Properties and Management Implications of Soils Developed from Volcanic Ash in North Sulawesi

Sifat-sifat dan Implikasi Pengelolaan Tanah-tanah yang Terbentuk dari Abu Vulkan di Sulawesi Utara

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Abstract. Soils formed from volcanic ash have unique properties and are among the most productive soils for agricultural use worldwide. The purpose of this study was to characterize mineralogical, physical, and chemical properties of volcanic ash soils. Four soil profiles developed from volcanic ash in North Sulawesi were described, sampled, and analyzed for their mineralogical, physical, and chemical properties. Results revealed that sand mineral composition was dominated by opaque, volcanic glass, labradorite, augite, and hypersthene followed by hornblende and olivine, whereas clay minerals were dominated by allophane and hydrated-halloysite. The mineral composition indicated that the soils were developed from andesitic to basaltic volcanic materials. Soil morphological characteristics were dark colors, weak to moderate sub-angular blocky structure, and friable to very friable consistency. The soils showed coarse to medium texture with sand content of > 40%. The bulk density ranged from 0.79 to 1.19 g cm^{-3} and water retention at 1,500 kPa were generally low to medium (6.3-18.5%). The soil reaction in the upper horizons was acid to slightly acid and pH_{H2O} and pH_{NaF} values ranged from 4.8-6.5 and 9.1 to 12.3, respectively. The soil organic carbon content and cation exchange capacity were low to high, while base saturation was moderate to high. Two soil profiles (P1 and P3) met the criteria of andic properties and are classified as Andisols. However, the other two profiles (P4 and P2) just met the criteria for vitrandic soil properties at subgroup level of Inceptisols and Entisols. All the studied soils are highly potential for agricultural production. However, some soils exhibit low organic carbon content and high P retention. Therefore, land management should be directed for increasing organic matter content and availability of P nutrient.

Abstrak. Tanah yang terbentuk dari abu vulkan memiliki sifat-sifat khas dan merupakan salah satu tanah cukup produktif bagi pengembangan pertanian. Tujuan penelitian ini adalah untuk mengetahui sifat mineralogi, fisika, dan kimia tanah-tanah yang terbentuk dari abu vulkan. Empat profil tanah terbentuk dari abu vulkan di Sulawesi Utara telah diambil contoh tanahnya dan dianalisis sifat-sifat mineralogi, fisika, dan kimianya. Hasil penelitian menunjukkan bahwa komposisi mineral fraksi pasir didominasi oleh opak, gelas vulkanik, labradorit, augit, hiperstin, hornblende, dan olivin, sedangkan mineral liat didominasi oleh alofan dan haloisit hidrat. Komposisi mineral tersebut menunjukkan bahwa tanah-tanah yang diteliti berkembang dari bahan vulkan andesitik hingga basaltik. Karakteristik morfologi tanah dicirikan oleh warna gelap, struktur gumpal agak bersudut dengan tingkat perkembangan lemah hingga sedang, dan konsistensi gembur hingga sangat gembur. Tekstur tanah sedang hingga kasar dengan kandungan pasir > 40%. Bobot isi tanah berkisar antara 0,79-1,19 g cm^{-3} dan retensi air pada 1.500 kPa umumnya rendah hingga sedang (6,3-18,5%). Reaksi tanah pada horison atas masam hingga agak masam dengan nilai pH_{H2O} dan pH_{NaF} masing-masing berkisar antara 4,8-6,5 dan 9,1-12,3. Kandungan karbon organik dan kapasitas tukar kation rendah hingga tinggi, sedangkan kejenuhan basa sedang hingga tinggi. Dua profil tanah (P1 dan P3) memenuhi kriteria sifat tanah andik dan diklasifikasikan sebagai Andisols. Sedangkan dua profil tanah lainnya (P4 dan P2) hanya memenuhi kriteria sifat tanah vitrandik pada tingkat subgrup Inceptisols dan Entisols. Semua tanah yang diteliti berpotensi tinggi untuk produksi pertanian. Akan tetapi, beberapa tanah mengandung bahan organik rendah dan mempunyai retensi P tinggi. Oleh karena itu, pengelolaan lahan perlu diarahkan pada peningkatan kadar bahan organik dan ketersediaan hara P.

Introduction

Soils formed from volcanic ashes, especially Quaternary deposits, have unique morphological, physical, chemical and mineralogical properties which are rarely encountered in soils formed from other volcanic materials. The term of volcanic ash is commonly given to various air-borne pyroclastic materials including ash, pumice, and scoria (Shoji *et al*. 1993). Because of the uniqueness, those soils have been given despite their low geographic

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distribution, about 124 million hectares or 0.84% of the earth's land surface (Leamy 1984; Takashi and Shoji 2002). The volcanic ash soils are generally classified as Andisols, Inceptisols, Entisols, and Mollisols orders, depending on weathering stages and soil forming processes (Shoji *et al*. 1993).

