

Adsorption and Desorption of Phosphorus in Andisol at Several Elevation Variations in the Catena of Mount Merbabu and Sindoro

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Abstract. Andisol is a potential soil but has problems related to phosphorus. Amorphous minerals absorb P in Andisol. But in certain conditions, P can be desorbed. This study aims to determine adsorption and desorption patterns and the soil properties in two different catenas, namely Mount Merbabu and Sindoro. This research uses the catena concept with 3 height variations, 800, 1400, and 2000 meters above sea level. Samples were taken on uncultivated land in horizons A and B. Tests were carried out in the laboratory. The data obtained were processed using ANOVA and Fisher's LSD test, Pearson Correlation, and regression graphs. The results of the P adsorption pattern showed the rate, capacity, and energy of adsorption binding increase with elevation. Despite high adsorption, desorption rates at 2000 masl are also high. However, different results were shown in the Mount Sindoro catena, where the highest desorption rates are found in horizon A at 800 masl and horizon B at 1400 masl. The soil properties most strongly correlated with phosphorus availability are organic matter and organic acids, particularly fulvic acid, as well as the soil's ability to retain phosphorus due to the presence of amorphous minerals such as allophane, imogolite, and amorphous Al/Fe compounds.

1 Introduction

Phosphorus (P) is one of the most required elements for plant growth, therefore phosphorus is also used as a main indicator in evaluating soil fertility [1]. P is needed for photosynthesis, respiration, energy transfer and storage, cell division and enlargement, and other processes. Additionally, this element is very useful for root elongation and germination [2].

This nutrient is essential for plants, irreplaceable, and cannot be synthetically produced, as even chemical phosphorus fertilizers still use natural materials [3]. The provision of P in soil has become a challenge. This is because P nutrient sources are difficult to obtain. The raw material for P fertilizers comes from phosphate rock, which is a non-renewable natural resource. Therefore, the application of phosphorus fertilizers must be efficient to meet plant needs and prevent environmental pollution from fertilizer.

Factors that may influence the availability of P in soil solutions are pH, Al, Fe, and Ca content [4]. In the soil, phosphorus is very reactive to the Al, Fe, Ca, and Mg content, forming compounds that are difficult to dissolve or in an adsorbed state [5]. Phosphorus is also absorbed by hydroxide (OH⁻), silicate clay which is composed of Al and Fe compounds (in tropical areas, these include kaolinite, montmorillonite, illite, and allophane) [6]. In Andisol, phosphate is usually bound to non-crystalline clay minerals such as allophane, imogolite and ferrihydrite, where allophane can hold up

to 97.8% P and the presence of amorphous Al and Fe can also bind P [7].

The slopes of Mount Merbabu and Mount Sindoro are areas with Andisol soil, primarily used for horticultural farming. So, it is important to know the dynamic of the nutrient in the soil especially phosphorus. The soil in the research site formed by volcanic materials. The lithology of Mount Merbabu and Sindoro is dominated by olivine ((Mg,Fe)₂SiO₄) and Augite (Ca₂(Al,Fe)₄(Mg,Fe)Si₆O₂₄), but in Mount Sindoro is also dominated by hypersthene ((Mg,Fe)SiO₃). All these primary minerals have a lot of Fe, Al, and Si that can be amorphous secondary minerals in a suitable environment (low temperature, high precipitation, high humidity). The amorphous secondary minerals can bind the phosphorus by chelation mechanism. This chelation usually occurs in other soils that have amorphous minerals or volcanic soils [7].

The agricultural land on the catena of Mount Merbabu and Sindoro is terraced, with varying elevations. This variation in elevation creates different environments, such as differences in climate conditions, landforms, and organic matter dynamics. These factors are part of the soil formation factors (which include climate, organisms, parent material, landforms, and time) [8]. Climates (especially temperature and rainfall) can potentially affect the availability of P in the soil both directly and indirectly. Directly, rain can cause the loss of P through runoff and leaching, which can subsequently lead to surface water pollution and

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eutrophication [9]. Temperature can also affect the adsorption and desorption of P in the soil [10]. Indirectly, temperature and rainfall can influence P availability through P mineralization, pH, organic matter, and soil microbial activity [11]. The higher the elevation, the lower the temperature, resulting in slower weathering, lower decomposition of organic carbon and P, and shallower effective soil depth [12].

Adsorption and desorption of phosphorus refer to the amount of P that accumulates between solids and soil solution. This value can determine the availability of P, including phosphorus that should be added through fertilization. The adsorption of P in Andisol soil occurs through ligand exchange reactions by incorporating anions into the coordination shell of Al and Fe [13] Phosphate ions exchange aluminol groups (Al-OH) through the process of dihydroxylation [14]. The soil will adsorb P until it reaches a certain stability, then gradually release it back into the soil solution; however, this process is not entirely reversible [15]. This process is called desorption. The adsorption and desorption process can be shown in the isotherm graph, Langmuir, and Freundlich equation. The equation can also determine some of the parameters related to soil adsorption and desorption process.

Factors influencing P adsorption and desorption include pH, type of clay minerals, Fe and Al oxides, particle distribution, mineral crystallization, and the content and quality of organic matter [16]. All soil components interact to form soil properties, including the soil's ability to bind and release phosphorus. Therefore, it is important to understand the patterns of adsorption and desorption and the soil properties that affect the availability of P nutrients in the soil. This knowledge can serve as a reference for good nutrient management practices, ensuring that phosphorus needs are fulfilled without excessive fertilizer application, which could negatively impact environmental sustainability, particularly the soil. This study aims to determine the adsorption and desorption patterns, and the soil properties related to phosphorus availability in two different catenas, in Mount Merbabu and Mount Sindoro.

