al(OH)_2^-$ or $Fe^{3+}$ to $Fe(OH)_2^-$ (Strawn et al., 2015; Yerima et al., 2020). The addition of EFBOP to soil results in decomposition and produces functional groups of organic matter capable of binding or adsorbing Al and Fe cations. This absorption prevents the production of $H^+$ ions and raises pH (Jiang et al., 2018; Wang et al., 2019).

The increase in pH because of using CFA was primarily related to the high contents of alkaline elements, including CaO and MgO (Table 1). These basic oxides participate in dissolution and hydrolysis reactions in the soil to produce $OH^-$ ions), which neutralize $H^+$ ions and increase the pH (Iyer, 2002). This result corroborated the observations by Tsadilas et al. (2018), who reported elevated pH from 4.75-5.25 to 7.15-7.52 with the application of CFA at 220 Mg $ha^{-1}$. In addition, Ahmad et al. (2021) stated that the CFA application at high rates of 30-50% increased the pH from 6.80 to 8.22-8.50. Hamanaka et al. (2022) also found a rise in pH ranging from 3.10-3.70 in the control compared to 7.87-11.22 when 5-50% of CFA was added. These results show that CFA can potentially be used as a lime material to ameliorate acidic soil.

Based on the results, the amount of available N ($NH_4^+$ and $NO_3^-$) also improved with the co-application of CFA and EFBOP. The available N in the control was 6 mg $kg^{-1}$, but after the treatment, it expanded to 8-12 mg $kg^{-1}$ with CFA (25-75 Mg $ha^{-1}$) and 20-41 mg $kg^{-1}$ with EFBOP (Figure 2C). The available N reached a range of 25-64 mg $kg^{-1}$ when both were applied in combination (Figure 2C). The increase in the amounts of available N was related to the mineralization from the added EFBOP. In the control, N mineralization was slow due to the significantly low organic N content and acidic pH (Table 1). However, CFA and EFBOP increased the amount of substrates for microbial decomposition, leading to an advancement in soil characteristics. The mineralization of N under ideal environmental conditions includes the conversion of organic N to $NH_4^+$ and then biochemical reactions to convert $NH_4^+$ to $NO_3^-$ (Marzi et al., 2020).

The conversion rate of organic N to $NO_3^-$ and $NH_4^+$ was regulated by the C/N ratio of added OM (Bonanomi et al., 2019; Li et al., 2020). As found by prior research, the threshold value of the C/N ratio for N mineralization varied between 15-19 (Calderón et al., 2005; Gale et al., 2006; Lazicki et al., 2020). EFBOP in this study had a C/N ratio <19 (Table 1); hence, this organic matter expanded the availability of N by elevating the activity of microorganisms in converting organic N into $NO_3^-$ and $NH_4^+$. These results were consistent with Jaafar (2007), who reported an increase in $NH_4^+$ and $NO_3^-$ concentrations with increasing amounts of EFBOP applied to soil.

The availability of P in RMS also increased with the application of CFA and EFBOP, rising from 3 mg $kg^{-1}$ in the control to 5-41 mg $kg^{-1}$ in various combinations of CFA and EFBOB (Figure 2D). The treatment improved several soil chemical properties related to the availability of P in the soil, such as soil pH and exchangeable Al, which in turn raised the available P. According to previous studies, pH is considered the most profound variable in controlling the solubility and availability of P in soil (Li et al., 2019; Daba et al., 2021). The maximum solubility of P was observed at pH values of 4.5 and 6.5, where the lowest level of P fixation by soil minerals such as Ca, Fe, and Al occurred (Penn and Camberato, 2019). In this study, the pH increased to a range of 4.48-6.23 following the application of CFA and EFBOP, compared to the control of 4.33 (Table 1). Several previous studies also reported increased available P with increasing pH in wetlands (Bai et al., 2017) and dry lands (Wuenscher et al., 2015). The improvement in the available P was also related to the deactivation of exchangeable and soluble Al and Fe hydroxides by functional groups produced from organic matter

