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The Linkage of Soil pH, Phosphorus Availability, and Exchangeable Aluminum in Andisol and Recommendations for Soil Improvement

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ABSTRACT

The Indonesian government implemented a program known as the Food Estate in Humbang Hasundutan to enhance food security. This initiative involved cultivating strategic food commodities on large-scale agricultural land. The soil type in this area is classified as Andisol, which is naturally fertile. Nevertheless, the food and horticultural crop practices in Andisols scarcely consider soil health, fertility, and sustainability. This study was conducted on the Andisols of Humbang Hasundutan to determine the limiting factors of soil chemical properties to support sustainable land management. Soil samples were collected from the topsoil layer (0–30 cm) at 95 locations using a grid-based sampling system. These samples were analyzed for pH, phosphorus availability, and exchangeable aluminum. The data were examined through correlation tests, with soil improvement levels identified using K-means clustering. The results showed that the Andisols in Humbang Hasundutan had an acidic pH level (5.30), extremely high organic carbon content (8.23%), moderate total nitrogen level (0.44%), extremely low potential and available phosphorus levels (12.66 mg 100g^{-1} and 4.36 ppm), very low base saturation (6.48%), and relatively high exchangeable aluminum (Al_{exch}) (1.36 cmol kg^{-1}). Correlation analysis revealed a negative relationship between pH and P availability, while Al_{exch} showed a positive correlation with P availability. However, P availability in Andisols was not significantly influenced by variations in Al_{exch} or soil pH. Soil improvement recommendations were categorized into three groups: 60 locations requiring very high P fertilization, 28 locations requiring high P fertilization, and 7 locations requiring moderate P fertilization, along with the application of soil amendments, such as dolomite or guano phosphate, to reduce aluminum levels.

Keywords: andisol, exchangeable-Al, P availability, soil acidity

INTRODUCTION

Currently, numerous types of natural disasters are associated with climate change, resulting in food crises. According to Mokhov (2022), empirical evidence demonstrates that an increase in global surface air temperature is linked to a rapid increase in the number of natural disasters, mostly caused by meteorological and hydrological anomalies. The short-term effects of hydrological and climatic anomalies in the atmosphere do not have an immediate impact on the agricultural sector because agricultural productivity shows a positive correlation with temporary CO_2 emissions in the short term (Ozdemir 2022). Long-term agricultural production can be significantly influenced by climate change due to its correlation with variables such as rising global temperatures, increased pest and disease outbreaks, and the occurrence of natural disasters. Agricultural cultivation practices themselves are also among the drivers of changes to microclimate, which ultimately lead to decreased productivity and the emergence of a food crisis over the long term. It is important to consider the potential consequences of agricultural cultivation practices, as these practices could contribute to future declines in agricultural productivity and potentially lead to a food crisis. It is crucial to preserve agricultural culture by ensuring food security (Agnoletti and Santoro 2022).

The prioritization of food security in Indonesia has consistently been a matter of national concern, aimed at addressing the dietary requirements of its expanding population. Currently, the country is home to over 278 million individuals, with an annual growth rate of 1.07%. The government has set a goal to achieve food self-sufficiency by 2045 (Fiantis *et al.* 2022). The Food Estate (FE) project is a program developed by the Indonesian government to ensure food security through the production of essential food commodities on large-scale agricultural land (Juhandi *et al.* 2024). Efforts to attain food security through the FE Program in North Sumatra Province have been a proactive

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measure to address this issue. Programs that can meet both food demands and sustainability in the agricultural sector are required to ensure the continued availability of food in the face of a crisis. It is anticipated that the FE Program will be a key step toward achieving the goal of food security. Moreover, FE are one of the efforts that the government has adopted to mitigate the negative effects of climate change. In this region, the soil types found include Andisol, which is characterized by concerns regarding the availability of phosphorus (P) nutrients.

