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The effect of phosphate fertilizer and organic matter on phosphorus status, pH, and cabbage yield in Andisols

Abstract Andisols are characterized by high phosphorus (P) retention, which often limits P availability for crops. This study aimed to analyze the independent and interactive effects of P fertilizer and organic matter (i.e. manure and rice straw compost) on P retention, total P, available P, P uptake, soil pH, and cabbage yield. This research was conducted in pot experiments in plastic house, applying P fertilizer (0, 90, 180, 270 kg ha⁻¹) and organic matter (20 kg ha⁻¹ of chicken, sheep, cow manures and rice straw compost) on Andisols planted with cabbage. The experiment used a factorial randomized design. The results showed no significant interaction between P fertilizer and organic matter for all measured parameters. However, individual applications of organic matter, particularly manure, significantly improved P uptake, soil pH₀, and cabbage yield, demonstrating its superior effectiveness compared to rice straw compost. Overall, manure application consistently outperformed rice straw compost in enhancing crop growth and P uptake. These findings underscore the importance of proper nutrient management strategies in Andisols to improve P availability and sustain optimal crop productivity.

Keywords: P uptake · Manure · Phosphate fertilizer · Andisols

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Introduction

Andisols, are distributed only approximately 0.8% of the earth's surface, yet they possess great potential for agricultural production (Anda et al., 2021; Hati et al., 2021). In Indonesia, for instance, many of most productive regions and densely populated area are located near active or dormant volcanoes. The unique physical, chemical, and mineralogical properties of these soils, such as their high porosity, dark color, and abundance of amorphous materials (including allophane, imogolite, and ferrihydrite), sesquioxides (oxides and hydroxides of aluminum and iron), and Al-humus complexes distinguish them from soils formed from other parent materials and largely account for their high productivity (Takahashi, 2020; Takahashi & Dahlgren, 2016). These soils are commonly situated in the agro-ecosystem zone and are commonly utilized for cultivating plantation crop and upland vegetable fields. However, the productivity of Andisols is often constrained by phosphorus deficiency despite their inherent fertility (Marpaung et al., 2023; Velásquez et al., 2016). Therefore, appropriate soil management strategies are essential to optimize their productivity and prevent degradation.

Phosphorus (P) in one of the macro nutrients required for plant growth, yet in Andisols the availability of P for plant is often low due to the strong sorption of P by non-crystalline aluminum (Al) and iron (Fe) that forms insoluble metal-phosphorus compounds (Gypser et al., 2018; Marpaung et al., 2022; Wang et al., 2019). The amount of P retention is also affected by pH of the system. Phosphate retention is generally highest in acidic to near-neutral conditions, pH 5.5-7, due to strong absorption of P onto iron and aluminum oxide. Under alkaline conditions (i.e. pH > 7) and very acidic conditions (i.e. pH < 5) P retention may decrease due to formation of Ca-phosphate and reduced adsorption by Fe and Al oxides, respectively (Gustafsson et al., 2012; Penn & Camberato, 2019).

The chemistry of Andisols reflects the influence of high amounts of variable charge. The term 'variable charge' refers to characteristic of organic and inorganic soil constituents that possess varied charge on the reactive surface depending on the pH, ionic concentration, and composition of the soil solution (Van Ranst et al., 2017). In variable charge soils, P retention can be reduced by lowering the zero point of charge

(ZPC). ZPC arises from the properties of amphoteric oxides, e.g., aluminum (hydr-)oxide, allophane, or other amorphous substances in clay fractions which are the main characters of variable charged clay. According to Uehara & Gillman (1981), a decrease in point of zero net point charge (PZNPC) may increase the surface negative charge and increase cation exchange capacity. This surface charge characteristic is important in soil management since the physicochemical process that control nutrient availability occur at the soil particle surface (Uehara & Gillman, 1981). In tropical soil, Fe and Al oxides are the sources of variable charge and important agents in controlling P retention and its availability in topsoil (Barrow, 2017).