(Mohammed et al., 2021). The presence of these hydroxides tends to stabilize the available $H_2PO_4^-$ and $HPO_4^{-2}$ in soil into forms that plants cannot absorb. Furthermore, the expanding P availability also occurred through the mineralization of added organic material (Antil and Singh, 2007; Menšík et al., 2018). Tsadilas et al. (2018) reported a rise in available P from 18.25 mg kg$^{-1}$ to 51.70 mg kg$^{-1}$ after using CFA mixed with organic matter. These results imply that CFA and EFBOP significantly improve the P availability in RMS. The use of CFA and EFBOP also improved exchangeable Ca and Mg levels, increasing by 1.5-12.8 and 2.1-10.9 times, respectively (Figure 2E and 1F). These alterations were ascribed to functional groups of organic matter generated through the EFBOP decomposition, which promoted a negative charge of soil and the high Ca and Mg contents in the added CFA. This corroborated the observations of Yunusa et al. (2012) and He et al. (2017), who discovered a noteworthy improvement in plant growth due to increasing levels of exchangeable Ca and Mg with the application of CFA and EFBOB.

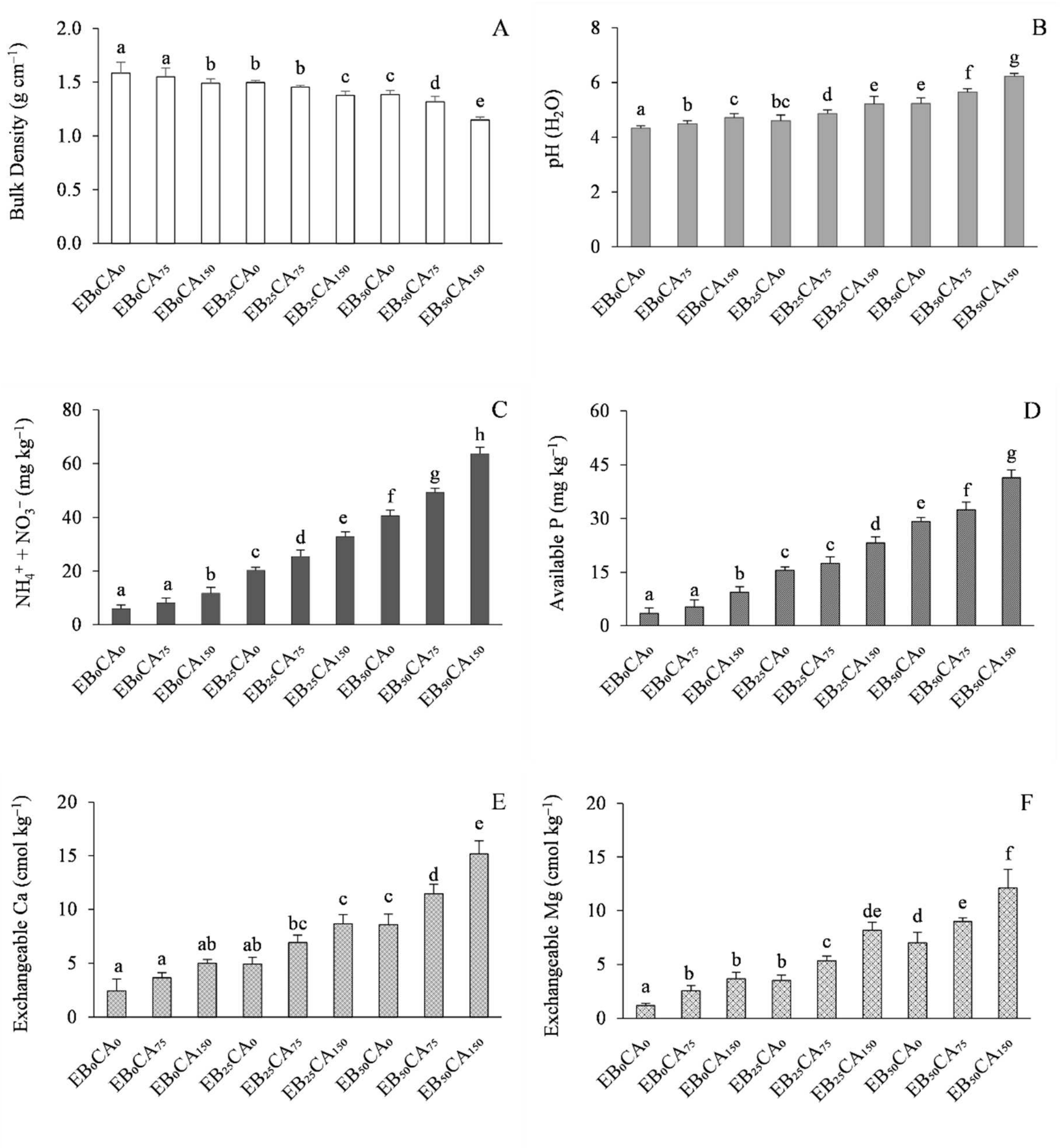

Figure 2. Changes in bulk density (A), pH (B), mineral N ($NH_4^+$ and $NO_3^-$) (C), available P (D), exchangeable Ca (E), and exchangeable Mg (F) as influenced by different amounts of empty fruit bunch of oil palm (EB) and coal fly ash (CA) applications. The lines above bars represent the standard deviation of the mean (n=3). Similar letters above the lines indicate the effect of the treatments is not significantly different based on the least significant difference (LSD) test at $p<0.05$.

Table 3. Effect of CFA and EFBOP on changes in exchangeable Al and CEC. The number after ± is the standard deviation of the mean (n=9). Similar letters after the standard deviation indicate the effect of the treatments is not significantly different based on the least significant difference (LSD) test at p<0.05.

| **Treatments** | **Exchangeable Al (cmol kg$^{-1}$)** | **CEC (cmol kg$^{-1}$)** |
|---|---|---|
| Coal fly ash (Mg ha$^{-1}$) | | |
| 0 | 2.31 ± 1.27 a | 29.13 ± 5.95 a |