As one of the areas within the world's "rings of fire," the distribution of Andisols in Indonesia is quite extensive. Andisols are soils originating from volcanic material, specifically volcanic ash/glass, and cover approximately 3.4% of Indonesia's total land area (Yatno and Suharta 2011), have different characteristics depending on their utilization and management practices. Hati *et al.* (2021) found that horticultural soils had lower organic carbon levels but higher levels of available phosphorus (P), total potassium (K), soil pH, exchangeable bases, and base saturation than pine forest soils. The development of chemical properties in Andisol has limitations for the growth of horticultural plants. High P retention (>85%) in Andisols can limit agricultural productivity by restricting P availability for plants (Subardja *et al.* 2014). This deficiency arises from the transformation of P availability into unavailable forms owing to P retention by minerals such as allophane, imogolite, and amorphous iron (Fe) and aluminum (Al) oxides (Anda and Dahlgren 2020; Nash *et al.* 2014).

Phosphorus plays an important role in plant growth. The availability of phosphate is a crucial factor for plant growth because phosphate plays an essential role in photosynthesis, cell division, and the formation of the plant's genetic structure (Malhotra *et al.* 2018). However, under acidic conditions (pH <5.0), the base cations on the soil surface are replaced by Al^{3+}, resulting in an increase in the concentration of Al^{3+}. Consequently, these conditions are toxic to plants (Kariuki *et al.* 2007; Lollato *et al.* 2013; Gillespie *et al.* 2021). Anindita *et al.* (2022) also highlights the relationship between Al, organic materials, and non-crystalline materials in the retention of base cations. According to Nanzyo *et al.* (1993), aluminum-humus complexes are highly reactive with phosphate and fluoride compared to allophonic clays.

Understanding soil characteristics is essential for achieving food security through sustainable agriculture. One of the FE locations with the Andisol type is in Ria-ria Village, Pollung District, Humbang Hasundutan Regency, North Sumatra Province. This study was conducted to determine the extent of the relationship between soil acidity and exchangeable Al (Al_{exch}) on the P availability for plants in that location. This information can guide recommendations for soil improvement and balanced fertilization for sustainable agriculture in this region. Gaur and Verma (2023) stated that the combination of intensive agricultural practices and excessive fertilization can affect the environment at both local and international levels. Therefore, understanding the role of pH, Al_{exch}, and their linkage with P availability is important for sustainable farming in Andisol.

METHODS

Study Area

The research was conducted in Ria-ria Village, Pollung District, Humbang Hasundutan Regency, North Sumatra Province (Figure 1). The geographical coordinates of the site are approximately 98°43'6.815" Eastern and 02°24'14.484" Northern. At the site, there were three groups of farmers: Ria Kerja, Ria Bersinar, and Ganda Marsada. The soil type at the research site is Andisol with dacitic tuff parent material, and the location is characterized by a volcanic plateau landform with wavy slopes (12%).

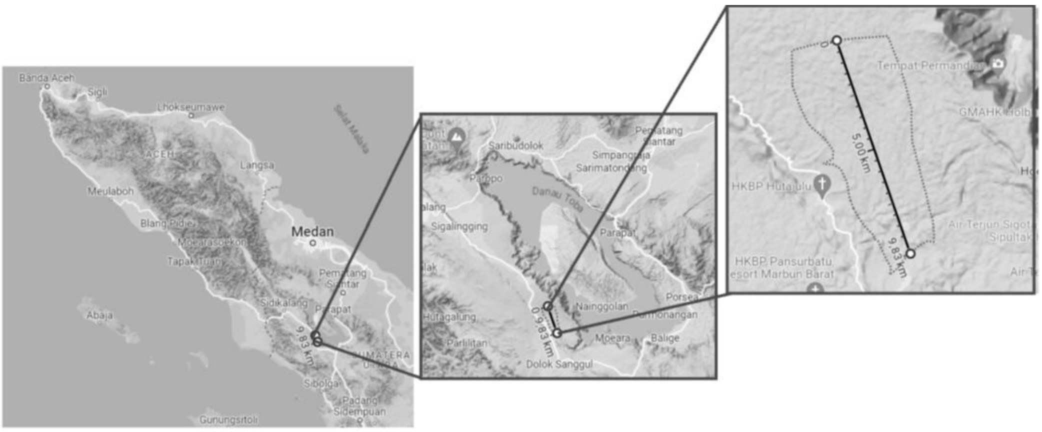

Figure 1 Research site in Ria-ria Village, Pollung District, Humbang Hasundutan Regency, North Sumatera Province.