2 Materials and Method

2.1 Study area and soil sample collection

Research area in the Merbabu and Sindoro mountain catenas in Indonesia. This study utilized varying elevations at 800, 1400, and 2000 meters above sea level (masl). The soil in the research locations is Andisol, proved by the data showing the andic soil properties (Table 1) based on soil survey staff FAO in the book "Soil Taxonomy" (Andic soil properties = $Al\ NH_4\text{-oxalate} + \frac{1}{2}\ Fe\ NH_4\text{-oxalate} > 2$). The research commenced in November 2023 until May 2024. This research uses purposive sampling with 12 field samples and 12 x 7 (treatment) in the laboratory. The samples were taken on transect lines along the slope. Soil samples were collected from the A and B horizons. The soil samples were air-dried, crumbled, and passed

through a 2 mm and 0,5 mm sieve before being analyzed.

Laboratory tests were conducted to measure soil properties related to P adsorption and desorption patterns. Texture was measured using the sediment/pipette method. Bulk density was measured using ring methods. Particle density was determined using pycnometry. Porosity was calculated using (1-(Bulk density/Particle density)) formula. The soil organic carbon content was determined using muffle furnace. The humic and fulvic acids were determined using acid and base solutions. The pH was measured using pH meter in a 1:2,5 soil/water mixture. pH NaF was measured using sodium fluoride in 1:10 mixture. CEC was measured using ammonium chloride.

The available P was extracted with ammonium fluoride and hydrochloric acid and then determined by ascorbic acid-molybdophosphate blue method using Spectrophotometer. The potential P was extracted using hydrochloric acids 25% and then determined by vanadomolybdate using Spectrophotometer. The amorphous minerals were measured using three selective solvent: ammonium oxalate (o), Dithionite Citrate Bicarbonate (DCB) pH 3 (d), dan 0.1M sodium pyrophosphate (p) and then calculated using formula:

$$Fe/Al\text{-humic} = Fe/Al\ Na\text{-pyrophosphate} \quad (1)$$

$$Fe/Al\ (amorphous) = Fe_o/Al_o - Fe_p/Al_p \quad (2)$$

$$Allophane + Imogolite = \%Si\ NH_4\text{-oxalate} \times 7.1 \quad (3)$$

$$\% Allophane = \%Si(100/y) \quad (4)$$

$$Andic\ soil\ properties = Al_o + \frac{1}{2}\ Fe_p > 2 \quad (5)$$

Table 1. Andic soil properties in research site

Elevation	Al NH ₄ -oxalate+ ½ Fe NH ₄ -oxalate			
	Merbabu		Sindoro	
	Horizon A	Horizon B	Horizon A	Horizon B
800 masl	5,65	6,44	8,89	9,18
1400 masl	4,44	3,03	4,08	2,62
2000 masl	3,46	2,10	2,92	5,14

2.2 Phosphate Adsorption and Desorption Analyses

Adsorption isotherms were acquired using the batch equilibrium method with some modifications [17]. 2,5g air-dried soil (0,5 mm) was added to each centrifuge tube and then 0.01 mol/L KCl solution at pH 7.0 which contained P (from KH₂PO₄) at appropriate concentrations to give samples with P concentrations of 0, 10, 20, 30, 40, 50, and 60 mg/L was added to give a soil/solution ratio (w/v) of 1:20. Tubes containing the KCl and P solutions but no soil were analyzed to determine the amount of P that would have adsorbed to the tube and filter surfaces. Three drops of chloroform were added to each tube to inhibit microbial activity, then the tubes were shaken at 150 oscillations per minute at 25°C for 24 hours to allow equilibrium to be reached and centrifuged at 5000 rpm for 10 min. The contents of each tube were then passed through a 0.45 µm

membrane filter, and the P concentration in the solution was determined colorimetrically using the ascorbic acid– molybdophosphate blue method.

The amount of P that had been adsorbed was defined as the difference between the initial amount of P added and the amount in the equilibrated solution. 25 mL saturated NaCl solution at pH 7.0 was added to the supernatant after an adsorption experiment had been completed. It is to extract the adsorbed P, and this process was repeated two times. The solution was removed. Then, 25 mL 0.01 mol/L KCl solution at pH 7.0 was added to replace the adsorbed P. The tubes were shaken, centrifuged, and then determined as described above. The P concentration in the solutions was defined as desorbed P.

2.3 Statistical Analyses

Data correlated using Pearson's Correlation. Analysis of Variance (ANOVA) is used to test the significance of elevation and horizon variations on soil properties. If the varied factor shows a significant effect at the 5% level, further LSD (Least Significant Difference) tests at the 5% level are conducted to determine significant variations using R-studio.

The adsorption and desorption patterns of P nutrients are presented in the form of linear curve equations, Langmuir equation, and Freundlich equation. The Langmuir equation is $C/Q = C/Q_m + 1/kQ_m$ and the Freundlich equation is $Q = aC^{1/n}$ and after linearization become $\text{Log } Q = \text{Log } k + 1/n \text{ Log } C$, where Q (mg/kg) is the amount of P adsorbed to soil at the equilibrium P concentration C (mg/L), Q_m (mg/kg) is the maximum amount of P adsorbed to the soil, and k (L/mg) is a constant related to the binding strength of P at the adsorption sites. $k \times Q_m$ is the maximum adsorption buffering capacity (MBC, L/kg).

Desorption can be described using the Langmuir equation ($C/D = C/D_m + 1/kD_m$) and the Freundlich equation ($D = aC^{1/n}$) and after linearization becomes $\text{Log } D = \text{Log } k + 1/n \text{ Log } C$, where D (mg/kg) is the amount of P desorbed from the soil at the equilibrium P concentration C (mg/L), k (L/mg) is a constant related to the desorbing strength, and D_m (mg/kg) is the maximum amount of P desorbed. The desorption ratio (D_r) is D_m/O_m .

3 Results and Discussion

3.1 Physical and Chemical Properties of the Soil

In Mount Merbabu, there was a significant effect of the elevation and soil horizon on the bulk density, particle density, porosity, organic carbon, and pH (Table 2). In the fulvic acid, humic acid, CEC, and pH NaF parameters, there was a significant difference in elevation variation but no significant difference in soil horizon variation. The humic and fulvic acids ratio showed no significant difference in the elevation and soil horizon variation.