| 75 | 4.20 ± 1.54 b | 27.03 ± 6.85 b |
| 150 | 6.01 ± 1.46 c | 25.55 ± 7.60 c |
| Empty fruit bunch of oil palm (Mg ha$^{-1}$) | | |
| 0 | 5.64 ± 1.66 c | 20.36 ± 2.80 a |
| 25 | 4.30 ± 1.83 b | 25.80 ± 1.88 b |
| 50 | 2.58 ± 1.56 a | 35.56 ± 1.58 c |

Based on the ANOVA, the co-application of CFA and EFBOP did not significantly influence exchangeable Al and CEC ($p>0.05$), but the single application resulted in conflicting effects. The use of CFA (75-150 Mg ha$^{-1}$) increased exchangeable Al by 82-160%, while EFBOP (25-50 Mg ha$^{-1}$) caused a decrease amounting to 24-119% (Table 3). The increase was attributed to the high Al content present in CFA, which was released for exchange with other cations in soil solution. McCallister et al. (2002) found that CFA contributed to exchangeable Al in soil, particularly in acidic conditions. The decline in exchangeable Al with EFBOP was due to the presence of functional groups resulting from decomposition. Functional groups of organic matter may bind Al ions in soil (Vance et al., 1995), forming stable complexes that are not easily exchangeable. According to previous studies, OM suppresses exchangeable Al in soils (Antonangelo et al., 2022; Li et al., 2022). Long-term use of EFBOP for a period of 10 years significantly decreased the concentration of exchangeable Al (Abu-Bakar et al., 2011).

The use of CFA led to a decrease in CEC from 29 cmol kg$^{-1}$ to 26-27 cmol kg$^{-1}$, while the use of EFBOP resulted in an increase from 20 cmol kg$^{-1}$ to 26-36 cmol kg$^{-1}$ (Table 3). This contradictory result may be attributed to the different soil reactions after the treatments. Cations contained in CFA potentially bind to soil negative charge, leading to a decrease in CEC. On the other hand, the presence of EFBOP contributed to the negative charge of soil through the dissociation of functional groups, thereby increasing CEC. In a previous study, treatment with EFBOP as compost to RMS at rates of 5-10 Mg ha$^{-1}$ raised the CEC to 13-20 cmol kg$^{-1}$ (Neswati et al., 2022). The cumulative effect of EFBOP application for 10 years increased CEC to a depth of 60 cm (Abu-Bakar et al., 2011).