Materials

The field equipment used during the research included GPS devices, soil-filling forms, soil drills, Munsell soil color charts, field pH measurements (using NaF solution), and laboratory equipment for soil testing. Soil samples were collected for laboratory testing from a depth of 0–30 cm, which represents the general rooting depth of horticultural plants. To identify the special characteristics of the soil, soil profiles and minipits were created, depending on the field conditions. The soil description procedure followed the guidelines for soil profile descriptions in the field proposed by Sukarman *et al.* (2017).

Procedures

The research location points in the field were determined using the purposive sampling method. Observations, profiles and minipit making, and soil sampling were conducted based on a grid system, with each point being 500 m apart. A pH measurement field using a NaF solution was also performed to determine the presence of andic material (allophane). The soil samples were then subjected to laboratory analysis to determine soil texture, pH, organic carbon (C), total nitrogen (N), potential phosphorus (P), available phosphorus (P availability), base cations, base saturation, and exchangeable-Al (Alexch). The soil texture was determined using the pipette method. Soil pH was measured in water extract (1:2.5 ratio) and NaF solution (1:50 ratio). The organic carbon content was determined using the Walkley and Black method, the Kjeldahl method was used to determine total nitrogen, available P was estimated using the Bray 1 extraction, and the potential P was analyzed using a 25% HCl extract. Base cations and base saturation were extracted using NH4-Acetate 1N pH 7. Alexch was extracted using KCl 1N. All soil chemical analysis were based on the Technical Guidelines for Chemical Soil, Water, and Fertilizer Analysis (Eviati et al. 2023).

Statistical Analysis

The results of determining pH (H_2O), Al_{exch}, and P availability were then analyzed further using a correlation test (Equation 1) in Microsoft Excel. The relationships formed were determined based on the significance of the *F*-test, coefficient value, and p-value (<5%; significant effect).

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][[n\sum y^2-(\sum y)^2]}} \text{ (Equation 1)}$$

where:
r = correlation coefficient
n = number of data
x and *y* = variables being analyzed

The 95 P-availability and Al_{exch} data were also analyzed using the *K-means* clustering approach to classify the level of soil improvement or fertilization. *K*-means clustering is a partitioning method in which objects are classified into one of the *K*-clusters based on their proximity or Euclidian distance from each other (Supriyatna *et al.* 2020; Liu *et al.* 2017; Arora *et al.* 2016). The result of the partitioning method is a set of *K*-clusters in which each object from the dataset belongs to a specific cluster. Within each cluster, there may be a centroid or several alternative centroids designated as cluster representatives. The basic algorithm for *K*-means is as follows: (1) determine the number of clusters (*K*), then set the cluster centers to be arbitrary, (2) calculate the distance of each cluster data center (Equation 2), (3) group the data into clusters based on the shortest distance, (4) calculate the new cluster centers (Equation 3), and (5) repeat steps two to four until no more data are moved to another cluster.

$$d(x,y) = \sqrt{\sum_{i=1}^{n}(xi-yi)^2} \text{ (Equation 2)}$$
$$vi = \frac{1}{ci}\sum_{j=1}^{ci} xi \text{ (Equation 3)}$$

where:
d = euclidean distance
v_i = new cluster center
c_i = number of data points in the i^{th} cluster

RESULTS AND DISCUSSION

Soil Chemical Properties

One criterion for identifying Andisol is the presence of andic properties, which can be determined in the field using NaF pH measurements (Soil Survey Staff 2022). The results showed that field NaF pH measurements indicated andic properties, with values ranging from 10 to 11. These values, which are higher than the threshold of 9.4, are indicative of the presence of an allophane, a material that dominates the soil exchange complex. This characteristic is due to the exchange of ligands between F^- and OH groups on the periphery of allophane, resulting in the release of OH^- and a rapid increase in solution pH (Wada 1978). Arifin *et al.* (2022) also reported high NaF pH measurements (9.4 to 11), further confirming that the soil exchange complex is dominated by amorphous materials characteristic of Andisol.

