

Amelioration of Ultisol Acidity Using Coal Ash and Lignite-Enriched Compost

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Abstract

Prolonged use of Ultisols can degrade soil quality, notably by increasing acidity. To address this, proper management practices such as adding lime, compost, coal ash, and lignite are essential. This study evaluated the ability of coal ash and lignite-enriched compost to reduce Ultisol's acidity. A split-plot experiment was conducted with main treatments including compost (K), compost combined with FABA (Fly and bottom ash) (KF), and compost with FABA plus lignite (KFL), all at a rate of 50 tons per hectare. Sub-plot involved different application methods: broadcasting and banding (in crop rows). Results indicated that banded application of KFL raised soil pH to 5.50. Additionally, banded application significantly enhanced cation exchange capacity (CEC) and base saturation (BS) by 11.94 me 100 g⁻¹ and 45.51%, respectively, while decreasing exchangeable Al by 0.208 me 100 g⁻¹ compared to broadcasting.

1. Introduction

Prolonged monoculture cultivation can degrade soil as a growing medium, leading to a decline in overall soil quality. This process undermines long-term soil sustainability as a consequence of declining biological, physical, and chemical quality (Osman, 2014; Wahyunto and Dariah, 2014). Biologically, soil degradation reduces the abundance and diversity of soil organisms (Gershuni and Smillie, 1999). Physically, it promotes soil compaction and deteriorates soil structure, thereby lowering soil physical quality (Shukla, 2014). Chemically, soil degradation results in the depletion of essential soil nutrients and a decline in key chemical properties, including soil pH and CEC (Cahyono et al., 2019; Foth and Ellis, 1997; Havlin et al., 2017). Soil degradation can occur across various soil types, with more pronounced effects in highly weathered soils such as Ultisols (Buol et al., 2011).

Ultisols are a soil order that has undergone advanced pedogenic development, resulting in relatively low soil fertility (Buol et al., 2011; Havlin et al., 2017; Tisdale et al., 1985). They are distinguished by low soil pH, reduced CEC, and BS < 35% (Soil Survey Staff, 2010). Additionally, Ultisols contain elevated levels of aluminum (Al) and iron (Fe), which can restrict nutrient availability and hinder plant growth (Buol et al., 2011; Mulyani et al., 2010; Ramadhani et al., 2021). The presence of argillic and/or kandic horizons within the endopedon further limits their water retention, resulting in significant water loss via runoff (Fiantis, 2015). This runoff accelerates nutrient leaching, especially of base cations, leading to nutrient-poor, acidic conditions marked by the prevalence of Al and Fe compounds (Fajarindo et al., 2023; Soil Survey Staff, 2010).

Cahyono et al. (2020b), Fajarindo et al. (2023), and Ramadhani et al. (2021) found that Ultisol at Great Giant Company (GGC) has a low pH of 3.97-4.76, along with low levels of CEC, nutrients, and organic matter (Eviati and Sulaeman, 2009). Additionally, this soil exhibits relatively high concentrations of Al and Fe (Eviati and Sulaeman, 2009). These conditions necessitate proper management of monoculture cultivation on Ultisol to ensure that plant nutrient needs are met and productivity stays optimal. To address these issues and enhance Ultisol's

quality, several approaches can be employed, such as adding organic matter (Cahyono et al., 2020a; Ramadhani et al., 2022), coal ash (Agustini et al., 2017; Hamanaka et al., 2022), lignite (Rezki et al., 2022; Tahir et al., 2011), and liming (Cahyono et al., 2019).

Organic materials like compost offer numerous benefits for improving soil quality. Compost has been shown to enhance Ultisols within four months of application, with the pH increasing from 4.76 to 5.88 when 50 tons per hectare are applied (Cahyono et al., 2020b). In addition, the treatment enhanced soil nutrient status, including carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), by 2.25%; 0.22%; 0.032 g kg⁻¹; 0.13 g kg⁻¹; 0.84 g kg⁻¹; and 0.32 g kg⁻¹, respectively, from initial levels of 1.59%; 0.16%; 0.01 g kg⁻¹; 0.10 g kg⁻¹; 0.22 g kg⁻¹; and 0.12 g kg⁻¹ (Cahyono et al., 2020b). The addition of complementary materials, such as fly ash, can optimize soil improvement through organic matter application (Jayasinghe et al., 2009; Jayasinghe and Tokashiki, 2012), bottom ash (Sondari and Nurkhalidah, 2012; Sriningsih et al., 2022), and lignite (Sarlaki et al., 2019; Wang et al., 2017) to improve soil properties.