### *Effect of CFA and EFBOP application on plant growth and heavy metal contents of plant*

The research results showed that EFBOP and CFA, whether applied singly or in combination, increased plant height and plant-dried weight. Application of EFBOP at a rate of 50 Mg ha$^{-1}$ and CFA at a rate of 150 Mg ha$^{-1}$ increased plant height from 91 cm in the control (soil without treatment) to 126 cm and 138 cm, respectively (Figure 3A). Plant height increased significantly to 153 cm when EFBOP and CFA were applied concurrently (Figure 3A). Single or combined application of EFBOP and CFA also increased dried plant weight compared to untreated soil. Plant-dried weight increased by 40% with the application of EFBOP at a rate of 50 Mg ha$^{-1}$ and increased to 51% with the application of CFA at a rate of 150 Mg ha$^{-1}$ compared to the control (Figure 3B). An increase in plant dry weight of 92% was observed when EFBOP and CFA were applied together (Figure 3B).

Increases in plant growth and production are related to the increasing properties and nutrients of soils with the application of EFBOP and CFA. The results of this research showed that the application of EFBOP and CFA increased soil bulk density, pH, and the availability of N, P, Ca, and Mg (Figure 3). Improving several soil properties and increasing nutrient availability ultimately increases plant height and plant dried weight. Increasing nutrient availability with the application of EFBOP and CFA is also indicated by increasing the amount of N and P nutrients taken up by plants and accumulated in plant tissue. The N and P contents in plant tissue increased from 10 mg g$^{-1}$ and 6 mg g$^{-1}$ in the control to 15 mg g$^{-1}$ and 9 mg g$^{-1}$ with EFBOP application and increased to 15 mg g$^{-1}$ and 10 mg g$^{-1}$ with the CFA application (Figures 2C and 2D). There were increases in the N and P contents in plant tissue by 84% and 99%, respectively, when EFBOP and CFA were applied concurrently to soils (Figures 3C and 3D).

Increases in plant growth associated with increasing nutrient uptake by plants with CFA application are supported by a significant correlation between plant height and dried weight and the amount of N and P in plant tissue. Plant height correlated significantly with N of plant tissue ($r = 0.84$; $p<0.001$) and P of plant tissue ($r = 0.83$; $p<0.001$), while plant dried weight had a significant correlation with N of plant tissue ($r = 0.86$; $p<0.001$) and P of plant tissue ($r = 0.71$; $p<0.001$) (data not shown). Results obtained in this study align with He et al. (2017), who reported that CFA application increased P availability in soils and P uptake by plants, followed by an increase in plant production.