Table 1 presents the average soil chemical properties of the 95 topsoil samples collected from the study area. The investigated Andisols exhibited acidic conditions, with an average pH (H_2O) of 5.3. The pH measured in KCl was lower than that (H_2O), averaging 4.38. The acidic pH and low base content of the soil can be attributed to the dacitic tuff parent material and high annual rainfall. The average annual rainfall at the study site was 3,257 mm. Rainfall exceeding 100 mm often leads to intense leaching of base cations. Mulidzi *et al.* (2020) showed that cation leaching is influenced by soil texture and rainfall intensity.

Table 1 Soil chemical properties of Andisol

	Soil chemical properties	Mean	Criteria/class*
Soil pH	pH H_2O	5.30	Acidic
	pH KCl	5.38	Acidic
Organic matter	Organic C	8.23 %	Very high
	N total	0.44 %	Medium
Phosphorus (P)	Potential P	12.66 mg.100g^{-1}	Very low
	Available P	4.36 ppm	Very low
Exchangeable bases	Ca	0.76 cmol kg^{-1}	Very low
	Mg	0.21 cmol kg^{-1}	Very low
	K	0.18 cmol kg^{-1}	Low
	Na	0.19 cmol kg^{-1}	Low
Cation exchange capacity		21.56 cmol kg^{-1}	Medium
Base saturation		6.48 %	Very low
Exchangeable-Al		1.36 cmol kg^{-1}	Very high

Remarks: (*) Criteria by Soil Research Institute (Eviati *et al.* 2023).

The soil texture in the study area was dominated by sandy loam. The dominant color of the upper horizon was black, suggesting a high organic matter content, whereas the lower horizons transitioned to dark brown and gray, reflecting a decline in organic matter with depth. The organic matter content in the topsoil was reflected by the very high organic carbon content of 8.23%. Similar findings were reported by Anda and Dahlgren (2020) in the topsoil of Mount Tangkuban Perahu, West Java Province, Indonesia, where organic carbon content ranged from 6 to 8%. Furthermore, the total nitrogen (N) content in the soil was 0.44%, categorized as moderate. The elevated organic matter content highlights the potential of Andisols to serve as excellent carbon sinks, contributing to global carbon sequestration and the mitigation of climate change.

High P retention is a distinctive characteristic of Andisols, resulting in very low levels of both potential and available P. Total and available P were low, averaging of 12.66 mg 100g^{-1} and 4.36 ppm, respectively. The soil also exhibited very low base saturation (6.48%), attributed to high rainfall, which caused intense leaching of base cations. This low base saturation indicates a deficiency in base content. The concentrations of cations such as Ca (0.76 cmol kg^{-1}), Mg (0.21 cmol kg^{-1}), K (0.18 cmol kg^{-1}), and Na (0.19 cmol kg^{-1}) were categorized as low to very low. In contrast, the low pH led to high Al solubility, as evidenced by the exchangeable-Al of 1.36 cmol kg^{-1}.

Despite the high organic carbon (C) content and moderate cation exchange capacity (CEC), the organic soil colloids were unable to function effectively in nutrient storage. This inefficiency is likely due to the characteristics of the soil, which are influenced by acidity. The hydrolysis of a single mole of Al^{3+} produces three moles of H^+, resulting in decreased soil pH. This process results in the immobilization of nutrients, such as phosphorus, making them inaccessible to plants. Equation 4 illustrates this reaction.

$$Al(OH)^3 + H_2PO_4^- \rightarrow Al(OH)_2H_2PO_4 + OH^- \text{ (Equation 4)}$$

An Al oxide layer can form on the surface of soil minerals, effectively trapping P. This mechanism is critical for nutrient immobilization because it involves ligand exchange reactions and surface deposition. Moreover, precipitation may occur rapidly when P concentration in the soil solution is high (Johan *et al.* 2021). In addition, Hanyabui *et al.* (2020) specified that at pH levels ranging from 2 to 5, P retention was mainly attributed to the gradual dissolution of Al oxides, which was subsequently reprecipitated as phosphate.

