
The effect of Coal Fly Ash-Biochar–Organic fertilizer combinations on the physical properties of post-mining type C soil after maize cultivation

Rainaldus Susanto¹, Retno Wilujeng^{2*}, I Made Indra Agastya³, Utik Tri Wulan Cahya⁴, Amir Hamzah⁵

^{1,2,3,4,5}Tribhuwana Tungadewi University, Jl. Telaga Warna, Tlogomas, Malang, Indonesia

Keywords

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*Correspondence Email:

Retno.wilujeng@unitri.ac.id

Abstract

C Quarry mining causes significant soil degradation due to the loss of topsoil, resulting in land with poor physical structure, low pH and minimal nutrient content. Post-mining soil fertility recovery encourages the implementation of amelioration with materials such as coal fly ash (CFA), biochar and organic matter. This study aims to evaluate the effectiveness of CFA, biochar, and organic matter applications on the physical properties of post-C Quarry mining soil after corn planting. The study was conducted from July to October 2025 using a completely randomized design (CRD) with 7 treatments of a combination of biochar and CFA (5% of the soil weight of 15 kg) with organic fertilizer (chicken manure, goat manure and compost 20 t/ha). Corn cultivation was carried out, and observations were made on the physical properties of the soil bulk density, particle density soil porosity and soil water holding capacity at harvest. Analysis of variance with advanced BNT tests. The results showed no significant differences in soil bulk density, particle density, and porosity but significantly different in soil water holding capacity. The BCM treatment showed the lowest bulk density (1.09 g /m³), the CCM treatment showed the lowest particle density value (g/cm³), the CGM treatment showed the highest porosity (56%) and the BGM treatment showed highest water holding capacity (88%).

1. Introduction

Post-mining land is one of the most severely degraded landforms in Indonesia, characterized by the loss of topsoil, low organic matter content, damaged soil structure, extreme pH, and very low water-holding capacity (Yuningsih et al., 2021; Pratiwi et al., 2025). This condition results in minimal soil productivity, making it difficult to support plant growth (Pratiwi et al., 2021). This damage poses significant challenges to land rehabilitation efforts, especially when the land is to be reconverted to agriculture or revegetation (Agustian et al., 2021). Therefore, amelioration interventions that can improve the physical, chemical, and biological quality of the soil in an integrated manner are essential (Lim et al., 2022).

The physical properties of post-mining land are often very limited in supporting plant growth (Nadia & Pulunggono, 2020). Soils tend to have high bulk density, coarse or sandy texture, low porosity, and poor water-holding capacity (Mulyadi & Makhrawie, 2023). Unevenly compacted or loose soil structure makes it difficult

for roots to penetrate, thus inhibiting plant growth (Hartemink & Minasny, 2014). These conditions also increase the risk of erosion and further degradation, making improving physical properties with ameliorant materials a crucial initial step before improving chemical and biological soil fertility (Sui et al., 2025).

One widely developed strategy is the use of ameliorant materials with specific functions to improve soil conditions, derived from both industrial waste and local biomass (Sutardi et al., 2025). Coal Fly Ash (CFA), a coal combustion residue, is known to contain calcium, magnesium, potassium, and silicate minerals that are essential for improving soil acidity and adding certain nutrients (McCallister et al., 2002; Ram & Masto, 2014). In post-mining soils, which are generally acidic and mineral-poor, CFA acts as a potential ameliorant, increasing pH and providing essential plant nutrients (He et al., 2017). Research by Jubaedah et al., (2025) demonstrated that CFA application reduced soil bulk density (BD) at 6% and 12% rates due to CFA's lower BD than the soil.

On the other hand, coconut fiber biochar is an alternative biomass-based ameliorate that can improve soil structure, increase water retention, and increase cation adsorption capacity (Masiello et al., 2015; liu et al., 2016). The stable carbon content in biochar also acts as a long-term nutrient reservoir, which is particularly beneficial in post-mining soils that tend to be less able to retain nutrients (Tang, 2025). Meanwhile, organic fertilizers such as chicken manure, goat manure, and compost increase soil microbial activity, improve soil aggregation, and add organic carbon, which is essential for long-term soil fertility restoration (Yan et al., 2023). This study aims to evaluate the effect of a combination of coal fly ash, biochar, and organic fertilizer on improving the physical properties of post-mining soil type C after corn cultivation, specifically including changes in bulk density, particle density, porosity, and soil water holding capacity.