The volcanic ash soils have many distinctive properties, including dark color, high organic matter, high water holding capacity, low bulk density, high porosity, high P retention, high content of amorphous materials, and high weatherable mineral reserve (Nanzyo 2002). The soils are generally found at high elevation (> 700 m asl.), despite some findings have been reported at low elevation, such as in North and West Sumatra (Tan 1998). Most volcanic ashes soils are classified into Andisols if they meet the requirements for andic or vitric properties. The andic and vitric soil properties are based on physical, chemical, and mineralogical properties, namely bulk density, P retention, Al and Fe extractable in acid ammonium oxalate, and content of volcanic glass (Soil Survey Staff 2014). The main characteristic of volcanic ash soils is the dominance of non-crystalline minerals (allophane, imogolite, ferrihydrite) and Al-Fe humus complexes. The formation of non-crystalline minerals is the result of rapid weathering of volcanic glass and other weatherable minerals, the least resistant to chemical weathering. Allophane and imogolite in soils could be chemically evaluated from Al and Si extractable in acid oxalate, and Al extractable in pyrophosphate (Parfitt and Kimble 1989).

In Indonesia, the volcanic ash soils have large geographic distribution, covering approximately 5.4 million hectares or 2.9% of the total Indonesian land surface (Subagjo *et al*. 2000). These soils are distributed widely along the islands of Sumatra, Java, Bali, Nusa Tenggara, South and North Sulawesi, and Halmahera North Maluku. Recent results of volcanic ash soil investigation had been reported, such as from Sumatra (Fiantis *et al*. 2000; Prasetyo *et al*. 2009), Java (Van Ranst *et al*. 2002; Yatno and Zauyah 2005), Flores island (Hikmatullah and Nugroho 2010), and West Halmahera (Hikmatullah 2009). Yatno and Zauyah (2005) reported that volcanic ash soils from southern part of Mt. Tangkuban Perahu, West Java were characterized by low bulk density and friable to very friable consistence. P retention, organic carbon content, and cation exchange capacity were high. Mineralogical composition was dominated by honblende and allophane in sand and clay fractions, respectively.

In North Sulawesi Province, the volcanic ash soils cover large area and most of them have been intensively used for food, highland vegetable, and annual crops (ICALRD 2010). However, investigation of the volcanic ash soils in that area is still scarce and lack of documentation. Extensive information on these soil properties is necessary for better understanding and documentation for sustainable land utilization.

The purposes of the study were to characterize morphological, physical, chemical, and mineralogical properties, and to classify the soils according to Keys to Soil Taxonomy (Soil Survey Staff 2014) and "Klasifikasi Tanah Nasional" (Subardja *et al*. 2014).

Materials and Methods

Description of the study area

The study area belongs to humid tropical climate type and B rainfall type (Schmidt and Ferguson 1951). The mean annual rainfall ranged from 1,696 mm (Bitung station) to 1,715 mm (Tondano station). The rainy season generally occurs from November to May. The mean monthly air temperature varies between 27.5^{o}C in Bitung area till 22.9^{o}C in Tondano area. The study area has a udic soil moisture regime, with an isohyperthermic (< 900 m asl.) soil temperature regimes. In general, the areas are mainly cultivated for maize, highland vegetables (carrot, cabbage, and potatoes), and coconut.

The areas are dominated by andesitic to basaltic volcanic rocks of Holocene to Pleistocene age consisting

Table 1. Location and description of the studied profiles

Tabel 1. Lokasi dan deskripsi profil tanah yang diteliti

Profiles	Location	Coordinate	Elevation	Landscape position	slope	Parent material	Landuse
			m asl		%		
P1	Bitung	01°30'08" N 125°09'30" E	600	Middle slope of Mt.Tangkoko	8	Andesitic volcanic ash	Dryland, coconut
P2	Airmadidi	01°29'15" N 125°01'30" E	500	Lower slope of Mt. Kelabat	5	Basaltic volcanic ash	Maize, coconut
P3	Kakaskasen	01°20'30" N 124°47'15" E	880	Middle slope of Mt. Lokon	30	Basaltic volcanic ash	Maize, vegetables
P4	Raringis	01°09'20" N 124°47'00" E	800	Lower slope of Mt. Soputan	5	Basaltic volcanic ash	Maize

of lava, lapilli, and ash. The soils were formed on several active strato volcanoes, such as Soputan, Lokon, Klabat, and Tangkoko mountains (Effendi and Bawono 1997). Relieves of the studied areas are undulating to hilly with slope gradient of 5 to 30%.

Methods

Four soil profiles were selected from different volcanoes at different elevations. The morphological properties of profiles were described in the field following the Soil Survey Manual (Soil Survey Division Staff 1993). Twenty two soil samples were taken from each horizon of these profiles for laboratory analysis. The location and description of the studied profiles are presented in Table 1.