Relationship between Soil pH, Exchangeable-Al, and P-availability

The results of laboratory and statistical analysis revealed a significant inverse relationship between soil pH and Al_{exch} (Figure 2). A correlation coefficient of –0.56 indicates a moderate negative relationship between soil pH and Al_{exch} value. A correlation closeness level (*r*) of 56% confirmed this inverse relationship. Specifically, a decrease in soil pH by 0.1 corresponded to an approximate increase in Al_{exch} of 0.18 cmol kg^{-1}. This trend implies that Al_{exch} levels tend to increase as soil pH value decreases. Low soil pH can render Al inaccessible to plants, but an excessive concentration of exchangeable Al can lead to plant toxicity. An accumulation of exchangeable Al can also result from excessive urea fertilization, which exacerbates soil acidification. This condition poses risks to both plant health and the surrounding environment. According to Briffa *et al.* (2020), soil acidification enhances the solubility and mobility of metals in the soil, thereby increasing their uptake by plants. Consequently, such elements may enter the food chain and pose potential hazards to animals and humans.

There was no significant correlation (*r* = –0.29) between soil pH and P availability in the Andisols studied (Figure 3). The variation in P availability remains unexplained and may not be directly related with rising soil pH levels at the site. Phosphorus availability in Andisols is typically limited due to their high P retention capacity. This finding is aligned with

Anda and Dahlgren (2020), which reported a strong correlation between P retention and soil pH (*r* = 0.88), where the level of P retention gradually decreased following the application of organic fertilizers to the surface layer of Andisols. Such a pattern suggests an inverse relationship between P availability and soil pH in Andisols, as reflected by the negative correlation coefficient. Therefore, soil pH within a certain range (5.0–5.5) may actually promote higher levels of both P availability and Al_{exch}, compared to conditions where pH exceeds 5.5. Figure 4 shows a positive correlation

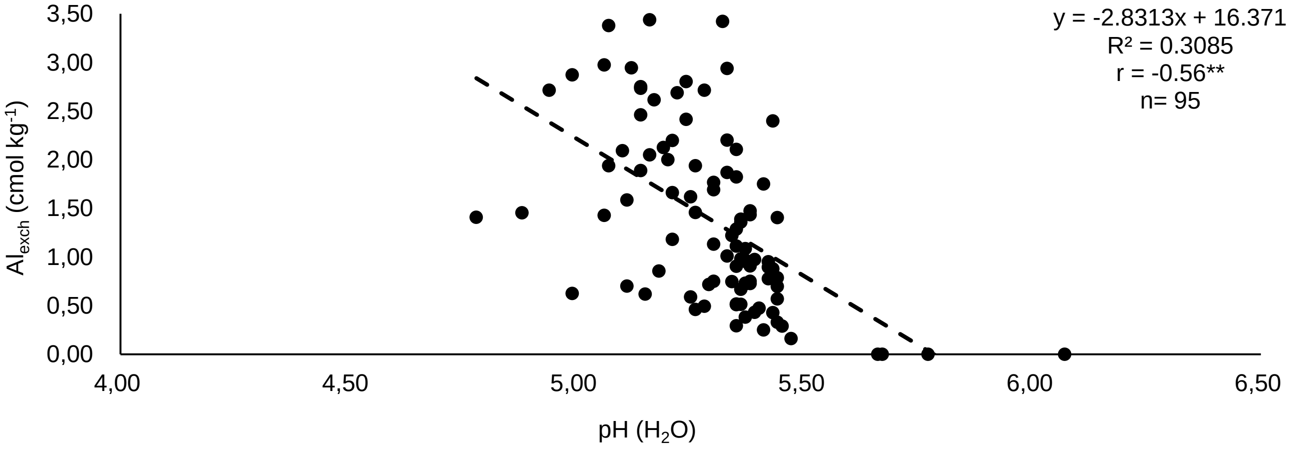

Figure 2 The correlation between pH and exchangeable Al at a depth of 0–30 cm, in Ria-ria Village.