The incorporation of organic matter (OM) into the soil is one way to lower PZNPC (Van Ranst et al., 2017) and it also well known to soil fertility and productivity (Tong et al., 2020). OM has a low PZNPC, about pH 4, thereby playing a role in lowering PZNPC of the soils. The adsorption of organic anion secreted from plant roots or produced from the decomposition of plant residue can lower PZNPC of variable charge soils through increasing negative surface charge and masking positive charge. In addition, OM, particularly manure, can be the source of macro and micro-nutrients including phosphorus (Fang et al., 2021; Goldan et al., 2023). These studies also underlined that manure applications can reduce the use of phosphorus fertilizer. Recent research showed an appropriate fertilizer, combination NPK and organic fertilizer, can improve P uptake (Chen et al., 2023; Gao et al., 2023). This positive outcome underscores the potency of organic fertilizer in addressing challenges related to the use of P fertilizer, considering the rising of fertilizer price and its limited availability faced by farmers.

Andisols are characterized by high phosphorus fixation which often limits P availability. Although numerous studies have reported the beneficial effects of phosphate fertilizers and organic amendments on chemical soil properties and crop yield, results remain inconsistent in Andisols. Several cases showed that the application of phosphate fertilizer or/and organic matter did not lead to the expected improvement in P availability due to its interaction with amorphous Al and Fe compounds (Mabagala & Mng'ong'o, 2022; Velásquez et al., 2016). In addition, the low phosphorus zero point of charge (pH₀)

characteristic of Andisols plays a critical role in regulating nutrient dynamics, as soil pH relative to pH_0 strongly influences surface charge properties. Information on how different doses and types of organic matter influence P dynamics, either independently or in interaction with phosphate fertilizer remains limited. Understanding these effects is essential. Therefore, there is a need to evaluate both the individual and interactive effects of phosphate fertilizer and diverse organic matter types applied at different rates to identify nutrient management strategies that can effectively improve P availability and cabbage yield in Andisols.

Material and Method

Research areas. The research was conducted in plastic house at the experimental garden, Faculty of Agriculture, Universitas Padjadjaran, West Java (6°55' 0.728" S, 107°46' 18.4606" E). The research area has annual temperature and precipitation were ± 25 °C and ± 1500 -2000 mm per year, respectively. The soil used in this experiment was classified as Andisols originated from Pangalengan (Herdiansyah et al., 2024). We used the top layer (at 30 cm depth) of Andisols Pangalengan which was formerly planted by potato (*Solanum tuberosum*).

Materials and Tools. The treatments applied organic fertilizer such as cow manure, chicken manure, sheep manure, and rice straw compost, and inorganic fertilizer such as SP-36 (36% P_2O_5) as well as basic fertilizer such as urea, ZA, and KCl fertilizers. Cabbage (*Brassica oleraceae* var Grand 11) were used as plant indicator. Laboratory equipments and chemical reagents used in this research were analytical balance, pH meter, pipette, mechanical shaker, centrifuge, volumetric flask, H_2SO_4 , H_2O_2 , ammonium molybdate, $HClO_4$, Bray P, KH_2PO_4 , and KCl or $CaCl_2$.

Experimental Design and Treatments. The experiment used a Factorial Randomized Block Design (RBD) consisting of two factors (P fertilizer and organic fertilizer) with different types and doses (nine treatments). The treatments were $a_0 = 0$ kg ha^{-1} $P_2O_5 = 0$ g polybag⁻¹ SP-36; a_1 90 kg ha^{-1} $P_2O_5 = 1.6$ g polybag⁻¹ SP-36; a_2 180 kg ha^{-1} $P_2O_5 = 3.1$ g polybag⁻¹ SP-36; a_3 270 kg ha^{-1} $P_2O_5 = 4.6$ g polybag⁻¹ SP-36; $b_0 =$ without organic matter; $b_1 = 20$ ton ha^{-1} cow manure; $b_2 = 20$ ton ha^{-1}

$b_3 = 20$ ton ha^{-1} sheep manure; $b_4 = 20$ ton ha^{-1} rice straw compost, and five replicates for each treatment, thus total samples were 45 samples.