Laboratory analysis consisted of soil physical, chemical, and mineralogical properties. Particle size distribution was determined using the pipette method. Bulk density was measured by gravimetric method. Water retention at 33 kPa and 1,500 kPa was determined by using the pressure membrane method on air-dried samples. The pH was measured with a glass electrode in water using a soil: solution ratio of 1:2.5 and in 1M NaF using a soil: solution ratio of 1:50. Organic carbon was determined by the Walkley-Black wet combustion method. Exchangeable bases were extracted with 1M NH_4OAc at pH 7.0 and determined by atomic absorption spectrometry (AAS). Cation exchange capacity (CEC) was determined by saturation with 1 M NH_4OAc at pH 7.0. Exchangeable acidity was determined using the KCl extraction method. Phosphate retention was determined by the method of Soluble Al, Fe and Si were extracted by acid ammonium oxalate solution (Al_o, Fe_o, Si_o), soluble Al and Fe were also extracted by sodium pyrophosphate solution (Al_p, Fe_p) (Blakemore *et al.* 1987). Soluble Al and Fe were extracted by dithionite-citrate bicarbonate (Al_d, Fe_d) (Mehra and Jackson 1960). The allophane content (%) was estimated from the Si_o content (Parfitt and Wilson 1985) and the ferrihydrite content (%) was estimated from the Fe_o content (Child *et al.* 1991). The procedures of soil analysis are described in Soil Survey Laboratory Methods Manual (Burt 2004).

Mineralogical composition of total sand fraction was identified on a glass slide using a petrographic microscope, and the minerals were then counted according to the line counting method (Buurman 1990). Clay mineralogy was determined by X-ray diffraction analysis using the oriented clay specimens (< 2 um) after the treatments with Mg^{2+} saturated, Mg^{2+} saturated and glycerol solvated, K^+ saturated, and K^+ saturated heated at 550 ^oC. Soil classification was determined according to *Keys to Soil Taxonomy* (Soil Survey Staff 2014) at a subgroup level, and "Klasifikasi Tanah Nasional" (Subardja *et al*. 2014).

Result and Discussion

Morphological properties

All the profiles show dark color of A horizons and deep soils (> 100 cm) with stratification of distinct ash deposits. The thickness of A horizons ranged from 16 to 65 cm and those of B horizons are generally > 50 cm (Table 2). The hue colors were generally 7.5 YR to 10 YR and the value colors ranged from 2 to 3. The chroma colors ranged from 1 to 3 in the A horizons and from 2.5 to 4 in the B horizons. The color of A horizons is darker than that of B horizons, which may be due to higher organic matter content in A horizons. All profiles have good drainage and friable to very friable moist consistency that support easiness for soil tillage. Most of the soil horizons exhibit varying degrees of smeariness which reflects the presence of volcanic amorphous materials.

These soils have a weak to moderate and subangular blocky to granular structure, and these different stages of structure development may be due to the difference in nature parent materials (ashfall) and the chronology of the materials deposited during volcanic eruption. All the profiles show buried horizons which are characterized by distinct ash deposits. The clear smooth horizon boundaries, textural stratification and buried sequences mostly reflect the intermittent accumulation of volcanic ash. These unique properties are commonly found in volcanic ash soils (Shoji *et al.* 1993).

Mineralogical properties

The total sand minerals of the studied profiles (Table 3) show lithologic discontinuity which is marked by contrasting different mineral percentage within depth. This indicated different chronology of volcanic materials deposits during eruption. The sand minerals are dominated by opaque, volcanic glasses, and weatherable minerals. The volcanic glass content ranges from 9 to 70% and weatherable minerals are composed of labradorite (2-23%), augite (1-13%), hypersthene (1-26%), hornblende (1-2%), and olivine (1-2%). Olivine are only found in profiles P2, P3, and P4. Rock fragments are generally low (< 17%), except in profile P3 in which it is dominant (30-42%), and weathered minerals are generally found in most profiles (1-11%).

The association of these minerals indicates that the volcanic materials belong to andesitic properties for profile P1 and basaltic properties for profiles P2, P3, and P4. The total percentage of weatherable mineral reserve is classified as high to very high, ranging from 47 to 83%. Hence, the soil nutrient reserves would be supplied from the weathered minerals for long terms. The percentage of resistant minerals (opaque, quartz) is generally low, except for profile P4 which has relatively higher weathering. stage.