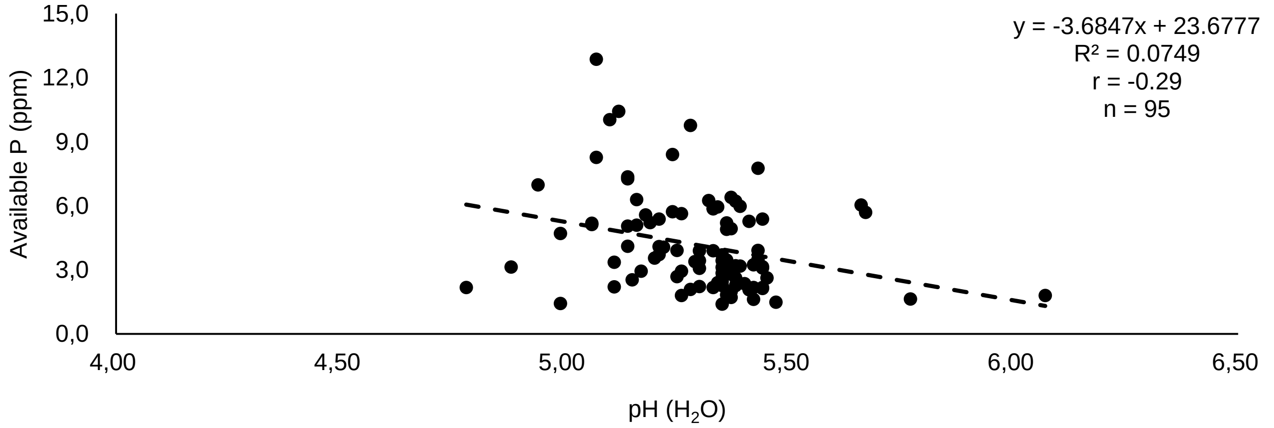

Figure 3 The correlation between pH and P availability at a depth of 0–30 cm, in Ria-ria Village.

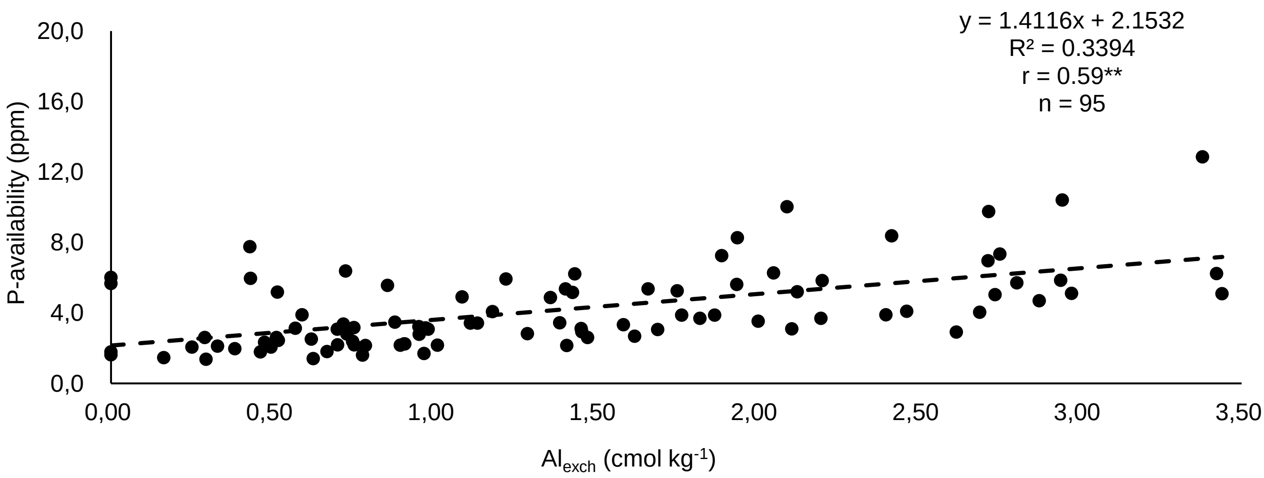

Figure 4 The correlation between exchangeable Al and P availability at a depth of 0–30 cm, in Ria-ria Village.

between increased Al_{exch} and P availability, with a correlation coefficient (*r*) of 0.59.

The statistical analysis indicates that the increase in Al_{exch} value is directly proportional to P availability. This relationship signals a strong retention of orthophosphate by Al within the soil colloids. Thus, the amount of P released into the solution is proportional to the concentration of Al_{exch}. This suggests that improving soil P availability should be combined with suppressing Al availability. Such an integrated approach would increase the amount of P accessible to plants while mitigating the risk of aluminum toxicity.