Research Procedures. The Andisol from Pangalengan were prepared as planting medium for pot experiment after cleaning the soils from the grass, filtered with 2 mm sieve, then weighed approximately 10 kg of field moist for each polybag with size 40 x 50 cm. Each polybag was filled with the soil and organic fertilizer was added in accordance with the treatments, then the mixed soils were stirred homogeneously. Watering was done every day until it reached the field capacity then incubated. The length of incubation was two weeks. After the incubation period, P fertilizer was applied in accordance with the treatment, as well as basic fertilizer N (Urea + ZA) of 0.61 g and 1.52 g polybag⁻¹, respectively. Urea and ZA were given first, followed by KCl fertilizer about 1.22 g polybag⁻¹. Cabbage seedlings were transplanted 21 days after sowing, with one seedling planted per polybag.

Laboratory Analysis. Selected chemical properties were conducted to analyze the effect of the dose of P fertilizer and the type of organic matter. Soil pH was measured in H_2O with a glass electrode pH meter at 1:5 soil:solution ratio. Soil pH_0 was conducted using pH-drift method in which we identified the point where changing the solution ionic strength does not produce a corresponding change in solution pH. P retention was determined by the method of Blakemore et al. (1981). Total P, available P, and P uptake were analyzed following the procedure by ISRIC (Van Reeuwijk, 2002). At harvest, the gross weight of cabbage was measured immediately after cutting, including the head and outer wrapper leaves. The wrapper leaves were then removed manually, and the fresh crop weight of the cabbage head was weighed. All weights were recorded in digital balance and expressed in grams per plant. Some observations that were not tested statistically were visual growth of plants, plastic house temperature, pest attack, and elemental deficiency symptoms. Chemical properties of organic materials (i.e. cow manure, chicken manure, sheep manure, and rice straw) were added in Supplementary 1. Fertilizer efficiency (g g⁻¹) was calculated following the formula:

$$P \text{ recovery efficiency} = \frac{(P \text{ uptake treatment} - P \text{ uptake control})}{\text{applied P}} \quad (\text{Eq.1})$$

Data Analysis. Statistical data analysis was done using IBM SPSS statistics for Windows version. Analysis of variance (ANOVA) was used to determine the effects of P fertilizer and organic matter independently and their interaction on measured variables, i.e. P-retention, P-total, P-available, P-uptake, pH, pH_0 , crop weight and gross weight. When ANOVA indicated significant effects, mean comparisons were performed using Duncan Multiple Range Test (DMRT) at 5% level, after checking assumptions of normality and homogeneity of variances (transformations applied where necessary).

Results and Discussion

Initial Soil Properties. The same soil type, namely Andisol originated from Pangalengan, as used in the study by Herdiansyah et al. (2024) was employed in this experiment. According to their morphological soil description, the soil was classified as Typic Hapludands with dominant silt loam and silty clay loam at the depth of 0-30 cm, soil P available 11.2-13.3 ppm, CEC 14.84-35.72 me. 100 g^{-1} , K_2O 0.14-0.22 $\text{mg}\cdot 100\text{ g}^{-1}$, and organic carbon between 3.99-4.17%.

The effect of P fertilizer on measured variables. The application of various doses of P fertilizer did not have significant effect on all measured variables (i.e. P-retention, P-total, P-available, P-uptake, pH, pH_0 , crop weight, and gross weight) (Table 1 and 2). We observed that the P-total content increased with increasing the dose of P fertilizer although not significant. Increasing the P-total after being treated is expected due to the nature of P in the soil that always leads to the unabsorbed P form (immobile). On the other hand, the available P content tended to decrease with increasing doses of P fertilizer. It is suspected that some of the available P form were absorbed by plant and part of P was unavailable (i.e., total P or P retention). We observed there was a little gap between initial P available (section 3.1) and control P available. The difference may be attributed to soil re-equilibration processes during incubation and plant growth.

The increase doses of P fertilizer did not have significant effect on P-uptake, though the amount tended to increase. The lack of significant