Table 2. Morphological properties of the studied profiles

Tabel 2. Sifat morfologi dari profil tanah yang diteliti

Profile	Horizon	Depth	Matrix color	Structure[1]	Consistence	Smeariness[2]
		cm				
P1	Ap	0-16	7.5YR3/2	1.f.sb	friable	ns
	Bw	16-37	10YR3/2	1.f.sb	friable	ns
	C	37-56	10YR3/2	f.sg	friable	ns
	2Ab	56-70	10YR2/1	f.sg	friable	ns
	2Bwb	70-125	10YR3/3	1.f.sb	friable	ns
P2	Ap	0-22	7.5YR2.5/2	1.f.g	very friable	ns
	2A1	22-48	7.5YR2.5/1	0.f.sg	very friable	ns
	2A2	48-65	7.5YR2.5/1	0.f.sg	very friable	ns
	2Bw1	65-95	7.5YR4/4	1.f.g	friable	ms
	2Bw2	95-135	7.5YR3/6	1.f.g	friable	ms
P3	Ap	0-21	10YR2/2	1.f.sb	friable	ns
	Bw	21-47	7.5YR3/2	1.f.sb	friable	vs
	2Bw1	47-84	7.5YR3/2	1.m.sb	friable	vs
	2Bw2	84-155	7.5YR3/4	1.m.sb	friable	vs
	2Bw3	155-180	7.5YR4/4	1.m.sb	friable	vs
P4	Ap	0-22	7.5YR2.5/1	1.f.sb	friable	ns
	AB	22-50	7.5YR2.5/1	1.f.sb	friable	ms
	Bw	50-82	7.5YR2.5/3	2.m.sb	friable	ns
	2Bw1	82-100	7.5YR3/4	2.m.sb	friable	ms
	2Bw2	100-125	7.5YR3/3	2.m.sb	friable	ms
	2Bw3	125-160	7.5YR4/4	2.m.sb	friable	ns
	3BC	160-180	2.5Y5/3	1.m.sb	friable	ns

1) Structure: *Grade* 0 = structureless; 1 = weak; 2 = moderate; 3 = strong; *Size* f = fine; m = medium; *Shape* sb = subangular blocky; g = granular; sg = single grain

2) Smeariness: ns = not smeary; ms = moderate smeary; vs = very smeary

Table 3. Mineral composition of sand fraction of the studied profiles

Tabel 3. Komposisi mineral fraksi pasir dari profil tanah yang diteliti

Profile	Horizon	Op	Qz	Fe	Lm	Wm	Rf	Vg	An	Lb	Bi	Ar	Hb	Au	Hp	Ol	En
		……………………………………………………. % ……………………………………………………..															
P1	Ap	14	-	-	-	1	2	62	-	17	1	-	-	1	2	-	-
	Bw	16	-	-	-	-	1	68	-	13	-	-	-	1	1	-	-
	C	17	-	-	-	-	2	66	-	12	1	-	-	1	1	-	-
	2Ab	16	-	-	-	-	1	70	-	10	1	-	-	1	1	-	-
	2Bwb	11	-	-	-	-	2	63	1	16	-	-	-	3	4	-	-
P2	Ap	14	-	-	-	-	5	25	2	22	3	1	1	13	7	1	6
	2A1	8	-	-	-	-	8	57	-	16	2	1	1	3	3	-	1
	2A2	9	-	-	-	-	17	39	-	21	3	2	-	3	3	1	2
	2Bw1	19	-	-	-	-	3	16	1	25	4	1	2	10	11	2	6
	2Bw2	15	-	-	-	-	3	20	1	21	6	4	2	12	11	1	4
P3	Ap	10	-	3	-	2	41	27	9	2	-	-	-	4	2	-	-
	Bw	11	-	2	-	1	42	28	6	3	-	1	-	3	2	1	-
	2Bw1	12	-	2	-	1	30	37	8	2	-	-	-	4	3	1	-
	2Bw2	10	-	3	-	1	32	39	6	2	-	-	-	3	4	-	-
P4	Ap	14	-	-	2	3	14	34	1	14	2	-	1	4	9	2	-
	AB	43	3	-	-	3	4	9	2	9	1	1	-	4	19	2	-
	Bw	35	10	-	-	5	2	17	7	6	1	-	-	4	13	-	-
	2Bw1	33	3	-	-	11	1	15	7	9	-	1	1	6	13	-	-
	2Bw2	46	9	-	-	4	-	16	5	11	-	-	-	2	7	-	-
	2Bw3	12	8	-	-	4	2	26	16	23	-	-	-	1	8	-	-
	3BC	20	3	-	-	1	2	23	5	12	-	-	-	8	26	-	-

Note: Op = opaque, Qz = quartz, Fe = iron concretion, Lm = limonite, Wm = weathered minerals, Rf = rock fragment, Vg = volcanic glass, An = andesine, Lb = labradorite, Bi = bitownite, Ar = anortit, Hb = hornblende, Au = augite, Hp = hiperstene, Ol = olivine, En = enstatite

Mineral composition of clay fraction of the studied profiles showed that the soils were dominated by non-crystalline minerals (allophane), especially in profiles P1 and P3, with trace amounts of labradorite (Table 4, Figure 1). The other profiles (P2 and P4) were dominated by hydrated-halloysite, followed by minor or trace amounts of quartz and feldspar. This means that all the studied profiles are young soils which have low degree of weathering stage. However, the dominance of hydrated-halloysite in profiles P2 and P4 indicates that those soils are relatively more weathered than profiles P1 and P3. This is indicated by Fe_o/Fe_d ratio of profiles P2 and P4 which is higher than that of profiles P1 and P3 (Table 7).