The correlation between available P and Al_{exch} indirectly indicates that soil pH influences P availability. Although in this study, only a partial value of pH can explain its effect on P availability, the statistical evidence supporting this relationship was relatively weak. The pH dependence of phosphate adsorption-desorption equilibrium in soils exhibits only a slight shift (Curtin and Syers 2021). As soil pH declines, Al availability increases. This rise in Al availability is followed by increased P uptake, resulting in decreased available P in the soil. Nobile *et al.* (2020) denoted that P uptake tends to decrease as soil pH increases.

Soil Improvement Recommendations

Available P can be enhanced through the application of dolomite or guano phosphate. Devnita *et al.* (2018) showed that rock phosphate can reduce P retention and increases P availability. Yang *et al.* (2019) also reported that increasing soil organic matter improves P availability in black soils in China. This shows that increasing P availability in the soil can be carried out separately or simultaneously with the reduction of Al_{exch} concentrations. Accordingly, the observation data should be simplified into defined clusters (Table 2).

Considerations for determining fertilization and soil amendment recommendations were based on clusters from K-means analysis of P availability and Al_{exch} in the soil. Three clusters were identified: the first cluster is soils with very low available P and very high Al_{exch}; the second cluster is low available P and very high Al_{exch}; and the third cluster is medium available P and very high Al_{exch}. Thus, the first cluster requires a very high rate of inorganic P fertilization, the second cluster requires high rate of inorganic P, and the third cluster requires moderate application of inorganic P. To overcome Al_{exch}, the application of soil ameliorants is

Table 2 The average of P-availability, exchangeable-Al, and soil improvement recommendations in 95 study locations using the *K*-means clustering approach.

Clusters	Average of P-availability (ppm)*	Average of exchangeable-Al ($cmol^+.kg^{-1}$)**	Improvement applications
1	2.76	1.05	Very high inorganic P fertilizer + biofertilizers + low to moderate application of soil amendment
2	5.75	1.86	High inorganic P fertilizer + biofertilizers + moderate to high application of soil amendment
3	9.65	2.27	Moderate inorganic P fertilizer + biofertilizers + high application of soil amendment

Remarks: *≤ 10 ppm P (P deficiency), **> 3 $cmol^+.kg^{-1}$ (toxic Al) (Setiadi and Anira 2015).

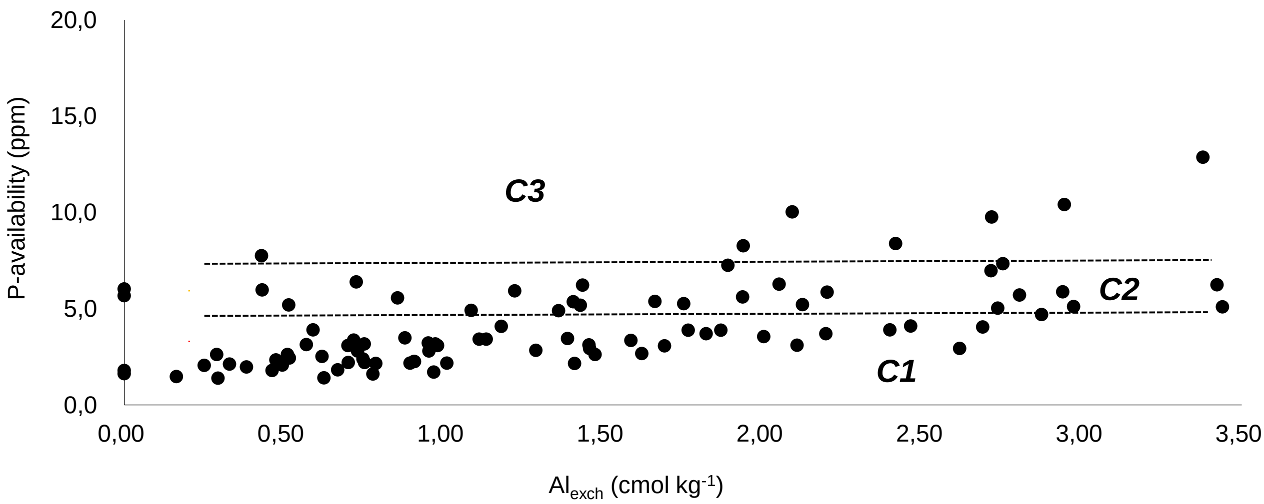

Figure 5 The illustration of four clusters of correlation exchangeable-Al and P-availability using the *K*-means approach (the boundary line was created based on the centroid value of the P-availability). Note: C1 = very low P-availability, C2 = low P-availability, C3 = moderate P-availability.

recommended, with increasing doses along with the rising Al_{exch} levels from cluster 1 to cluster 3.