In Mount Sindoro, there was significant effect of the elevation and soil horizon on the bulk density, particle density, porosity, and pH. In the organic-C, pH NaF, and CEC parameters, there was a significant difference in elevation variation but no significant difference in soil horizon variation (Table 3). In the humic and fulvic acids there was no significant difference in the elevation and soil horizon variation. The significant difference in elevation and soil horizon variation is due to different environments.

The higher the elevation, the lower the bulk density and particle density. This is because soil organic matter increases with the rise in elevation [1]. The organic matter in Andisol soil is very high due to the presence of amorphous aluminum hydroxide at cold temperatures [18]. This can inhibit the decomposition of organic matter because it forms complex compounds with amorphous aluminum. The higher the elevation, the lower the temperature. Cold temperatures affect the activity of microorganisms in the decomposition process. Microorganisms are less active at lower temperatures. The decomposition process produces organic acids such as humic and fulvic acid [19].

The organic acids can affect the adsorption and desorption of P due to the presence of carboxylate and phenolate groups. The humic and fulvic acid ratio indicates the decomposition processes in the soil. The presence of organic acids also affects the pH of the soil because it can release H^+ into the soil. The parent material of soil also affects the pH. The Andisol soil at the research site formed in an area with high rainfall and parent materials of andesitic and andesitic basaltic nature, resulting in soil pH that is not too acidic [7]. Andisol has a variable charge, so the CEC (Cation Exchangeable Capacity) depends on the soil pH. The value of pH NaF more than 9,4 indicates the presence of the amorphous minerals [22].

The soil texture (Table 4) at the research location shows an increase in texture class in the B horizon and at lower elevations. This is due to the accumulation of clay. Generally, clay accumulates in the B horizon as a result of leaching from the A horizon. Clay can also accumulate in lower and flatter areas due to erosion by rainwater.

Table 2. Soil properties of the Mount Merbabu

Parameter	Horizon	Elevation			Parameter	Horizon	Elevation		
		800 masl	1400 masl	2000 masl			800 masl	1400 masl	2000 masl
Bulk density (g/m ³)	A	0,75b	0,78b	0,53d	Humic Acids (%)	A	0,98ab	1,24ab	1,71a
	B	0,91a	0,86a	0,63c		B	1,06ab	0,7b	1,42ab
Particle density (g/m ³)	A	1,77b	1,59d	1,49e	Fulvic Acids (%)	A	0,77c	1,29abc	1,52a
	B	1,94a	1,67c	1,51e		B	0,79bc	0,85abc	1,42ab
Porosity (%)	A	57,41b	50,67d	64,42a	pH	A	5,9b	5,7bc	5,5a
	B	54,04c	46,46e	58,55b		B	6,2a	5,9b	5,9b
Organic Carbon (%)	A	6,42b	5,74bc	12,26a	pH NaF	A	11,1c	11,5a	11,6a
	B	5,47c	4,04d	6,17bc		B	11,3b	11,7a	11,7a
Humic and Fulvic Acids Ratio	A	1,236a	1,013a	1,236a	CEC (cmol(+)/ kg)	A	13,37a	4,97c	6,26bc
	B	1,923a	0,934a	0,783a		B	14,26a	5,2c	8,18b

Note: Numbers followed by different letters indicate significant differences between factors (elevation and horizon) in the 5% LSD test.

Table 3. Soil properties of the Mount Sindoro

Parameter	Horizon	Elevation			Parameter	Horizon	Elevation		
		800 masl	1400 masl	2000 masl			800 masl	1400 masl	2000 masl
Bulk density (g/m ³)	A	0,89a	0,66d	0,68d	Humic Acids (%)	A	0,56a	1,15a	1,32a
	B	0,8b	0,74c	0,48e		B	1,04a	0,99a	1,06a
Particle density (g/m ³)	A	1,23c	1,09d	1,29b	Fulvic Acids (%)	A	0,5a	1,07a	0,94a
	B	1,32b	1,44a	0,7e		B	0,51a	0,96a	1,23a
Porosity (%)	A	27,69d	39,1b	47,11a	pH	A	6,2b	5,0d	5,1d
	B	39,26b	48,51a	31,46c		B	6,8a	5,1d	5,3c
Organic Carbon (%)	A	5,7b	6,23b	7,56a	pH NaF	A	9,9c	11,1b	11,6a
	B	5,86b	5,66b	7,84a		B	9,9c	11,1b	11,5a
Humic and Fulvic Acids Ratio	A	1,48a	1,01a	1,25a	CEC (cmol(+)/kg)	A	32,38a	13,00b	5,43d
	B	1,34a	0,93a	1,00a		B	36,86a	16,91bc	8,88cd

Note: Numbers followed by different letters indicate significant differences between factors (elevation and horizon) in the 5% LSD test.

Table 4. Soil texture in research site

Elevation	Horizon	Fraction	Merbabu		Sindoro	
			% Fraction	Texture	% Fraction	Texture
800 masl	A	Sand	33	Clay loam	21	Clay
		Silt	35		38	
		Clay	33		41	
	B	Sand	32	Clay loam	22	Clay Loam
		Silt	35		42	
		Clay	33		37	
1400 masl	A	Sand	63	Sandy Loam	25	Clay loam
		Silt	21		38	
		Clay	17		37	
	B	Sand	58	Sandy Clay Loam	29	Loam
		Silt	21		44	
		Clay	21		27	
2000 masl	A	Sand	62	Sandy Loam	38	Loam
		Silt	26		37	
		Clay	12		25	
	B	Sand	57	Sandy Loam	22	Clay
		Silt	24		33	
		Clay	19		45	

3.2 Minerals of The Soil

Table 5 show mineral of the soil in the research site. Minerals in Andisol are dominated by non-crystalline minerals such as allophane ($Al_2O_3 \cdot SiO_2 \cdot 2,5H_2O$), imogolite ($(OH)_3Al_2O_3 \cdot SiOH$), and ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$ atau $Fe_5HO_8 \cdot 4H_2O$). Amorphous Al and Fe, which are the main products of volcanic ash weathering, combine with humic to form dark-colored, weather-resistant substances (Al-Humic and Fe Humic).