influence of additional P fertilizer on the content of these P forms stands in contrast to results reported in earlier studies (Liu et al., 2024; Velásquez et al., 2016). The reason may be due to amount of initial P levels or strong P fixation through sorption by amorphous Fe or Al oxides so added P can be rapidly fixed into stable forms, preventing increases in available P, total P, or P uptake, which is common in Andisols (Gonzalez-Rodriguez & Fernandez-Marcos, 2018; Redel et al., 2016). We observed that the P-retention was between 55-64% (Table 1), which is lower than the typical Andisols ($\geq 85\%$). It may be attributed to a combination of methodological differences and intrinsic soil properties such as soil-solution ratio, short-range-order mineral content, organic matter-Al complexation, and legacy phosphorus saturation. Nevertheless, P retention values exceeding 60% remained within the high category, confirming the strong P-fixing nature of the Andisols studied. In addition, the limited response of P fertilizer on P form can be due to inadequate amount of P fertilizer (the highest treatment dose was $270\text{ kg ha}^{-1}\text{ P}_2\text{O}_5$) and narrow range of doses application. As an illustration, farmers in Pangalengan, based on their experience, applied P fertilizer with dose up to 360 kg ha^{-1} for cabbage plants.

The results indicated that P fertilization had no significant effect on soil pH which contrasts with findings reported in previous studies (Qaswar et al., 2020; von Tucher et al., 2018). It is possibly due to high buffering soil capacity, e.g. volcanic ash soils in Andisols or fertilizer application rate that was too low to influence pH. Regarding to pH_0 , the addition of P fertilizer to variable charged soils can increase negative surface charge which tends to decrease pH_0 . However, since Andisols have strong buffering of surface charge, addition of P fertilizer may not change the pH_0 . Furthermore, the absence of a significant effect of P fertilization on crop weight likely reflects adequate initial soil P availability, strong P fixation reducing plant uptake, and the possibility that other environmental or nutritional factors limited crop growth more than P supply. Previous studies found that additional P fertilizer with lime could strongly increase the crop weight (Dejene et al., 2023; Qaswar et al., 2020).

Table 1. Effect of phosphorus (P) fertilizer and organic material on average of P-retention, P-total, P-available, and P-Uptake

	P-Retention %	P-Total mg 100g ⁻¹	P-Available ppm	P-Uptake mg pot ⁻¹
P Fertilizer				
a ₀ (0 kg ha ⁻¹ P ₂ O ₅)	61.3 a	197.94 a	7.45 a	1387 a
a ₁ (90 kg ha ⁻¹ P ₂ O ₅)	63.0 a	197.53 a	8.84 a	1505 a
a ₂ (180 kg ha ⁻¹ P ₂ O ₅)	62.1 a	211.53 a	5.84 a	1433 a
a ₃ (270 kg ha ⁻¹ P ₂ O ₅)	61.7 a	202.02 a	6.81 a	1821 a
Organic Matter				
b ₀ (without organic matter)	62.9 a	206.14 a	7.06 a	1135 c
b ₁ (20 ton ha ⁻¹ cow manure)	62.4 a	195.30 a	6.02 a	1457 bc
b ₂ (20 ton ha ⁻¹ chicken manure)	64.8 a	208.31 a	6.36 a	1824 ab
b ₃ (20 ton ha ⁻¹ sheep manure)	55.8 a	201.48 a	7.32 a	2063 a
b ₄ (20 ton ha ⁻¹ rice straw compost)	64.3 a	200.06 a	9.42 a	1204 c

Note: Means followed by the same letter are not significantly different according to Duncan's multiple range test at the 5% significance level.

Table 2. Effect of phosphorus (P) fertilizer and organic material on average of pH, pH₀, crop weight, and gross weight

	pH	pH ₀	Crop weight g	Gross Weight g
P Fertilizer				
a ₀ (0 kg ha ⁻¹ P ₂ O ₅)	5.07 a	4.22 a	79.04 a	203.85 a
a ₁ (90 kg ha ⁻¹ P ₂ O ₅)	5.07 a	4.26 a	87.33 a	206.71 a
a ₂ (180 kg ha ⁻¹ P ₂ O ₅)	5.07 a	4.29 a	86.29 a	201.16 a
a ₃ (270 kg ha ⁻¹ P ₂ O ₅)	5.08 a	4.25 a	91.45 a	202.31 a
Organic matter				
b ₀ (without organic matter)	5.15 a	4.18 b	55.62 c	246.77 c
b ₁ (20 ton ha ⁻¹ cow manure)	5.15 a	4.30 a	77.14 b	287.86 b
b ₂ (20 ton ha ⁻¹ chicken manure)	5.16 a	4.27 ab	117.09 a	398.29 a
b ₃ (20 ton ha ⁻¹ sheep manure)	5.11 a	4.30 a	112.86 a	386.18 a
b ₄ (20 ton ha ⁻¹ rice straw compost)	5.17 a	4.23 ab	67.42 bc	281.94 b

Note: Means followed by the same letter are not significantly different according to Duncan's multiple range test at the 5% significance level.