The cluster descriptions are presented in Table 2 and Figure 5. There are 60 observation locations included in cluster one, where most Andisols in Ria-ria Village require a very high input of inorganic P fertilizer. Horticultural crops require readily available P sources. In cluster one, farmers are recommended to apply very high doses of inorganic P fertilizers in combination with soil amendments (such as dolomite or guano) and optionally biofertilizers (manure with phosphate-solubilizing microorganisms (PSM)). In the second cluster, which includes 28 observation locations, high doses of inorganic P fertilizers are recommended, along with biofertilizers (manure with PSM) and moderate amounts of soil amendments (dolomite or guano).

For the third cluster, which consists of seven observation locations, a similar treatment to that recommended for the second cluster can be applied. However, the dosage of inorganic fertilizer may be reduced in this cluster. In addition, the presence of Al_{exch} should be monitored by adding high doses of soil amendments to mitigate potential aluminum toxicity in plants.

In each cluster, the use of biofertilizers is recommended given the long-term benefits and their potential to enhance the effectiveness of ameliorants in suppressing Al_{exch} and improving P availability. The application of biological fertilizers, in this case manure and PSM, has been proven to maintain soil health, especially by reducing the solubility of Al and increasing the P availability in Andisols. Organic acids produced from the decomposition of organic matter and microbial activity can reduce the solubility of Al and bind it into complex bonds. On the other hand, orthophosphate at a certain concentration, which initially bound to aluminum or complexed with organic matter may become soluble and available to plants. Li *et al.* (2022) reported that soil organic matter not only improves the buffering capacity of acidic soils but also limits the mobilization of soil aluminum, inhibiting the formation of exchangeable and soluble Al. Furthermore, Anda and Dahlgren (2020) observed that intensively cultivated horticultural Andisols exhibit several notable alterations, including increased extractable mineral nitrogen, reduced fixation of P, improved P availability, elevated soil pH, and increased concentrations of exchangeable base cations (Ca, Mg, and K) as well as micronutrients (Zn, Mn, and Cu). PSM contributes to phosphate solubilization bound in organic matter, thereby providing a source of P aside from what is supplied by inorganic fertilizer. Zaidi *et al.* (2009) stated that phosphate-solubilizing microorganisms (PSM), such as bacteria, have emerged as viable biotechnological options in sustainable agriculture to fulfill the P needs of plants.

Finally, this study showed that P availability is not always limited by solubility of aluminum. It remains important to apply amendments to Andisols that can reduce aluminum solubility and prevent its toxic effect on plants. The soil pH should also be controlled to manage the solubility of aluminum. Further laboratory investigations are required to better understand the connection between phosphorus availability and elevated aluminum levels, rather than soil pH, particularly in Humbang Hasundutan Andisols.

CONCLUSIONS

It can be concluded that a significant association exists between soil pH and exchangeable Al (*P*-value = 0.00; sig. 0.05), indicating a negative correlation (r = –0.56). Similarly, a significant relationship between exchangeable Al and P availability (*P*-value = 0.00; sig. 0.05), indicating a positive correlation (r = 0.59). While the mechanisms remain unclear, it is likely that soil acidity influences P availability. This is evidenced by the high levels of both P availability and exchangeable Al in soils with low pH values. Additionally, the trend indicates that exchangeable Al tends to increase with increasing P availability. This clustering analysis determined the average P availability in Andisols Humbang Hasundutan Regency within three clusters: 2.76 ppm requiring very intensive improvement, 5.75 ppm requiring significant improvement, and 9.65 ppm requiring moderate improvement recommendations.

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