Aluminum released from volcanic ash can be retained by humic, which contains a lot of organic matter, forming allophane humic or aluminum humic complexes (chelates) [7]. On Andisol, phosphate usually bound to non-crystalline minerals such as allophane, imogolite, and ferrihydrite, where allophane can retain P up to 97.8%. The presence of Al and Fe in amorphous forms can also bind P [7]. Groups on amorphous Al and Fe are very reactive to P and subsequently form very strong Al-P and Fe-P bonds [23].

Table 5. Minerals of the soil in the research site

Parameter	Horizon	Merbabu			Sindoro		
		800 masl	1400 masl	2000 masl	800 masl	1400 masl	2000 masl
Fe-Amorphous	A	5,13b	3,61c	0,56e	8,8a	0,37e	1,74d
	B	5,87a	0,13f	1,19d	8,02b	0,24e	5,63c
Al-Amorphous	A	1,07bc	0,3d	1,41b	3,24b	2,17c	0,17e
	B	2,44a	0,73c	0,17d	4,20a	1,41d	0,58e
Fe-Humic	A	0,22b	0,16c	0,26a	0,26a	0,21b	0,20bc
	B	0,2b	0,16c	0,12d	0,21b	0,16d	0,17cd
Al-Humic	A	1,91b	2,26a	1,65c	1,12c	1,62b	1,78a
	B	0,97c	2,15a	1,27d	0,87d	1,01cd	1,66ab
Imogolite	A	0,57c	1,96b	0,65c	1,66b	1,63b	4,32a
	B	0,43c	1,59b	2,84a	0,85c	2,32b	4,31a
Allophane	A	4,57b	3,72b	5,94a	9,99b	9,72c	6,93d
	B	4,74b	4,52b	4,72b	10,71a	7,72d	7,99cd
Ferrihydrite	A	8,71b	6,13c	0,95e	14,95a	0,63e	2,96d
	B	9,98a	0,23f	2,02d	13,63b	0,41e	9,57c

Note: Numbers followed by different letters indicate significant differences between factors (elevation and horizon) in the 5% LSD test.

3.3 Phosphorus Retention and Availability

The phosphorus retention and availability are summarized in Table 6. In Mount Merbabu catena, available P and potential P show significant differences in the elevation and horizon variation. However, the P-retention shows a significant difference only in the elevation variation. In Mount Sindoro catena, potential P and P retention significantly differ in the elevation and horizon variation, while the available P shows difference but not significant.

At all locations, the available P was very low because of the presence of amorphous minerals. At both catenas, the highest available P and the lowest P retention at an elevation of 2000 masl. This is due to the lowest content of allophane and ferrihydrite. The fulvic acid content at

this elevation is also the highest. Fulvic acid is soluble in all pH conditions, making it more easily absorbed by plants. Nutrient transportation in fulvic acid is also more effective. Fulvic acid contributes negative charges to the soil because it has carboxyl (-COOH) and phenol (-OH) groups that can interact with the P nutrient through hydrogen or ionic bonds, preventing P from being bound by other elements and maintaining its availability [24]. Meanwhile, potential-P is phosphorous that can be available through the mineralization processes. Adding organic matter, phosphate solubilizing microorganisms and silica fertilizer can boost the mineralization process. Si is easily soluble in the form of silicic acid and can increase P availability through the anion substitution process [25].

Table 6. Phosphorus retention and availability in research site

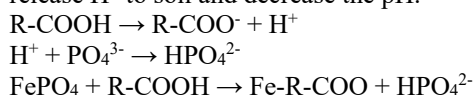
Parameter	Horizon	Merbabu			Sindoro		
		800 masl	1400 masl	2000 masl	800 masl	1400 masl	2000 masl
Available P (mg/100g)	A	0,07d	0,09b	0,11a	0,088b	0,123ab	0,100ab
	B	0,08c	0,08c	0,09b	0,093ab	0,110ab	0,163a
Potential P (mg/100g)	A	19,36c	44,9a	32,35b	93,53a	27,37c	30,27c
	B	6,22d	28,96bc	26,76bc	93,86a	29,55c	67,97b
P Retention (%)	A	99,9861b	99,9855b	99,9854c	99,983b	99,982c	99,982c
	B	99,9866a	99,9858b	99,9851c	99,982c	99,985a	99,976d

Note: Numbers followed by different letters indicate significant differences between factors (elevation and horizon) in the 5% LSD test.

3.4 Correlation Between Soil Properties and Phosphorus

The strongest positive correlation with available P is shown by the fulvic acid parameter (R=0.75) on Mount Merbabu, while on Mount Sindoro, it is shown by the organic C parameter (R=0.6) (Fig. 1). The strongest negative correlation in the Mount Merbabu catena is shown by the P-retention and pH parameters (R= -0.62), while on Mount Sindoro, it is shown by the P-retention parameter alone (R= -0.65). P-retention shows the ability of soil to chelate P, so it can't be available for plant. In Andisol mostly P is bound to amorphous minerals such as

such as allophane ($\text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot 2,5\text{H}_2\text{O}$), imogolite ($(\text{OH})_3\text{Al}_2\text{O}_3 \cdot \text{SiOH}$), ferrihydrite ($5\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$ atau $\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$) and amorphous Al/Fe [7]. However, C-organic can become a source of available P through mineralization and release of amorphous mineral chelation to P via organic acids such as humic and fulvic acids. The increase in P availability by organic acids such as fulvic acid is primarily due to the role of phenolic (-OH) and carboxyl (-COOH) groups [20]. This reaction release H^+ to soil and decrease the pH.