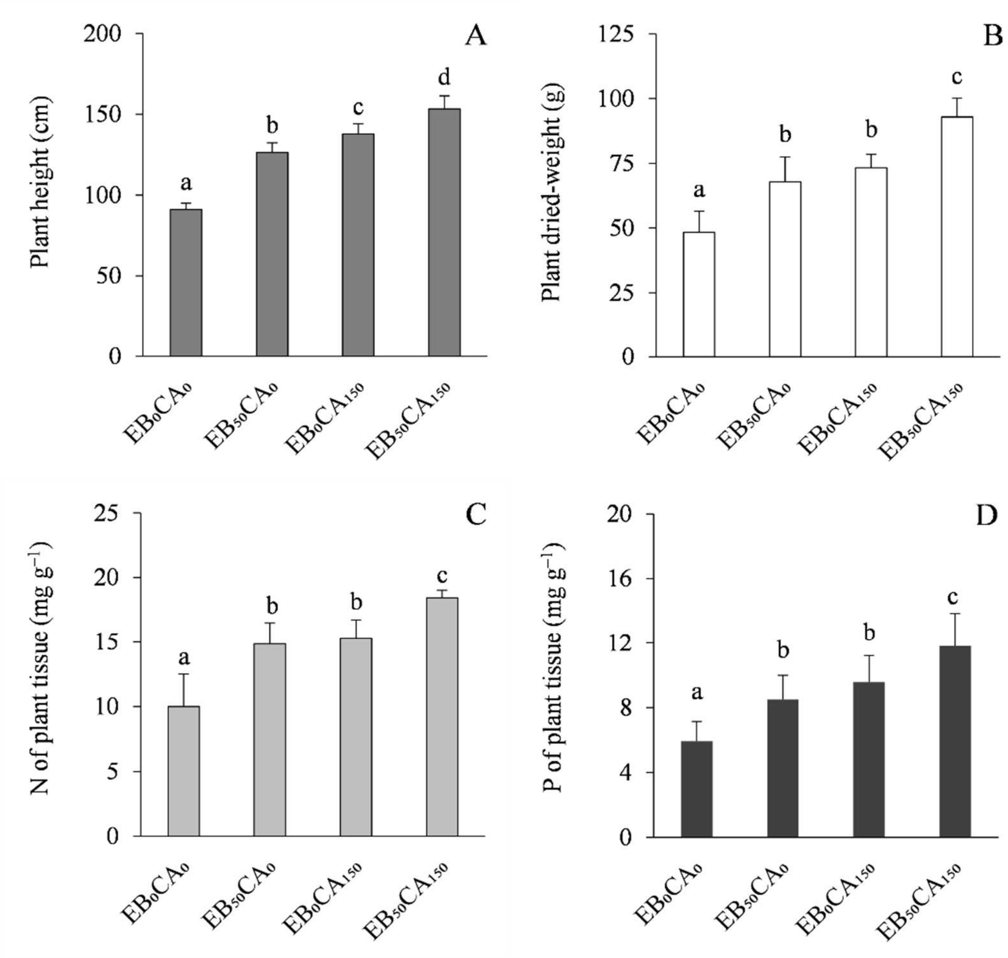

Figure 3. Effect of empty fruit bunch of oil palm (EB) and coal fly ash (CA) applications on plant height (A), dried-weight (B), the amount of N in plant tissue (C), and the amount of P in plant tissue (D). The lines above bars represent the standard deviation of the mean (n=5). Similar letters above the lines indicate the effect of the treatments is not significantly different based on the least significant difference (LSD) test at $p < 0.05$.

Varshney et al. (2021) reviewed articles on the utilization of CFA in agriculture and reported that CFA application had an effect on increasing elemental uptake from soils and eventually improving plant growth. CFA application at a rate of 50 Mg ha$^{-1}$ increased the yield of onion (*Allium cepa* L.) by 32%, in which crop yield correlated significantly with P of plant tissue (Parab et al., 2015).

Besides containing nutrients required by plants, CFA also contains a number of heavy metals; thus, CFA application to soils leads to higher levels of heavy metals in plants. The application of CFA at a rate of 150 Mg ha$^{-1}$ to soils in this study resulted in increases in the contents of Mn, Co, Cr, and Pb in plant tissue by 49%, 28%, 24%, and 56%, respectively (Figure 4). The results obtained in this study agree with those reported in several previous studies, which showed that the concentrations of heavy metals in plant tissue tended to increase with the amount of CFA application (Yu et al., 2019; Varshney et al., 2021). The application of CFA at a rate of 45% to soils resulted in increases in Pb and Cu contents in plant tissue by 964% and 611%, respectively, when compared to soils without CFA application (Rahmawati et al., 2020). Based on a comprehensive meta-analysis of 85 articles on CFA application to soils, Yu et al. (2019) synthesized that CFA should be applied at a rate of less than 25% to enhance plant biomass and yield but avoid high accumulations of heavy metals. The application of OM suppresses heavy metals uptake and their accumulation in plant tissue. Application of EFBOP at a rate of 50 Mg ha$^{-1}$ reduced Mn, Co, Cr, and Pb contents by 33%, 37%, 41%, and 38%, respectively (Figure 4). When applied together with CFA, EFBOP suppressed the accumulation of heavy metals in plant tissue by 77-88%, depending on the type of heavy metals (Figure 4). A decrease in the amount of heavy metals in plant tissue with the presence of OM is also reported in previous studies (Hou et al., 2019; Stefanowicz et al., 2020). The decrease in heavy metal content in plant tissue with the presence of OM is related to the ability of OM to form complexes with metals. The decomposition of OM produces functional groups that are negatively charged and may act as binding sites for heavy metals (Kwiatkowska-Malina, 2018; Luo et al., 2019). Among these binding sites, carboxylic and phenolic groups are particularly important in controlling metal binding (Czikkely et al., 2018). The results of this study highlight the crucial role of OM in reducing heavy metal availability in soils. OM binds to the metals, reducing their mobility and making them less accessible to plants. As a result, plants take up fewer heavy metals, leading to lower accumulation in plant tissues.