Coal ash comprises fly ash (FA) (Yu et al., 2019) and bottom ash (BA) (Nurmegawati et al., 2019), collectively known as FABA. This waste results from coal combustion in steam power plants (PLTU) and cannot be reused for electricity generation. Typically, it accumulates in the PLTU area. Coal ash possesses a high pH and provides macro and micronutrients that can positively influence soil fertility (Fajarindo et al., 2023; Huculak-Mączka et al., 2018). Its use as a soil amendment has been widely documented for improving soil and plant health. Sriningsih et al. (2022) found that FABA from the Surabaya PLTU has an alkaline pH of 11.28 for FA and 8.86 for BA, indicating it can raise soil pH. They also reported that applying 1 kg 15 kg⁻¹ of FABA and 50% coal to the soil increased pH, CEC, and BS, while decreasing exchangeable-Al content. Lignite has potential as a soil ameliorant in Ultisols because its carboxyl (R-COOH) and phenolic (6-C with aromatic OH ring) functional groups enhance the retention of base cations, thereby increasing soil pH and CEC (Foth and Ellis, 1997; Havlin et al., 2017; Rais et al., 2021).

Lignite, or brown coal, represents an early stage of coal formation. It has low calorific value due to its low energy content and is not typically used as fuel in coal-fired power plants. Characterized by its high water content and relatively soft structure, lignite differs from other coal types (Jones, 2016; Sao et al., 2010). It is also used as an ameliorant because it contains humic and fulvic compounds, which can enhance soil organic matter (Huculak-Mączka et al., 2018; Rezki et al., 2022; Saha et al., 2016; Suwardi, 2021). The study was conducted to examine the benefits of integrating coal ash and lignite into compost as a strategy to mitigate Ultisol's acidity in Way Pengubuan Subdistrict, Central Lampung, Lampung Province.

2. Research Methods

This study was conducted in Way Pengubuan Subdistrict, Central Lampung, Lampung Province. Soil samples were collected two months after planting (MAP). The experimental layout followed a split-plot design embedded within a randomized block design, with treatments allocated to main and subplots. Main plots were established with three types of ameliorants: compost alone (100%; K), compost amended with 25% FABA (KF), and compost amended with 20% FABA and 10% lignite (KFL). The subplots involved two application methods: broadcast (Broadcast/T) and banding (along crop rows/P). All soil conditioners were applied at a single dosage of 50 tons ha⁻¹ at the onset of the experiment. Each treatment was replicated 4 times, for a total of 24 plots. The data obtained was statistically analyzed using Minitab. Results were subjected to mixed-model ANOVA at $p \leq 0.05$, and treatment means were compared using Tukey's honest significant difference (HSD) test at a 95% confidence level. Details of the soil ameliorants' compositions are shown in Table 1.

Table 1. Ameliorants dosage

Treatment	Compost	FABA (tons ha ⁻¹)	Lignite
K	50.0	0.0	0.0
KF	37.5	12.5	0.0
KFL	35.0	10.0	15.0

The plant used in this research was pineapple (*Ananas comosus* L. Merr). The treatment plots measured 12 x 4 m, with a planting distance of 50 x 27.5 cm per planting, resulting in 360 plants per treatment plot. The plants were watered once a week or when the soil was dry. Initial soil sampling was conducted by Fajarindo et al. (2023). Final soil sampling was conducted using a composite sample from 5 points per treatment plot, collected with a soil auger at a depth of 0-20 cm. Soil, fertilizer, and plant analysis were conducted at GGC laboratory facilities. The ameliorants analysis covered pH, organic carbon (C), and humic and fulvic acids. The soil properties analyzed included pH, CEC, Al, and BS. Initial soil and ameliorant characterization data are summarized in Table 2.

Table 2. Initial soil and ameliorant properties

Parameters	Unit	Soil	Level*	K	KF	KFL
pH H ₂ O	-	4.50	Acid	7.43	8.89	8.13
Organic Carbon	%	1.25	Low	15.40	15.12	17.48
Cation exchange capacity	me 100 g ⁻¹	7.77	Low	-	-	-
Base Saturation	%	35.65	Low	-	-	-
Exchangeable Al	me 100 g ⁻¹	-	-	-	-	-
Humic	%	-	-	9.35	8.46	8.21
Fulvic	%	-	-	2.94	2.81	2.81

Note: **Fajarindo et al. (2023); *Based on the assessment of soil analysis results by Eviati and Sulaeman, 2009;

3. Results and Discussion

3.1 Ultisol's Characteristics

The study used Ultisol soil collected from fields formerly cultivated with cassava (*Manihot esculenta*). Based on Table 2, the Ultisol exhibited acidic soil characteristics, as indicated by its low pH, and was characterized by low CEC and BS (Buol et al., 2011; Soil Survey Staff, 2010), according to the criteria established by Eviati and Sulaeman (2009).

3.2 Ameliorant's Characteristics

Table 2 shows that the ameliorants had pH values ranging from neutral (K) to alkaline (KF and KFL). The ameliorants also exhibited high organic carbon contents, accompanied by humic and fulvic substances. The properties of the ameliorants met the Indonesian National Standard (SNI) criteria as described by Eviati and Sulaeman (2009). Hence, the use of compost, compost-FABA combinations, and compost amended with FABA and lignite is projected to improve the overall quality of Ultisols, particularly in Ultisols of Way Pengubuan District.