2. Research Methods

The research was conducted in Junrejo Village, Beji District, Batu City, from July to November 2025. Post-harvest soil physical properties were analyzed in a soil laboratory according to research procedures referred to Wilujeng et al. (2020). The study used a Randomized Block Design (RBD) with seven treatments and three replications. The treatments consisted of a combination of CFA and biochar with three types of organic fertilizer, as well as a control with no additional materials. Treatment descriptions are presented in Table 1.

Table 1. Research Treatment

<i>Code</i>	<i>Treatment Description</i>
CONTROL	No additional treatment
CCM	Coal fly ash 20 t/ha +5% Chicken manure
CGM	Coal fly ash 20 t/ha +5% Goat manure
CPT	Coal fly ash 20 t/ha +5% Compost
BCM	Biochar 20 t/ha +5% Chicken manure
BGM	Biochar 20 t/ha +5% Goat manure
BPT	Biochar 20 t/ha +5% Compost

Soil was collected in post mining-C located at Trail babat Alas, Ketindan Village, Lawang District, Malang Regency to a depth of 20 cm, and placed in polybags containing 15 kg of soil. Coconut fiber biochar is made by pyrolysis combustion at 300 °C in the renewable energy laboratory of Tribhuwana Tungadewi University. The CFA, biochar, and organic fertilizer were mixed two weeks before planting, with sufficient water added, and the soil moisture maintained until planting. Three Pertiwi 6 corn seeds were planted per polybag, after 1 week they were eliminated to 1 plant/polybag. Base fertilization was applied at a rate of 100 kg/ha of N, 50 kg/ha of P₂O₅, and 50 kg/ha of KCl, placed near the roots. At the end of planting, observations were made on soil bulk density, soil particle density, porosity, and soil water holding capacity (according to Nelson et al., 2023). The collected data were analyzed using ANOVA with a further honestly significant difference (LSD) test using *R.Studio* version 4.3.2. Soil physical properties data before application are presented in Table 2.

Table 2. Soil characteristics before treatment

Parameter	Bulk Density (g/cm ³)	Particle Density (g/cm ³)	Porosity (%)	% Sand	% Silt	% Clay	Texture (USDA)
post-mining type C soil	1.51	2.55	41	32	24	44	Clay

3. Results and Discussion

Soil Bulk Density

The results showed soil bulk density values ranged from 1.09 to 1.26 g/cm³ (Fig. 1). The BCM (Biochar 20 t/ha +5% Chicken manure) treatment showed the lowest bulk density after corn planting season and the control treatment showed the treatment with the highest bulk density value. Based on bulk density measurements indicate that although there was variation between treatments, statistically there was no significant difference between treatments (F: 1,292; p: 0,332).

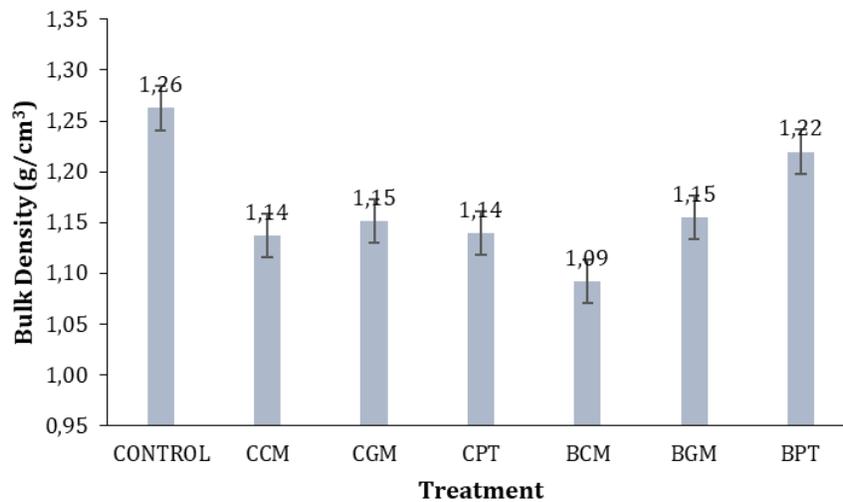


Fig. 1 Soil Bulk Density after combination of CFA-biochar-organic fertilizer applied

The absence of significant differences is likely due to several factors like the relatively short study duration may not have been sufficient to observe significant changes in bulk density, as post-mining soil structure typically requires longer to respond to ameliorant inputs (Song et al., 2026). This is consistent with Shukla et al. (2004), indicating that high-carbon materials such as biochar and organic fertilizers tend to increase soil aggregation and pore space, but the effects are only clearly visible with long-term application. Bulk density is a physical property which significant changes usually occur after the ameliorant material decomposes or interacts for a longer period with soil aggregates (García-Orenes et al., 2004).