Profile P1 showed convex shape of the diffractogram (Figure 1), indicating the dominance of amorphous minerals (allophane), while profile P4 was dominated by hydrated-halloysite. This is indicated by small XRD peaks (10.26 Å and 4.47 Å) by Mg^{2+} treatment. These peaks changed after treatment of Mg^{2+} plus glycerol salvation, and further the peaks collapsed after treatments of K^+ and K^+ plus heating at 550°C. The other minerals were labradorite, quartz, and feldspar in minor to trace amounts.

Soil physical properties

The soil texture class varied from loamy sand, sandy loam, to loam. The sand contents of profiles P1 and P2 were higher than those of profiles P3 and P4, but the silt contents of profiles P1 and P2 were lower than those of profile P3 and P4. The sand and silt contents of profile P1 and P2 ranged from 46 to 93% and 4 to 37%, respectively, while the sand and silt contents of profile P3 and P4 ranged from 41 to 62% and 28 to 44%, respectively. In general, all of the studied profiles have high sand content (> 40%) (Table 5). The higher sand content may indicate a low rate of weathering.

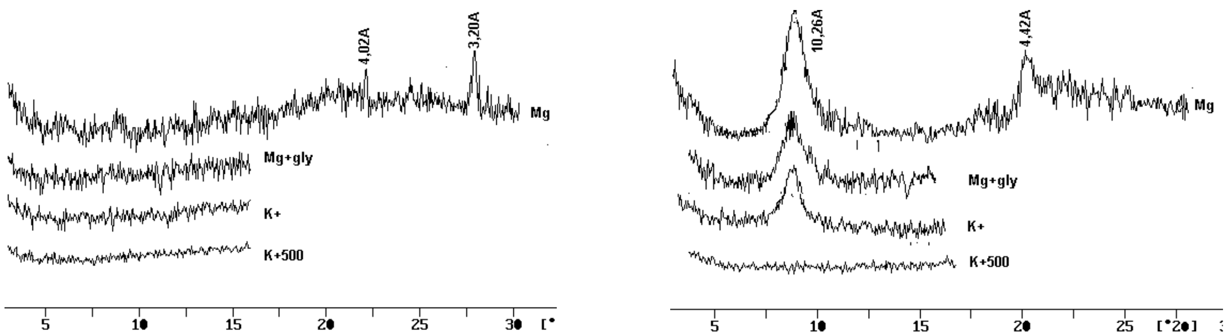
The soil bulk density (BD) ranged from 0.79 to 1.19 g cm^{-3}. Profile P1, P2, and P3 have lower BD than profile P4. According to Shoji *et al.* (1993) the low BD is a typical for volcanic ash soils at the weathering stage where a porous soil structure has developed, which is strongly influenced by non-crystalline materials and high organic matter concentration. The high BD of profile P4 was due to the presence of low organic matter content (Table 6).

Table 4. Composition of clay minerals of the studied profiles

Tabel 4. Komposisi mineral liat dari profil tanah yang diteliti

Profile	Horizon	Allophane	Hydrated- halloysite	Labradorite	Quartz	Feldspar
P1	Ap	++++		(+)		
	C	++++		(+)		
P2	Ap		++++			+
	2A2		++		(+)	+
P3	Ap	+++				
	Bw	+++				
P4	Ap		++++			
	Bw		++++			

Note: ++++ = predominant; +++ = dominant; ++ = fair; + = minor; (+) = trace.



Profile P1 (37-56 cm)

Profile P4 (50-82 cm)

Figure 1. X-ray diffractogram of lower horizons of the studied profiles with Mg^{2+}, Mg^{2+} + glycerol, K^+, and K^+ + heating 500°C treatments

Gambar 1. Difraktogram sinar X dari horison bawah profil tanah yang diteliti dengan perlakuan Mg^{2+}, Mg^{2+} + gliserol, K^+, dan K^+ + pemanasan 500°C

Water retention at field capacity (33 kPa) ranged from 23.1 to 39.2% in upper horizons, and 27.8 to 35.4% in lower horizons. The water retention at wilting coefficient (1,500 kPa) is low to moderate which ranged from 7.1 to 18.5% in A horizon, and from 6.3 to 17.5% in B horizon. Some horizons of studied profiles have low water retention at field capacity (23-28%) and wilting coefficient (6-7%) as they have very high content of the sand fraction (Table 5). For soils with greater contents of sand (coarser texture), the amount of water held at field capacity and wilting coefficient tends to be lower (Brady and Weil 2000).