3.3 Effect of Ameliorants on Soil Acidity

Table 3 shows that the application of KFL on banding (KFL-P) reduced soil acidity more effectively than the alternative treatments, while showing no significant difference compared with KF on banding (KF-P). Despite this improvement, the soil was still classified as slightly acidic, as indicated by an increase in soil pH (Eviati and Sulaeman, 2009). The observed increase was associated with the high pH of the KFL-based ameliorant, which is alkaline. The presence of FABA in compost, combined with lignite, enhanced the ability to increase Ultisol's pH and exerted a liming effect, as FABA contains relatively high levels of Ca and Mg (Kumar and Samadder, 2015; Lu and Zhu, 2004; Mashfufah and Prasetya, 2019). The Ca content in KFL plays a role in reducing exchangeable Al in Ultisols by replacing two Al³⁺ ions with three Ca²⁺ ions in the soil exchange complex (Foth and Ellis, 1997; Havlin et al., 2017; Tisdale et al., 1985). The increase in Ultisol's pH can be attributed not only to the liming effect of Ca but also to contributions from organic matter.

Organic matter plays an important role as a pH buffer, defined as its ability to stabilize soil pH within a certain range, thereby contributing to an increase in Ultisol's pH (Foth and Ellis, 1997; Havlin et al., 2017; Rezki et al., 2022; Whalen et al., 2000). Furthermore, organic matter is capable of chelating Al and Fe in the soil, which consequently reduces soil acidity (Havlin et al., 2017). The increase in Ultisol's pH following KFL application was greater when the ameliorant was applied using the banding technique than with broadcast application. This is because banding places the ameliorant directly in the root zone rather than distributing it evenly across the entire field, resulting in a more targeted effect.

Table 3. Effect of ameliorants on soil pH

Treatment	pH
K-T	5.02 ^{bc}
K-P	4.91 ^c
KF-T	5.11 ^b
KF-P	5.30 ^{ab}
KFL-T	4.95 ^c
KFL-P	5.50 ^a

Note: Values in a given column that are denoted by the same letter are statistically similar as determined by Tukey's test at p ≤ 0.05.

A reduction in soil acidity was also indicated by increases in CEC and BS, along with lower exchangeable Al content (Fajarindo et al., 2023; Havlin et al., 2017). Although ameliorant application alone did not significantly affect CEC, BS, or exchangeable Al content, the application technique significantly influenced the reduction of Ultisol's acidity, as shown in Table 4.

Overall, ameliorant application had no significant effect on BS, CEC, or exchangeable Al in Ultisols; whereas, application technique had a significant influence on these soil properties. Banding application increased Ultisol's CEC (Table 4) and was accompanied by an increase in BS. These improvements were consistent with the increase in soil pH (Table 3), indicating that increases in soil pH correspond to greater occupancy of the soil exchange complex by base cations (Havlin et al., 2017). The increases in CEC and BS under band application suggest that this method provides greater benefits for improving soil quality than broadcast application, as the ameliorant is concentrated in the vicinity of the plant root zone.

Table 4. Effect of Ameliorants on BS, CEC, and Al

Application Technique	BS	CEC	Al
	%	me 100 g ⁻¹	
Banding	45.51 ^a	11.94 ^a	0.208 ^b
Broadcast	37.34 ^b	11.12 ^b	0.494 ^a

Note: Values in a given column that are denoted by the same letter are statistically similar as determined by Tukey's test at $p \leq 0.05$.

Organic matter decomposition in the ameliorant results in the formation of organic acids (such as oxalic, malonic, and tartaric), which consist of organic anions capable of complexing Al^{3+} in Ultisols. This mechanism is evidenced by the decrease in exchangeable Al content when the ameliorant was applied using the banding technique (Tisdale et al., 1985). The reduction in Al toxicity subsequently contributes to an increase in Ultisol's pH and CEC, thereby creating more favorable conditions for nutrient retention and availability.

In this context, several studies have reported that an increase in soil pH enhances P availability because higher pH promotes the release of P previously sorbed by Al and Fe, while Ca supplied by the ameliorant becomes preferentially sorbed (Fajarindo et al., 2023; Havlin et al., 2017; Prasetyo et al., 2022). The increase in Ultisol's pH is accompanied by an increase in CEC, as shown in Table 4 is therefore expected to increase the availability of K, Ca, Mg, and Na. This observation aligns with the conclusions drawn by Putri et al. (2023), who reported that the application of 25 t ha⁻¹ compost + FABA increased K, Ca, Mg, and sodium (Na) contents and reduced exchangeable Al in Ultisols of Central Lampung.

4. Conclusion

Coal ash with lignite-enriched compost and compost mixed with FABA effectively raised Ultisol pH, with banding along crop rows yielding the strongest results by boosting cation exchange capacity and base saturation while lowering exchangeable aluminum. This underscores the value of localized application for optimal soil amelioration. Future studies could explore long-term effects on crop yields, interactions with microbial activity, or optimal banding depths in varying Ultisol types.

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