The Effect of Organic Matter on Measured Variables. The results showed that the type of organic matter was seen to significantly affect P-uptake ($p < 0.05$), but not on P-retention, P-total, and P-available. The highest P-uptake was observed after applying sheep manure ($p < 0.05$), yet the carbon content on the sheep manure was 37.3%, lower than cow and rice straw compost (i.e. 65.2 and 47.7%, respectively) (Supplementary 1). Although sheep manure did not exhibit higher carbon content, P availability, or a lower C:P ratio compared with other organic amendments, its application resulted in the highest P uptake. This response suggests that P uptake in Andisols is governed not only by bulk soil P availability but also by rhizosphere processes and manure-soil interactions. In general, organic matter can

improve P-uptake efficiency by enhancing root growth, microbial activity, and P mobilization around the root zone (Poblete-Grant et al., 2025), even if the total measurable P in the bulk soil does not change. The increase of P-uptake can be due to the release of low molecular weight organic acids, e.g. citrate, oxalate, malate that bind strongly to Fe or Al oxides in Andisols releasing P from P-fixation. This result was in line with previous studies (Devaraja et al., 2021; Rahim et al., 2023). On the other hand, the lack of significant effect on P-available, P-total, or P-retention after organic matter application might be because plants immediately absorb P (i.e. real-time rhizosphere P), but not in bulk soil. Sheep and chicken manures was reported to increase phosphorus uptake because they contain more

phosphorus and release more rapid compared to cow manure (Mahmood et al., 2017). While beneficial for long-term soil organic matter, cow manure releases nutrients more slowly and is less effective for immediate crop P needs.

In general, the addition of organic fertilizer increased pH_0 (Table 2) than control b_0 , particularly cow and sheep manure ($p < 0.05$). This result was unexpected since organic matter generally tend to decrease pH_0 (Van Ranst et al., 2017). The rise of pH_0 after organic matter application is possibly due to the addition of basic cations (Ca^{2+} , Mg^{2+} , K^+) that increases soil positive charges and reduces the effective negative charge density of soil colloids. These processes shift the soil's point of zero charge to a higher pH. In variable-charge soils dominated by allophanic materials and Fe or Al oxides, this process can override the negative charge contribution from decomposed organic matter, thus an overall increase in pH_0 . Additionally, manure application induces the protonation of organic anions from the dissociation of weakly acidic functional groups on organic matter to form neutral molecules and this process can increase soil pH buffering capacity as some of exchangeable base cations release to soil solution, avoiding the soil from acidification (Shi et al., 2019). Furthermore, the crop weight was found to be significantly different after chicken and sheep manure applications than other treatments and control. This finding was in line with previous study which reported a moderate to high crop yield after chicken and sheep manure applications than cow manure (Mahmood et al., 2017; Mokgolo et al., 2019; Mukhtiar et al., 2018). Chicken and sheep manure significantly increase crop yield because they generally contain higher concentration of essential nutrients and decompose more rapidly. The application also improves soil chemical condition, i.e. P-uptake, as it was consistent with the increase of P-uptake in this research (Mahmood et al., 2017). In contrast, cow manure generally decomposes more slowly due to high fiber content and provides limited nutrient release, that possibly causes less crop yield than chicken manure.

The research also showed that manure fertilizers outperformed rice straw compost, as the rice straw compost application had less P content and crop yield (Table 1 and 2). Similar finding was reported by Dhaliwal et al. (2023). Manure fertilizer are generally more effective than straw compost,

especially in the short term, possibly due to faster nutrient mineralization (Zhao et al., 2024).