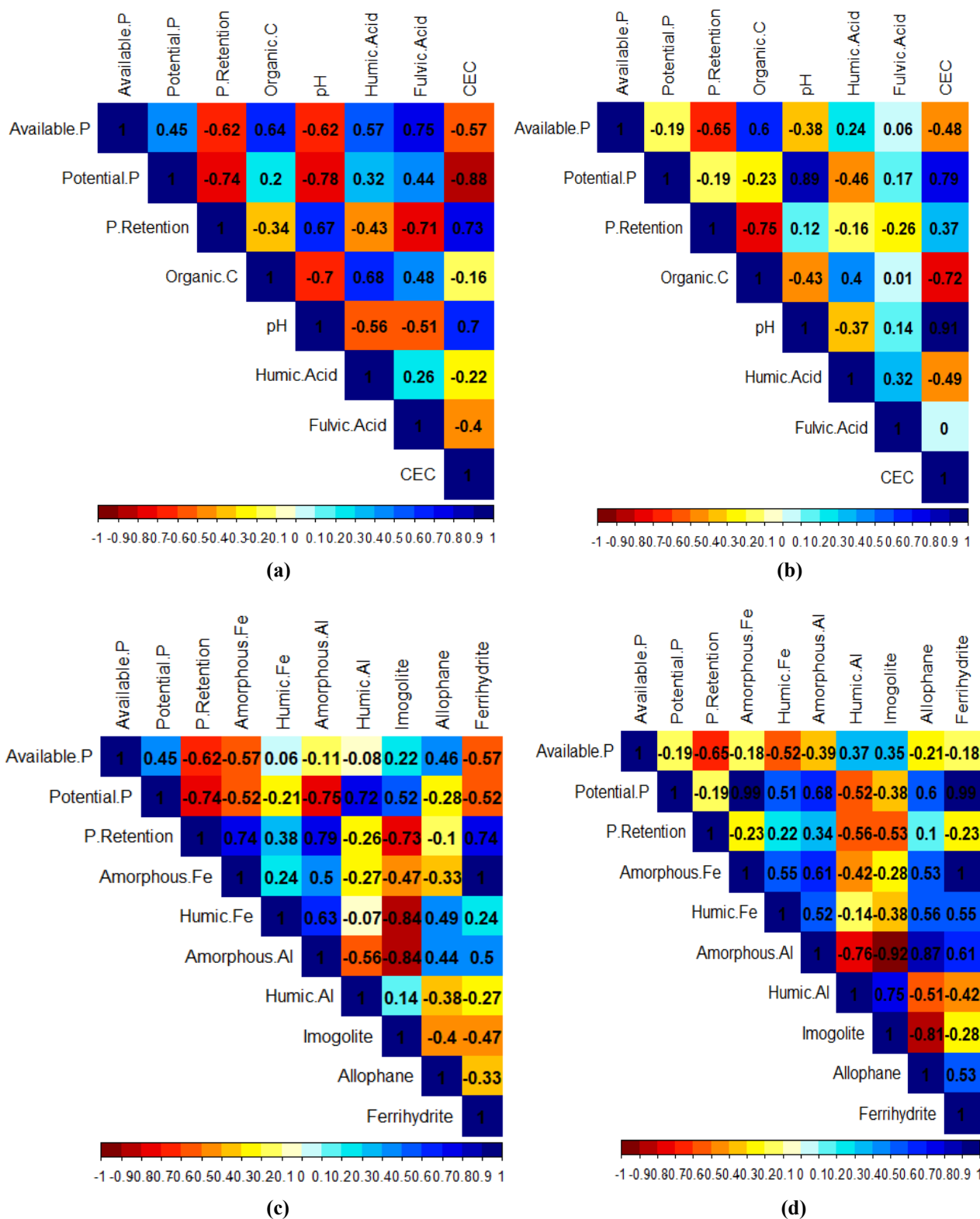


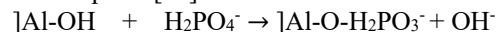
Fig 1. (a) Correlation between soil properties in Mount Merbabu (b) Correlation between soil properties in Mount Sindoro (c) Correlation between soil minerals in Mount Merbabu (d) Correlation between soil minerals in Mount Sindoro. The numbers in the image indicate the R values, which describe the strength of the correlation between parameters. An R value close to 1 indicates a strong positive relationship, while an R value close to -1 indicates a strong negative relationship. An R value close to 0 indicates a weak correlation. The R values in the image are distinguished by color, which can be seen on the scale.

3.5 Phosphorus Adsorption Isotherm, Equation, and Parameters

As the P concentration in the solution increases, the amount of adsorbed P also rises. This same phenomenon was also observed in the study Yang *et al.*, 2019 [17]. The adsorption of P by soil is considered a multi-stage kinetic process that includes an initial rapid adsorption phase, followed by a slower adsorption phase, and potentially additional stages. The chemical adsorption process rapidly decelerates at high P concentrations because the available adsorption sites quickly become saturated. Consequently, the P in the liquid is adsorbed to the soil at a slower rate through physico-chemical and physical adsorption mechanisms [15].

Based on Figure 2 in both catenas, the highest rate of P adsorption occurs at an elevation of 2000 meters above sea level. This can happen because, at this elevation on

Mount Merbabu and Mount Sindoro, the levels of allophane and imogolite are the highest. These amorphous minerals can retain P, resulting in very rapid P adsorption [14].



In both catenas, the adsorption rate in the B horizon is higher compared to the A horizon. This can occur because the A horizon has a higher accumulation of organic matter, which can prevent and release the binding of P with amorphous minerals in the soil [17] and [26] also found that soils with higher organic matter can prevent P binding by amorphous minerals, resulting in a lower adsorption rate. Soil organic matter (SOM) influences P adsorption in soil by blocking adsorption sites on metal oxides like Al and Fe oxides or by forming metal-SOM-P complexes with adaptable structures [27].