Chemical properties

The organic carbon contents in the upper horizons of P1 and P3 profiles were high (> 3.0%) except in P2 and P4 profiles were low (< 2.0%) (Table 6). The amounts of organic carbon tend to decrease with depth within the same sequum. Buried horizons were found with increasing organic carbon, and this pattern reflects the intermittent nature of volcanic ashfalls and rejuvenation of humus. The higher organic carbon contents of the allophanic profiles (P1 and P3) were presumably the result of interaction of amorphous minerals by forming Al-humus complexes (Nanzyo *et al*. 1993), thus they can accumulate more organic carbon than the halloisitic profiles (P2 and P4).

The soil pH_{H2O} values ranged from 4.8 to 6.7 and showed no distinct trend with depth and elevation. The higher pH values were generally found in profiles P1 and P4. The higher pH_{H2O} values of the soils may be attributed to relatively higher exchangeable cations, especially Ca^{2+} and Mg^{2+}. The pH values in KCl of all the studied soils are about one unit lower than those of pH_{H2O}, indicating that these soils have a net positive charge.

The values of pH_{NaF} in most of the profiles were between 9.1 and 12.3, which suggest that amorphous materials were dominant in the soil exchange complexes. The pH_{NaF} gave high positive correlation with content of allophane, with coefficient of determination R^2 = 0.59 (Figure 2d). It should be noted that pH_{NaF} is not a determinant for the presence of non-crystalline minerals in the clay fraction of volcanic soils, but rather is an indicator since the anion exchange is not selective for non-crystalline materials alone (Drouza *et al*. 2007).

The exchangeable cations of the soils were dominated by Ca^{2+} and Mg^{2+}, in the order of abundance of Ca^{2+} > Mg^{2+} > K^+ or Na^+ (Table 6). Profile P4 has higher values of exchangeable cations than the other profiles. The values of base saturation were generally high (> 35%) in all horizons, with an exception of the upper horizons of profile P3. This indicated a stage of early weathering and

Table 5. Physical properties of the studied profiles
Tabel 5. Sifat fisika dari profil tanah yang diteliti

Profile	Horizon	Depth	Texture				Bulk density	Water retention	
			Sand	Silt	Clay	Class		33 kPa	1,500kPa
		cm	………… % …………				g cm^{-3}	…………. % ………….	
P1	Ap	0-16	71	18	11	Sandy loam	0.92	31.8	14.5
	Bw	16-37	74	13	13	Sandy loam	-	-	-
	C	37-56	82	12	6	Loamy sand	1.13	28.5	10.6
	2Ab	56-70	86	9	5	Loamy sand			
	2Bwb	70-125	69	22	9	Sandy loam			
P2	Ap	0-22	69	13	18	Sandy loam	0.86	31.0	11.7
	2A1	22-48	93	4	3	Sand	-	-	-
	2A2	48-65	92	5	3	Sand	1.06	27.8	6.3
	2Bw1	65-95	50	34	16	Sandy loam			
	2Bw2	95-135	46	37	17	Loam			
P3	Ap	0-21	42	45	13	Loam	0.89	39.2	18.5
	Bw	21-47	41	44	15	Loam	-	-	-
	2Bw1	47-84	60	30	10	Sandy loam	0.79	35.4	16.0
	2Bw2	84-155	62	31	7	Sandy loam			
	2Bw3	155-180	54	36	10	Sandy loam			
P4	Ap	0-22	84	8	8	Loamy sand	1.19	23.1	7.1
	AB	22-50	47	28	25	Sandy clay loam	-	-	-
	Bw	50-82	42	32	26	Loam	0.98	34.7	17.5
	2Bw1	82-100	41	31	28	Loam			
	2Bw2	100-125	54	31	15	Sandy loam			
	2Bw3	125-160	59	28	13	Sandy loam			
	3BC	160-180	87	7	6	Loamy sand			

