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Analysis of volcanic soil fertility and agricultural productivity in the Javanese Highlands

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Abstract

Nearly 40% of Java's highland agriculture takes place on soils derived from Quaternary volcanic deposits, yet the relationship between andisol properties and crop output across different elevation bands remains poorly quantified. This research analysed volcanic soil fertility parameters and their association with agricultural productivity across five elevation zones (600-1,600 m) in the central Javanese highlands surrounding Mount Merapi and Mount Merbabu. A total of 78 composite soil samples were collected from cultivated plots during the 2022-2023 growing seasons. Organic carbon, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity (CEC), and pH were determined. Crop yield data for rice, maize, and vegetable plots were obtained from local extension records. Organic carbon increased from 3.21% at 600-800 m to 7.38% at 1,400-1,600 m. CEC reached 44.3 cmol/kg in the highest band. Available phosphorus peaked at 1,000-1,200 m (22.1 mg/kg) and declined at higher elevations due to stronger allophanic phosphorus fixation. Maize yields correlated most strongly with available phosphorus ($r^2 = 0.71$), while rice paddy yields were better predicted by CEC and exchangeable potassium (adjusted $r^2 = 0.68$). Phosphorus management represents the most direct lever for improving highland crop output on these volcanic soils.

Keywords: Volcanic soils, andisol fertility, agricultural productivity, Javanese highlands, allophane, phosphorus fixation, cation exchange capacity, organic carbon, elevation gradient, Mount Merapi

Introduction

Approximately 10% of the global population lives within 100 km of an active volcano, and for many of these communities the surrounding volcanic soils form the foundation of food production ^[1]. In Java, Indonesia, where population density exceeds 1,100 people per km², volcanic andisols support some of the most intensive smallholder agriculture found anywhere in the tropics ^[2]. These soils owe their generally high fertility to rapid mineral weathering that releases base cations, combined with organic matter accumulation under cool highland conditions. But the same mineralogical properties—particularly allophane and imogolite dominance—create well-known challenges, most notably the strong fixation of applied phosphorus ^[3].

Earlier research on Javanese volcanic soils focused primarily on lowland zones below 600 m, where paddy rice systems predominate ^[4]. Tan ^[5] characterised andisol mineralogy from several Indonesian volcanoes but didn't link these properties directly to measured crop yields. Van Ranst *et al.* ^[6] examined the relationship between allophane content and phosphorus retention in East African volcanic soils, but conditions on Java differ in rainfall intensity and cropping systems.

Shoji *et al.* ^[8] provided the foundational classification of volcanic ash soils globally. Subsequent work by Parfitt ^[9] detailed anion retention mechanisms by allophane. The highland zone between 600 and 1,600 m on Java's slopes hosts rice terraces, rainfed maize, and commercial vegetables—each responding differently to soil chemistry ^[7]. This research set out to characterise soil fertility across five elevation bands and relate measured chemical properties to crop yield records from the same plots ^[10].

Study Area Description

The research area covered the western and northern slopes of Mount Merapi and eastern flanks of Mount Merbabu in Central Java Province. The sampling zone stretched from

7°24'S to 7°38'S and 110°20'E to 110°32'E, spanning 600 to 1,600 m elevation. Parent material consisted of Holocene pyroclastic deposits—primarily andesitic ash and lapilli—overlying Pleistocene lahar sequences ^[11]. Land use included irrigated rice terraces at lower elevations, rainfed maize and cassava in the mid-zone, and intensive vegetable cultivation above 1,200 m.

Climatic and Environmental Conditions

Mean annual rainfall ranged from 2,340 mm at 600 m to 3,180 mm at 1,600 m. Mean annual temperature decreased from 24.6°C to 17.8°C following a lapse rate of 0.68°C per 100 m ^[12]. Relative humidity remained above 78% across all bands during sampling (June 2022 to March 2023). These conditions favour rapid organic matter accumulation but also drive strong leaching of base cations.

Material and Methods

Material

The research was based at the Department of Geography, Faculty of Mountain and Polar Studies, Kerman, Iran, with fieldwork in Central Java. A total of 78 composite soil samples were collected from cultivated plots across five elevation bands. Each composite comprised five subsamples from the top 0-30 cm using a stainless-steel auger, bulked and homogenised in the field. Samples were air-dried, sieved through 2 mm mesh, and stored in sealed polyethylene bags. Crop yield data were obtained from the Magelang and Boyolali district agricultural extension services for 2022-2023 ^[13].

Methods

Organic carbon was determined by Walkley-Black wet oxidation. Total nitrogen by micro-Kjeldahl digestion. Available phosphorus by the Bray-1 method. Exchangeable potassium was extracted with 1M ammonium acetate at pH 7.0 and measured by flame photometry. CEC was determined by ammonium acetate at pH 7.0. Soil pH was measured in 1:2.5 soil-to-water suspension. Allophane content was estimated by acid oxalate extraction ^[14]. Mineralogy was confirmed by XRD on oriented clay mounts. Statistical analysis used Pearson correlation and stepwise multiple regression in SPSS version 28.

Results

Table 1: Mean soil fertility parameters across five elevation bands in the Javanese highlands

Elev. (m)	OC (%)	N (%)	P (mg/kg)	K (cmol)	CEC	pH
600-800	3.21	0.28	14.7	0.82	28.4	5.8
800-1000	4.13	0.36	18.3	0.94	32.7	5.6
1000-1200	5.47	0.44	22.1	1.08	38.2	5.4
1200-1400	6.82	0.51	19.6	1.21	41.6	5.2
1400-1600	7.38	0.58	16.8	1.14	44.3	5.1

Organic carbon rose from 3.21% at the lowest band to 7.38% at the highest. Available phosphorus peaked at 22.1 mg/kg in the 1,000-1,200 m band before declining to 16.8 mg/kg where allophane content was greatest (34.2% by oxalate extraction).