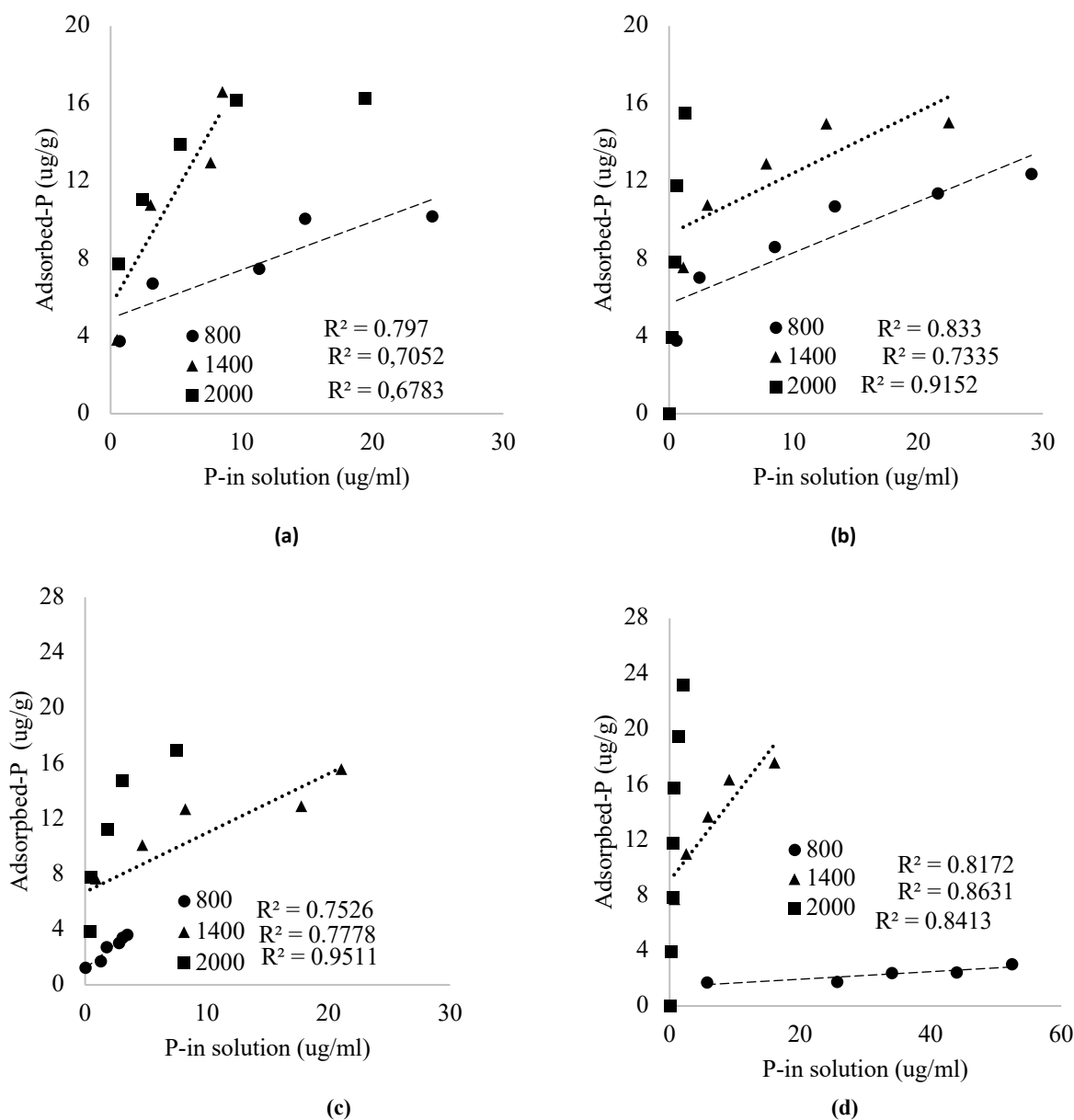
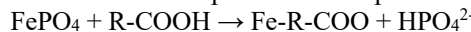


Fig 2. (a) The adsorption isotherm at A horizon in Mount Merbabu (b) The adsorption isotherm at B horizon in Mount Merbabu (c) The adsorption isotherm at A horizon in Mount Sindoro (d) The adsorption isotherm at B horizon in Mount Sindoro

Several models have been created to quantitatively describe phosphate adsorption isotherms. The most widely used models are the Langmuir and Freundlich equations [17]. Table 7 shows the equation in research site. Through these equations, several data points can be

obtained: Qm (the maximum amount of phosphorus that can be adsorbed), k (a constant related to the binding strength of P in the adsorption complex), and MBC (Maximum Adsorption Buffering Capacity or adsorption capacity).

Table 7. Adsorption equation in research site

Mount	Elevation	Horizon	Langmuir Equation		Freundlich Equation	
			$C/Q = C/Q_m + 1/kQ_m$	R ²	$\log Q = \log K + 1/n \log C$	R ²
Merbabu	800	A	$C/Q = 0,1047C + 0,0668$	0,9857	$\log Q = 0,2384 \log C + 0,6552$	0,8844
		B	$C/Q = 0,0798C + 0,1326$	0,9856	$\log Q = 0,4578 \log C + 0,5006$	0,8556
	1400	A	$C/Q = 0,0621C + 0,0506$	0,9868	$\log Q = 0,3285 \log C + 0,8352$	0,8312
		B	$C/Q = 0,0646C + 0,0527$	0,9949	$\log Q = 0,2993 \log C + 0,8326$	0,9610
	2000	A	$C/Q = 0,0587C + 0,0516$	0,9900	$\log Q = 0,2268 \log C + 0,9566$	0,9595
		B	$C/Q = 0,0517C + 0,0228$	0,9969	$\log Q = 0,4562 \log C + 0,9593$	0,8747
Sindoro	800	A	$C/Q = 0,2354C + 2,7726$	0,8742	$\log Q = 0,5678 \log C - 0,3867$	0,9606
		B	$C/Q = 0,3552C + 1,5289$	0,9115	$\log Q = 0,2035 \log C + 0,0716$	0,8524
	1400	A	$C/Q = 0,0667C + 0,0723$	0,9782	$\log Q = 0,2966 \log C + 0,7978$	0,8939
		B	$C/Q = 0,0537C + 0,0700$	0,9806	$\log Q = 0,5707 \log C + 0,6942$	0,8476
	2000	A	$C/Q = 0,0544C + 0,0388$	0,9932	$\log Q = 0,352 \log C + 0,9100$	0,8260
		B	$C/Q = 0,0263C + 0,0330$	0,8909	$\log Q = 0,952 \log C + 1,2249$	0,8830