Although there were no significant differences, the pattern of bulk density reduction in the biochar and organic fertilizer treatments still showed a positive trend. The BCM (Biochar 20 t/ha +5% Chicken manure) and CPT (Coal fly ash 20 t/ha +5% Compost) treatments showed lower values than the control, indicating improvements in soil structure, although not yet significant enough to be statistically detectable. This decrease in bulk density can be explained by the effects of biochar and organic fertilizer on soil structure and porosity. The light and porous nature of biochar can increase micro and macropore space (Zhu et al., 2025), while organic fertilizer adds organic matter, which helps form soil aggregates (Alagöz & Yilmaz, 2008; Acar et al., 2025). Both mechanisms make the soil more crumbly and less compact, resulting in a decrease in bulk density. CFA can also help improve soil structure by adding fine sand fractions and improving micro-drainage (Matsumoto et al.,

2016). The combination of these three materials cumulatively improves soil structure, although it has not yet had a statistically significant impact in the short term.

Soil Particle Density

The addition of a combination of biochar, coal fly ash, and organic fertilizer had no significant effect on soil particle density after maize cultivation (F: 1,292; p: 0,332). Particle Density typical values for mineral soils range from 2.4–2.9 g cm⁻³ (Rühlmann et al., 2006). Particle density measurements showed variation between treatments, with values ranging from 2.44 to 2.77 g/cm³. The control had a particle density of 2.68 g/cm³, while the biochar and organic fertilizer treatments (BCM, BGM, BPT) showed slightly lower values, ranging from 2.47 to 2.50 g/cm³ (Fig.2). The decrease in particle density in the biochar and organic fertilizer treatments indicates the contribution of porous and lightweight materials to soil composition.

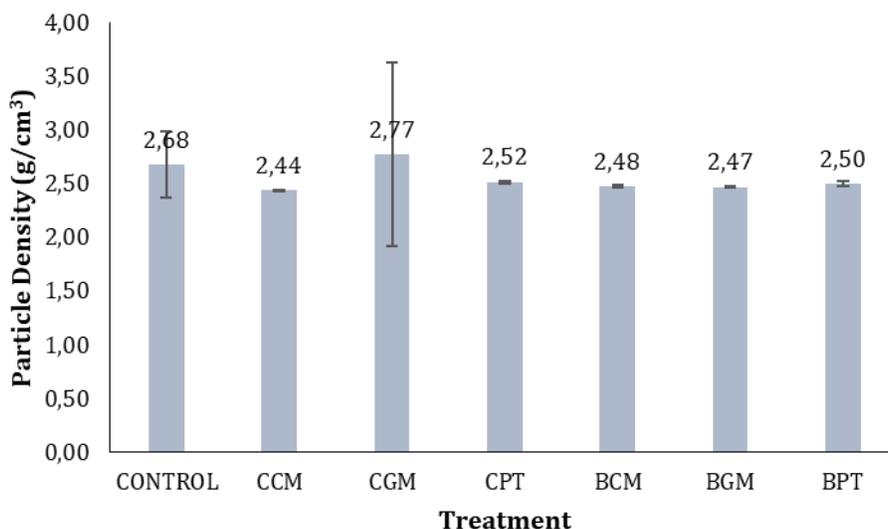


Fig. 2 Soil Particle Density after combination of CFA-biochar-organic fertilizer applied

The lack of significant differences in soil particle density is due to the more stable nature of this parameter compared to bulk density. Particle density only measures the mass of solid particles and is not affected by changes in soil pore size, structure, or compaction (Rühlmann et al., 2006). Because CFA, biochar, and organic fertilizer primarily improve structure and porosity (Jakubus et al., 2025), not mineral composition, it is understandable that the changes are small and not statistically significant. Another reason that could explain this phenomenon is the heterogeneous nature of the initial post-mining soil particles. Post-mining land typically contains high-density mineral and rock fragments (Sencindiver & Ammons, 2000; Gabarrón et al., 2019), so the effect of additional ameliorant materials such as CFA, biochar, and organic fertilizer is relatively limited in terms of overall particle density changes. Furthermore, the dosage and short incubation time may not have been sufficient to significantly alter the properties of soil particles.