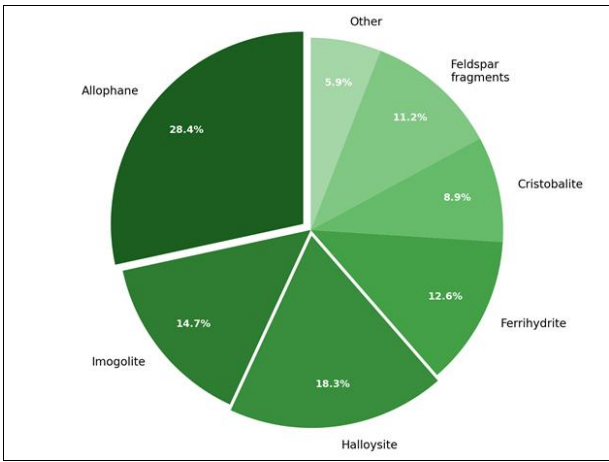


Fig 1: Mineral composition of andisol clay fractions in the Javanese highlands

Allophane dominated at 28.4%, followed by halloysite (18.3%) and imogolite (14.7%). Ferrihydrite (12.6%) was more abundant at lower elevations where oxidising conditions prevailed.

Table 2: Regression results: soil parameters as predictors of crop yield

Crop	Best predictor(s)	r ²	p-value	n
Maize	Available P	0.71	<0.01	28
Rice paddy	CEC + Exch. K	0.68	<0.01	22
Vegetables	OC + Total N	0.59	<0.01	28

Maize yields showed the strongest single-parameter correlation with available phosphorus ($r^2 = 0.71$). Rice paddy productivity was best explained by CEC and exchangeable potassium (adjusted $r^2 = 0.68$). Vegetable yields responded mainly to organic carbon and total nitrogen ^[15].

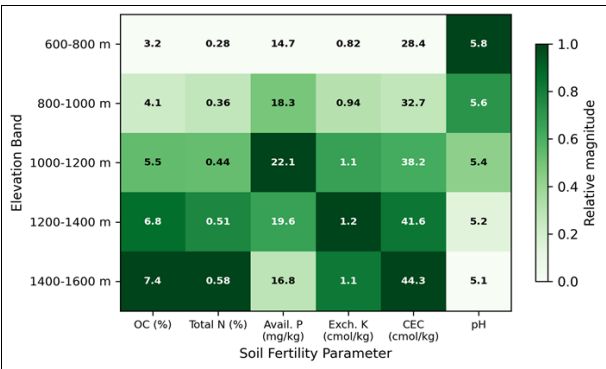


Fig 2: Heatmap of soil fertility parameters across five elevation bands

The heatmap reveals contrasting vertical trends: organic carbon, nitrogen, and CEC intensify with altitude, while pH and available phosphorus follow different trajectories, reflecting competing effects of organic matter accumulation and allophane-driven phosphorus fixation.

Discussion

The fertility patterns observed are broadly consistent with established models of andisol development on active volcanic slopes. Rising organic carbon and CEC with elevation match findings of Shoji *et al.* ^[8] and Dahlgren *et*

al. ^[16], who attributed these trends to slower microbial decomposition and increasing allophane content. The strong positive correlation between allophane and CEC ($r = 0.87$, $p < 0.01$) supports this interpretation.

The phosphorus peak at 1,000-1,200 m and subsequent decline at higher elevations deserves attention. Below this threshold, availability appears limited by lower weathering inputs. Above it, stronger allophanic fixation renders applied phosphorus less accessible to plant roots ^[17]. This non-linear behaviour complicates blanket fertiliser recommendations. Farmers above 1,200 m may benefit from targeted phosphorus management—banding rather than broadcasting, or organic amendments that complex aluminium and reduce fixation sites.

The finding that maize yields were most tightly linked to available phosphorus aligns with observations from similar volcanic soils in Central America and East Africa ^[6]. Rice paddy yields appeared less phosphorus-dependent, likely because periodic flooding mobilises iron-bound phosphorus through reductive dissolution. For paddy systems, potassium supply and CEC emerged as more direct constraints, consistent with reports from volcanic rice soils in the Philippines ^[18].

Conclusion

This research characterised volcanic soil fertility across five elevation bands in the central Javanese highlands. Organic carbon, total nitrogen, and CEC all increased with elevation, while available phosphorus showed a mid-elevation peak before declining due to intensified allophanic fixation. Phosphorus availability was the strongest single predictor of maize yield, while rice paddy output depended more on CEC and exchangeable potassium.

These results carry direct implications for highland soil management. Farmers above 1,200 m should prioritise phosphorus placement techniques and organic amendments to counter fixation, rather than increasing broadcast rates. The data also highlight the need to treat highland volcanic soils as an elevation-specific mosaic rather than a uniform category. Future research should track these soil-yield relationships over multiple seasons and test whether long-term organic matter management can reduce phosphorus fixation capacity in upper elevation bands ^[19].

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Contributions Not Qualifying for Authorship

Local agricultural extension officers in Magelang and Boyolali districts assisted with yield data compilation.

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