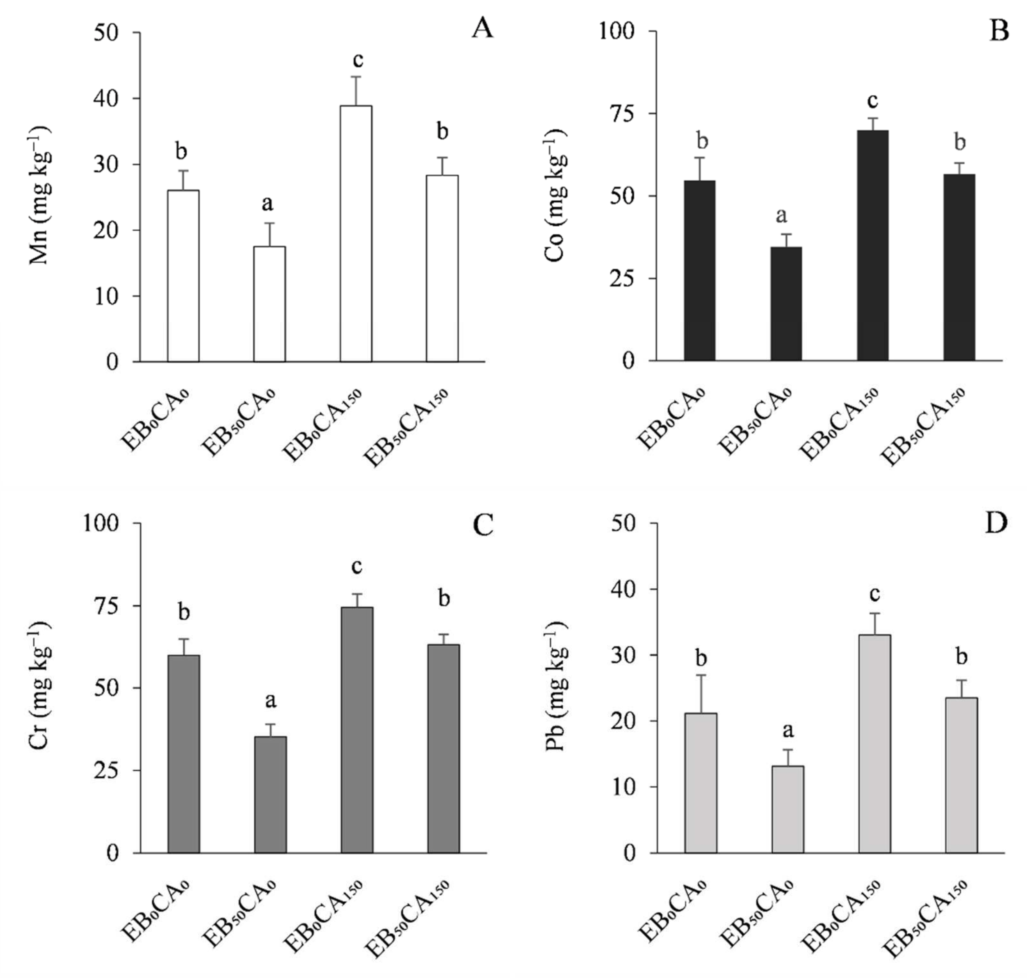

Figure 4. Effect of empty fruit bunch of oil palm (EB) and coal fly ash (CA) applications on Mn (A), Co (B), Cr (C), and Pb (D) in plant tissue. The lines above bars represent the standard deviation of the mean (n=5). Similar letters above the lines indicate the effect of the treatments is not significantly different based on the least significant difference (LSD) test at p<0.05.

## Conclusion

The combination CFA and EFBOP has been found to improve the bulk density, pH, mineral nitrogen ($NH_4^+ + NO_3^-$), available phosphorus, exchangeable calcium, and exchangeable magnesium in reclaimed mining soils. However, the co-application of CFA and EFBOP did not significantly impact exchangeable Al and CEC in the soils. Interestingly, when CFA or EFBOP is applied individually, they have conflicting effects on the exchangeable Al and CEC in the soils. This improvement in soil properties is attributed to the presence of basic cations in CFA, which act as soil-ameliorating agents. On the other hand, EFBOP contributes to soil improvement by undergoing a microbial decomposition process of organic matter contained in the EPBOP, resulting in the production of mineral nutrients and functional groups of organic matter. Results of this study also showed that CFA application to soils leads to increases in metal availability and results in increasing metal accumulation in plant tissue. The presence of organic matter in soils reduces heavy metal availability by binding to the metals and reducing their mobility. This process results in lower uptake of heavy metals by plants and, therefore, lower accumulation in plant tissues. These research findings highlight the crucial role of organic matter in reducing metal accumulation in plant tissue.

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