Based on Table 8 we can see that there is an increase in Qm with rising elevation in both catenas. The highest Qm in the Mount Merbabu and Mount Sindoro catenas is observed in the B horizon at an elevation of 2000 meters above sea level. This indicates that the soil at this location has the highest capacity to adsorb P. This finding shows that the soil's capacity to store P increases with higher SOM content [17]. The P bonding energy (k) is a crucial parameter that describes the soil's affinity for P. A higher k value signifies stronger P adsorption, making spontaneous adsorption more likely as the P

supply diminishes [15]. Based on Table 8, k increases with rising elevation. The high k and adsorption rate are due to the very high affinity (tendency to bind) between the adsorbate and adsorbent at low concentrations, causing adsorption to occur very quickly until it approaches saturation [17]. The MBC is a comprehensive parameter incorporating both Qm and k [15]. A higher MBC indicates that more P will be adsorbed [17]. Similarly to the parameters Qm and k, the higher the elevation, the higher the MBC.

Table 8. Phosphorus adsorption parameters describe with adsorption equation

Mount	Elevation	Horizon	Qm (ug/mg)	k (ml/ug)	MBC (ml/g)
Merbabu	800	A	9,55	1,57	14,97
		B	12,53	0,60	7,54
	1400	A	16,10	1,23	19,76
		B	15,48	1,23	18,98
	2000	A	17,04	3,67	62,50
		B	19,34	2,27	43,86
Sindoro	800	A	4,25	0,08	0,36
		B	2,82	0,23	0,65
	1400	A	14,99	0,92	13,83
		B	18,62	0,77	14,29
	2000	A	18,38	1,40	25,77
		B	38,02	0,80	30,30

3.6 Phosphorous Desorption Isotherm, Equation, and Parameters

Desorption of phosphorus from soil is considered the opposite of the adsorption process. It holds greater significance than adsorption due to the potential release of immobilized phosphorus back into the soil for reuse. Additionally, there are environmental concerns associated with phosphorus released from soil [15]. In each treatment, the amount of phosphorus desorbed

from the soil was found to be less than the amount adsorbed, indicating that while some adsorbed phosphorus can desorb and re-enter the soil solution, the adsorption process is not entirely reversible [15]. As the concentration of phosphorus in the solution increased, the adsorption sites on the soil colloids gradually became saturated, reducing the binding capacity of soil for phosphorus adsorption. This phase is typically referred to as the physical adsorption stage, where

phosphorus bound through physical adsorption can be readily desorbed [17].

Based on Figure 3 (a and b) show that The highest desorption rate of P in Mount Merbabu occurs at an elevation of 2000 meters above sea level. Even though the adsorption rate of this soil also high, P will mostly be desorbed after. This is because, in Mount Merbabu, both horizons A and B have the highest levels of organic matter, with the highest concentrations of humic and fulvic acids, which can release P adsorption. It is also shown in the [26]. This research shows that soil with high organic matter has a high adsorption rate, but a desorption rate is also high.

Based on Figure 3 (c and d), it can be seen in catena of Mount Sindoro that the highest desorption rate of P

in horizon A occurs in soil at an elevation of 800 masl. It is because the clay content of this site is high. Al-Kanani and MacKenzie (1991) in [28] state that phosphorus adsorbed by clay minerals can be desorbed more easily than phosphorus adsorbed by Fe/Al hydroxides. This implies that the stability of phosphorus adsorption to clay minerals is weaker than that to Fe/Al hydroxides, making phosphorus more readily available for plant uptake. In horizon B, the highest desorption rate of P is obtained at an elevation of 1400 masl. It is because the allophane and ferrihydrite are the lowest in this site. The release rate in horizon A is higher than in horizon B due to the accumulation of organic matter capable of releasing P chelates.