The Interaction Effect Between P Fertilizer and Organic Matter on Measured Variables. The interaction of P fertilizer and organic matter showed no significant effect with all the measured variables, i.e. P-retention, P-uptake, P-available, P-uptake, pH, pH_0 , crop yield, and gross weight. These results was in contrast to most studies that documented the improve soil pH, the availability of phosphorus, and the increase of crop yield after application of organic matter and P fertilizer (Jamal et al., 2023; Jin et al., 2023). The lack of significant effect after applying P fertilizer and organic matter indicating that both inputs may influence soil properties through independent mechanisms without producing synergistic or antagonistic effects. Nevertheless, each factor exhibited a significant individual effect (i.e. organic matter application increases P-uptake, crop yield, gross weight) which reflects their distinct pathways in modifying phosphorus dynamic in Andisols. This finding is consistent with Abbasi et al. (2015) who observed that the combined application of poultry manure, insoluble-rock phosphate, and phosphate-solubilizing bacteria resulted in growth, yield, and P uptake comparable to those obtained with individual treatments.

Fertilizer Phosphorus Efficiency. Chicken and sheep manures were shown to have the highest efficiency than other organic materials such as cow manure and rice straw compost (Fig.1). These types of manure contain P in a form that is more readily to plant, and this P is rapidly released (Mahmood et al., 2017). The chicken and sheep manures generally increase microbial biomass, stimulate phosphatase enzymes, and promote biological P cycling leading to higher P-uptake by the crop. We also found that the highest efficiency was with the dose of 90 kg ha^{-1} P in all different types of manure, and the efficiency decreased with higher doses. This result likely reflects the legacy effects of long-term phosphorus inputs. Repeated fertilization over time can lead to the accumulation of phosphorus in moderately labile and stable pools, thereby reducing crop responsiveness to additional P. Consequently, lower P applications may have better match to current crop demand, while higher rates predominantly contribute to non-productive P pools, leading to reduced fertilizer efficiency.

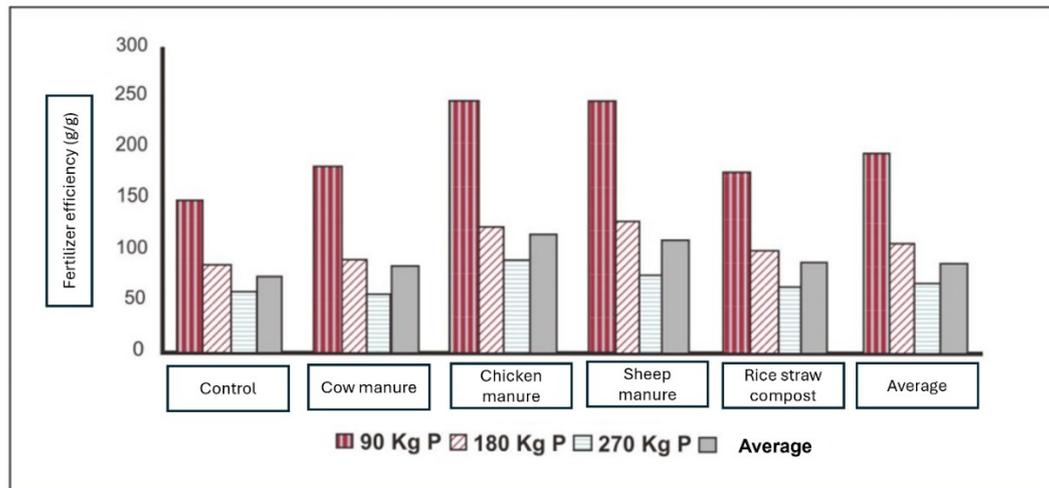


Figure 1. Phosphorus fertilizer efficiency (g g^{-1}) under different organic amendment and phosphorus application rates

Conclusions and Recommendation

Application of P fertilizer and organic matter on Andisols did not produce any significant interaction on P retention, total P, available P, P uptake, soil pH, and cabbage yield. However, each input, i.e. organic matter application, showed independent effect. Among the organic amendments tested, manure fertilizer significantly improved P uptake, increased soil pH₀, and enhanced cabbage yield. The highest efficiency of P fertilizer was at the dose of 90 kg ha⁻¹, underlining moderate P application rates over high inputs to maximize fertilizer efficiency. Overall, manure fertilizer performed better than rice straw compost in improving soil fertility and crop performance on Andisols. This highlights the critical importance of adopting effective nutrient management strategies in Andisols to optimize phosphorus availability and sustain high crop productivity.

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