Table 6. Chemical properties of the studied profiles

Tabel 6. Sifat kimia dari profil tanah yang diteliti

Profile	Horizon	Depth	pH			Org. C	Exch. cations (NH_4OAc pH 7)				Soil CEC	Extr Al^{3+}	Base sat.	P retention
			H_2O	KCl	NaF		Ca^{2+}	Mg^{2+}	K^+	Na^+				
		cm				%	…………………. cmol$_c$ kg^{-1} ………………….						……… % ………	
P1	Ap	0-16	6.5	5.0	10.3	3.49	8.67	1.51	0.33	0.20	14	0.00	78	91
	Bw	16-37	6.3	5.0	10.4	1.09	3.61	0.82	0.07	0.18	6	0.00	74	25
	C	37-56	6.5	5.0	10.2	0.62	2.46	0.60	0.07	0.14	4	0.00	87	18
	2Ab	56-70	6.7	5.1	9.9	0.20	1.08	0.23	0.03	0.05	2	0.00	71	9
	2Bwb	70-125	6.7	5.2	10.3	1.29	5.48	1.08	0.13	0.16	8	0.00	90	1
P2	Ap	0-22	5.4	5.2	9.5	1.95	7.75	1.97	1.10	0.17	20	0.01	56	22
	2A1	22-48	5.2	4.9	9.1	1.29	1.28	0.14	0.09	0.11	3	0.82	47	3
	2A2	48-65	5.2	4.9	9.2	1.14	1.57	0.16	0.11	0.08	4	0.60	49	5
	2Bw1	70-95	5.3	5.1	10.3	1.28	9.64	1.54	0.48	0.08	27	0.01	43	55
	2Bw2	95-135	5.3	5.0	9.9	0.96	11.27	1.93	0.65	0.07	29	0.01	49	36
P3	Ap	0-21	4.8	4.7	12.3	3.70	2.42	0.34	0.10	0.14	20	0.24	15	94
	Bw	21-47	5.1	4.8	12.3	5.57	5.03	0.55	0.11	0.20	31	0.28	19	97
	2Bw1	47-84	5.5	4.9	12.2	3.24	4.83	0.62	0.08	0.14	18	0.09	31	90
	2Bw2	84-155	5.6	5.0	12.2	2.97	5.08	0.71	0.06	0.11	18	0.14	33	
	2Bw3	155-180	5.5	5.1	12.2	3.06	5.76	0.72	0.10	0.16	25	0.00	27	
P4	Ap	0-22	5.4	4.7	9.1	1.48	6.35	0.90	0.89	0.66	15	0.01	59	2
	AB	22-50	5.7	5.0	9.3	0.99	12.34	2.43	3.89	0.59	28	0.00	68	12
	Bw	50-82	5.7	4.7	9.4	0.55	14.32	3.24	1.94	0.64	31	0.00	66	15
	2Bw1	82-100	5.8	4.8	9.5	0.37	18.92	5.42	2.21	0.69	38	0.00	71	16
	2Bw2	100-125	5.8	5.0	9.3	0.27	8.83	2.33	1.82	0.45	19	0.00	70	12
	2Bw3	125-160	5.9	5.0	9.4	0.23	7.12	1.94	1.40	0.61	19	0.00	59	14
	3BC	160-180	5.8	5.0	9.1	0.09	2.97	0.71	0.32	0.26	7	0.00	63	2

lower leaching of bases that might cause higher pH values. KCl-extractable Al contents in all profiles were very low, and this is in agreement with rather high pH values.

The values of soil cation exchange capacity (CEC) showed a wide variation ranging from 4 to 38 cmol$_c$ kg^{-1}. The higher values of CEC were found in profiles P3 and P4, whereas the lower values were found in profiles P1 and P2. The high CEC values were related Al and Fe extracted by sodium pyrophosphate (Al_p and Fe_p). The values of CEC tend to be increased with increasing Al_p and Fe_p values (Table 6 and 7).

P retention values of the studied soils varied. The A horizon of profile P1 and all horizons of profile P3 had a higher P retention (90-97%) than the other profiles (P2 and P4) (Table 6). The high values of P retention were positively correlated to the presence of amorphous materials such as allophane (Figure 2c), the high amount of Al_o (Figure 2a), and Si_o values (Figure 2b).

Selective dissolution analysis

The values for Fe_o, Al_o, and Si_o of the studied profiles are generally low and varying widely from 0.25 to 2.81%, 0.32 to 4.31%, and 0.03 to 2.67%, respectively (Table 7). The higher values of Al_o and Si_o in the profiles P1 and P3 are highlighting the higher content of allophane. The values of Al_o, Si_o, and allophane contents have positive correlation with P retention (R^2 = 0.63, 0.61, and 0.64; Figure 2a, 2b, and 2c). This means that the higher content of allophane may contribute to the higher phosphate retention in the soils.

The values for Fe_p and Al_p are low, ranging from 0.02 to 0.74% and from 0.04 to 2.08%, respectively. The values in upper horizons of the soils are higher than the lower horizons, which may be related to the organic matter contents. The low values of Fe_p and Al_p are due to the low organic matter content of the soils as well as low solubility of Al and Fe at pH greater than 5.5, resulting in the low Al and Fe-humus complexes. The values of Fe_d and Al_d are also low, indicating higher amounts of Fe- and Al-humus complexes and non-crystalline oxides.

The Al_p/Al_o ratio is used to indicate the degree of weathering of the soils (Mizota and Van Reeuwijk 1989). In profile P4, the ratio was generally > 0.50 showing that Al-humus complexes were dominant over allophane. The lower the ratio, the less weathered the soils are and indicating the presence of allophane.