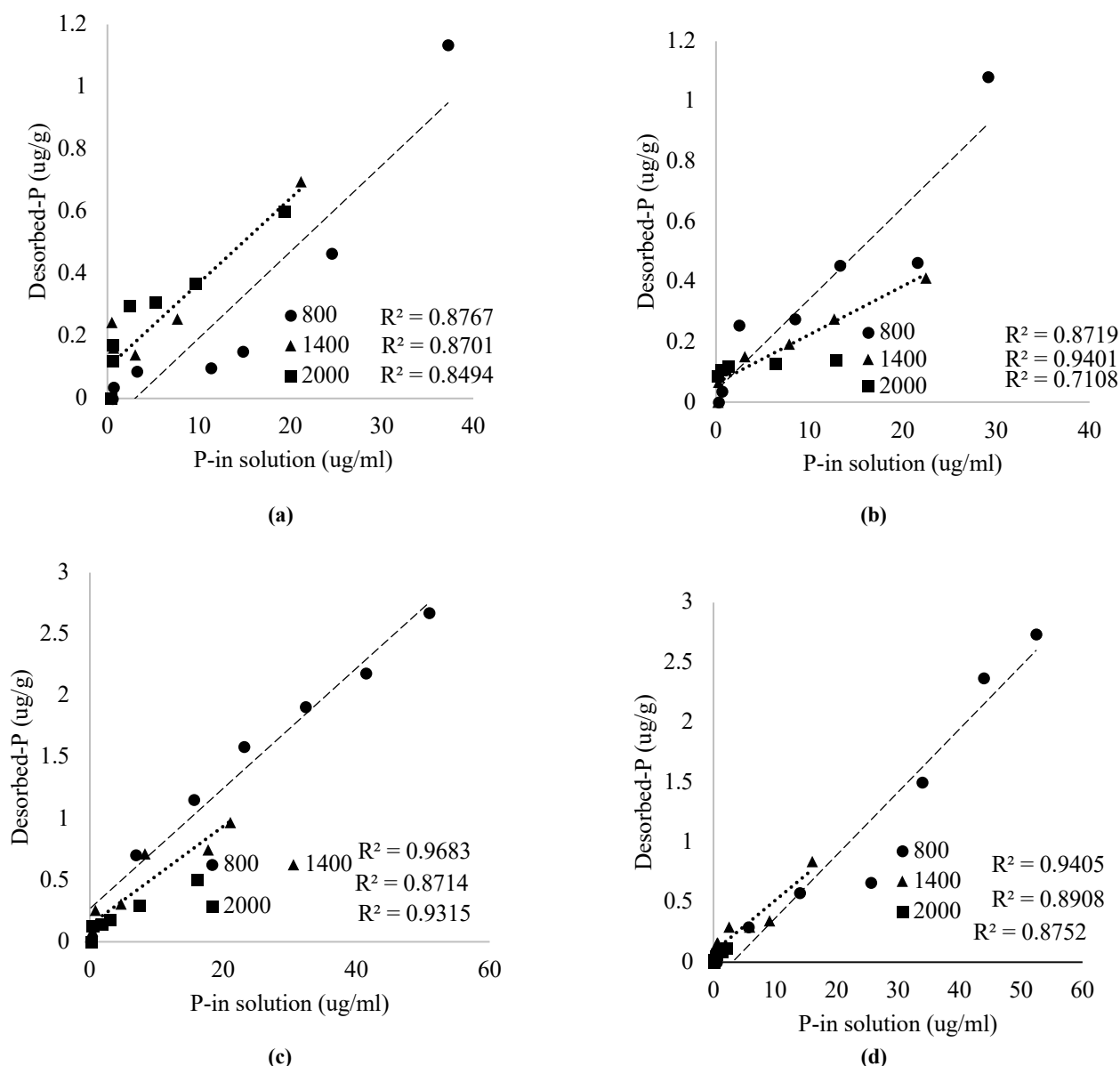


Fig 3. (a) The desorption isotherm at A horizon in Mount Merbabu (b) The desorption isotherm at B horizon in Mount Merbabu (c) The desorption isotherm at A horizon in Mount Sindoro (d) The desorption isotherm at B horizon in Mount Sindoro

The desorption rate also can quantitatively describe using Langmuir and Freundlich equation. Based on the equation, other data can be obtained, namely Dm

(maximum concentration of desorbable P) and Dr (desorption degree = Dm/Qm) [17].

Table 9. Desorption equation in research site

Mount	Elevation	Horizon	Equation Langmuir		Equation Freundlich	
			$C/D = C/D_m + 1/kD_m$	R^2	$\log D = \log K + 1/n \log C$	R^2
Merbabu	800	A	$C/D = 7,256C + 9,3269$	0,8903	$\log D = 0,769 \log C - 1,4064$	0,8763
		B	$C/D = 1,8286C + 7,8289$	0,8582	$\log D = 0,7285 \log C - 1,147$	0,8879
	1400	A	$C/D = 1,3833C + 1,3373$	0,9897	$\log D = 0,3046 \log C - 0,6294$	0,6585
		B	$C/D = 2,4334C + 8,4535$	0,8539	$\log D = 0,3741 \log C - 0,9715$	0,9617
	2000	A	$C/D = 1,6664C + 3,962$	0,8971	$\log D = 0,375 \log C - 0,7426$	0,9293
		B	$C/D = 7,1493C + 1,0237$	0,9987	$\log D = 0,0909 \log C - 0,9452$	0,8379
Sindoro	800	A	$C/D = 0,3547C + 4,5339$	0,7932	$\log D = 0,6563 \log C - 0,7072$	0,9964
		B	$C/D = 1,3821C + 4,6523$	0,9028	$\log D = 1,0023 \log C - 1,3628$	0,9002
	1400	A	$C/D = 0,9919C + 3,9179$	0,8492	$\log D = 0,5274 \log C - 0,7323$	0,8991
		B	$C/D = 2,8298C + 1,4168$	0,9833	$\log D = 0,4057 \log C - 0,7266$	0,8414
	2000	A	$C/D = 1,8942C + 5,3222$	0,8295	$\log D = 0,3369 \log C - 0,8124$	0,8445
		B	$C/D = 6,2203C + 5,086$	0,9122	$\log D = 0,5793 \log C - 1,0698$	0,9003

The maximum P desorption capacity (D_m) represents the amount of P that can be desorbed when the adsorbent is saturated with P, indicating the highest quantity of P introduced into the soil [17]. The highest D_m and D_r value in the Mount Merbabu chain is in horizon A at an elevation of 1400 masl because it has lowest amorphous mineral. While in the Mount Sindoro chain it is in horizon A at an elevation of 800 masl

because the P mostly binds with clay not Al/Fe hydroxide. It is more reversible than Al-P and Fe-P complex [28]. The efforts that can be done on land with high P adsorption and low P desorption include the addition of organic materials, humic and fulvic acids, silica fertilizers, and phosphate-solubilizing microorganisms.

Table 10. Phosphorus desorption parameters describe with adsorption equation

Mount	Elevation	Horizon	D_m (ug/mg)	D_r (%)
Merbabu	800	A	0,14	1,44
		B	0,55	4,36
	1400	A	0,72	4,49
		B	0,41	2,65
	2000	A	0,60	3,52
		B	0,14	0,72
Sindoro	800	A	2,82	66,37
		B	0,72	25,70
	1400	A	1,01	6,72
		B	0,35	1,90
	2000	A	0,53	2,87
		B	0,16	0,42

4 Conclusion

The rate, capacity, and energy of adsorption binding increase with elevation. Despite high adsorption, desorption rates at 2000 masl are also high due to the presence of organic materials, especially organic acids. However, different results were shown in the Mount Sindoro catena, where the highest desorption rates are

found in horizon A at 800 masl and horizon B at 1400 masl. This is because of low amorphous minerals and high clay content. The soil properties most strongly correlated with phosphorus availability are organic matter and organic acids, particularly fulvic acid, as well as the soil's ability to retain phosphorus due to the presence of amorphous minerals such as allophane, imogolite, and amorphous Al/Fe compounds.

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