Although the difference was not significant, the decreasing trend in particle density in the biochar and organic fertilizer treatments indicates potential improvements in soil structure. This decrease can increase soil porosity and allow for root growth, which has positive implications for water infiltration, aeration, and microbial activity. Therefore, even though particle density did not show significant statistical changes, the combined effect of biochar and organic fertilizer remains relevant as an early indicator of improvements in post-mining soil physical properties. The slightly decreasing particle density values in treatments containing organic matter, such as CCM (Coal fly ash 20 t/ha +5% Chicken manure), BCM (Biochar 20 t/ha +5% Chicken manure), and BGM (Biochar 20 t/ha +5% Goat manure), can be explained by the nature of organic matter and biochar, which have low particle density (around 1.2–1.5 g/cm³). The addition of organic matter to the soil can reduce soil particle density because organic particles replace a small portion of the mass of heavier minerals

(Ruehlmann & Korschens, 2020). Meanwhile, the higher soil particle value in CGM (Coal fly ash 20 t/ha +5% Goat manure) (2.77 g/cm^3) likely originates from natural variations in soil minerals, such as the presence of heavy minerals (Fe–Mn oxides) which are commonly found in post-mining soils (Adnan et al., 2025). Biochar, despite its low particle density, is relatively small in amount at 5–20 t/ha to drastically reduce soil particle density, especially since soil particle density is largely determined by dominant soil minerals such as quartz, feldspar, and clay fractions. Biochar-based fertilizers have the potential to reduce soil bulk density by increasing soil organic carbon, which makes the soil matrix lighter and more porous (Kizito et al., 2019).

Soil Porosity

Porosity measurements showed variation between treatments (Fig. 3), with values ranging from 51.15% to 56.49%. The result showed that the addition combination of CFA-biochar and organic fertilizer is not significantly different ($F: 0.374$; $p: 0.882$). The control soil had a porosity of 52.53%, while the CGM (Coal fly ash 20 t/ha +5% Goat manure) treatment showed the highest porosity, at 56.49%. The combination of biochar and organic fertilizer treatments (BCM, BGM, BPT) showed porosity values ranging from 51.15% to 55.91%, indicating an increase in soil pore space compared to the control.

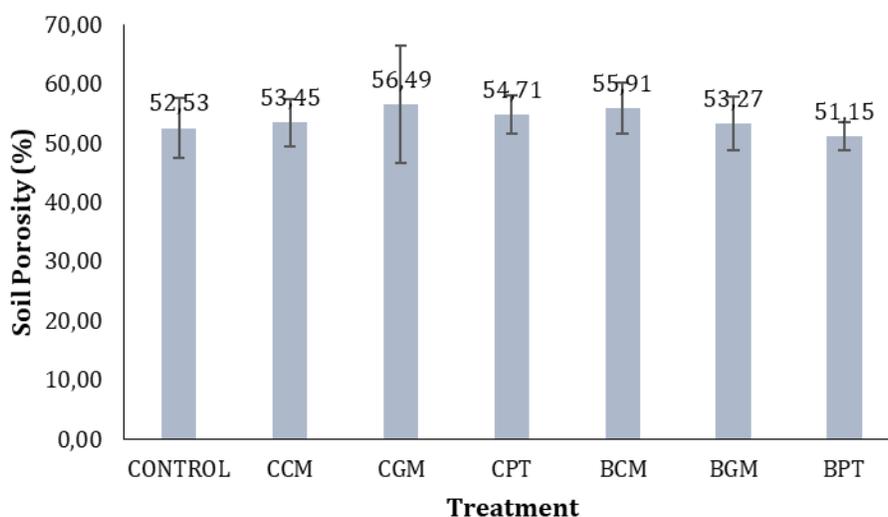


Fig. 3 Soil porosity after combination of CFA-biochar-organic fertilizer applied

This trend of increasing porosity aligns with previous bulk density results, which also showed a decreasing trend in the biochar, CFA, and organic fertilizer-based treatments. However, because the soil bulk density in all treatments was relatively constant and within the general range of mineral soils (approximately $2.6\text{--}2.7 \text{ g/cm}^3$), the pore structure was more influenced by initial soil compaction than by changes in the type of particle composition (Guan et al., 2025). This stable soil particle density made changes in porosity less pronounced.

Furthermore, post-mining soil type C, with its clayey texture (Table 2), tends to have a dense structure and a slow response to ameliorant materials. Jiang et al., (2025) suggests that biochar and organic matter can increase porosity through aggregate formation and reduced bulk density, but these effects are often more pronounced with long-term application or in less degraded soils. Therefore, the trend of increased porosity in some treatments was not strong enough to make a significant difference in the relatively short study period. Large-interconnected pores are essential for the transport of air and gas in compacted soil, so the creation of new pores will initiate a gradual recovery of the soil's physical properties from a few points to the entire soil (Keller et al., 2021).

Water Holding Capacity

Soil water holding capacity showed significant differences between treatments ($F: 151.123$; $p: 2 \times 10^{-16}$), with the highest value in the BGM (Biochar 20 t/ha +5% Goat manure) treatment (88%) and the lowest in the control (77%) (Fig. 4). Biochar-based treatments (BCM, BGM, BPT) tended to increase soil water holding capacity compared to the control, while several CFA + organic fertilizer combinations such as CPT (Coal fly ash 20 t/ha +5% Compost; 82%) and CGM (Coal fly ash 20 t/ha +5% Goat manure; 80%) were still slightly higher than the control, but not as high as the biochar-based treatment. This pattern indicates that the added amendments were able to improve soil water retention, although their effectiveness varied depending on the type of organic material and the characteristics of the amendment used.

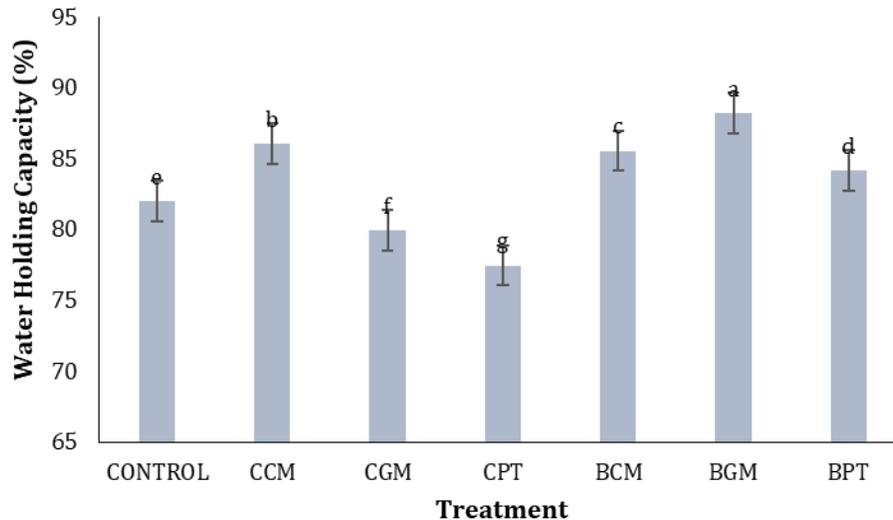


Fig. 4 Soil Water Holding Capacity after combination of CFA-biochar-organic fertilizer applied

The increase in water-holding capacity in biochar-based treatments is primarily related to biochar's highly porous nature, large surface area, and rich micropores, which allow it to store greater amounts of water than ordinary mineral soils. Biochar's pore structure also creates new pores in the soil, thereby increasing water retention, especially in clay-textured soils, which typically saturate quickly but struggle to release water to plants (Rasa et al., 2018; Liu et al., 2016). Conversely, the combination of CFA with organic fertilizer still resulted in increased water retention, but not as high as biochar. This may be due to CFA's ability to improve aggregate structure and increase macropores (Adriano & Weber, 2001), but it is less effective at increasing water-retaining micropores than biochar (Wang et al., 2019).

Biochar is known to increase water holding capacity by increasing the micro-meso pore fraction and the accumulation of stable organic matter, which improves soil structure (Cen et al., 2021). Numerous literature reports that the addition of 10–20 t/ha of biochar can significantly increase water holding capacity, especially in compacted soils or post-mining soils (Yu et al., 2013; Razzahgi et al., 2020; Wong et al., 2022; Toková et al., 2023). The increase in water retention in the combination of CFA + organic fertilizer is also in line with reports that inorganic ameliorant materials such as fly ash can improve soil aggregation, although the effect is greater on macropores than micropores (Ram & Mastro, 2014; Tu et al., 2022; Jubaedah et al., 2025).

4. Conclusions

The combination of coal fly ash, biochar, and organic fertilizer showed a tendency to improve the physical properties of post-mining soil type C after corn cultivation. Although there were no statistically significant differences in soil bulk density, soil particle density, and soil porosity, the results significantly affected soil water holding capacity. The BCM treatment showed the lowest bulk density (1.09 g/m³), the CCM treatment

showed the lowest particle density value (g/cm³), the CGM treatment showed the highest porosity (56%), and the BGM treatment showed the highest water holding capacity (88%).

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