The ratio of Fe_o/Fe_d has widely used to indicate the degree or index of crystallinity of iron oxides and has been found to reflect the degree of soil development in volcanic soils (Malucelli *et al.* 1999; Mizota and Van Reewijk

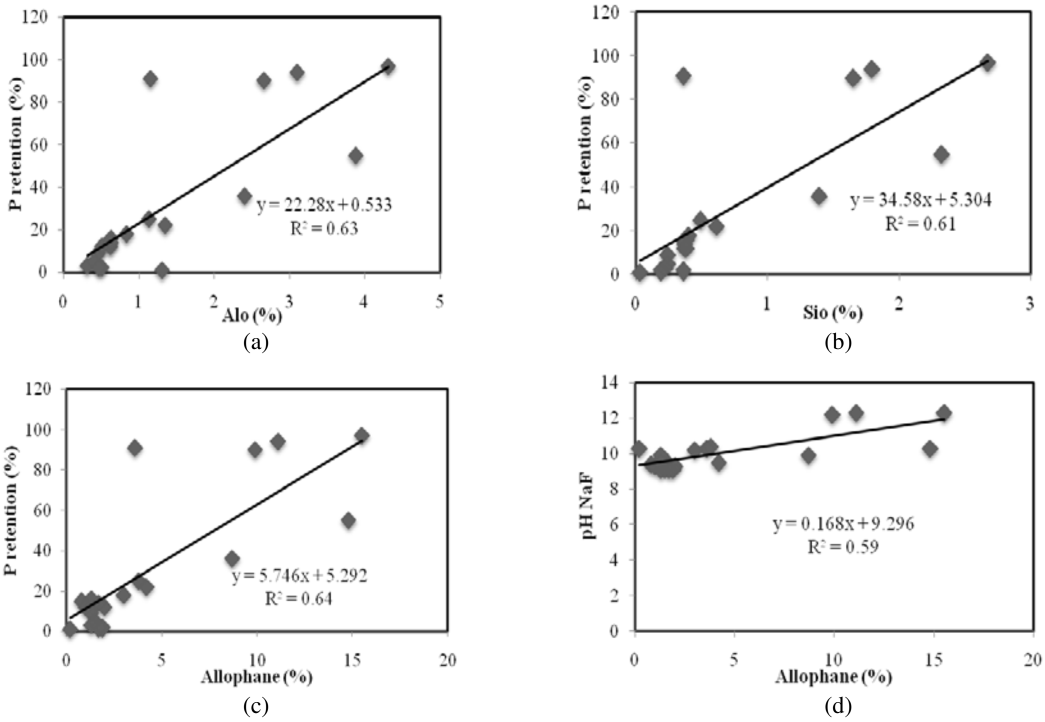


Figure 2. Correlation between various soil properties : (a) Relationship between Al_o vs P-retention, (b) Si_o vs P-retention, (c) Allophane vs P-retention, (d) Allophane vs pH-NaF of the volcanic ash soils from North Sulawesi

Gambar 2. Korelasi antara beberapa sifat-sifat tanah : (a) Hubungan antara Al_o vs retensi P, (b) Si_o vs Retensi P, (c) Allophane vs Retensi P, (d) Allophane vs pH-NaF tanah abu vulkan dari Sulawesi Utara

1989). For young volcanic ash soils like Andisols, the Fe_o/Fe_d ratio is > 0.75, whereas it is < 0.75 in the soils with advanced development. The decrease of the Fe_o/Fe_d ratio indicates the increasing level of weathering. In this study, all the profiles have Fe_o/Fe_d ratio of > 0.75 indicating that iron oxides of the soils have poorly crystalline as reflected by clay mineral composition.

Soil classification

Profile P3 met the first group criteria for andic properties as it has low bulk density (≤ 0.90 g cm^{-3}) (Table 5), high P retention (≥ 85%) (Table 6), and high values of $Al_o+0.5Fe_o$ (≥ 2.0%) (Table 7). Profile P1 fulfilled the second group criteria for andic properties because it has the fine-earth fraction (0.02- 2.0 mm in size) of ≥ 30%, P retention of ≥ 25%, the ($Al_o+0.5Fe_o$) value of ≥ 0.4%, volcanic glass content of ≥ 5%, and index value of [($Al_o+0.5Fe_o$) x 15.625] + [% volcanic glass] of ≥ 36.25. Hence, these two profiles (P1 and P3) could be classified as Andisols.

The other two profiles (P2 and P4) do not satisfy the requirements for the first or second group criteria of andic properties. However, they meet the criteria for vitrandic properties at subgroup level for Inceptisols (profile P4) and Entisols (profile P2). Vitrandic subgroup should meet the following criteria: (a) fine earth fraction contains ≥ 30% of fine-earth fraction (0.02-2 mm in size), (b) volcanic glass content in the fraction is ≥ 5%, and (c) the index value of [(($Al_o+0.5Fe_o$) x 60) + (%volcanic glass)] is ≥ 30.

At subgroup level, profile P1 is classified as Typic Udivitrands or *Andosol Vitrik*, since the water retention at 1,500 kPa < 15% on air-dried samples with udic moisture regime, and assume < 30% on undried samples. While the profile P3 is classified as Typic Hapludands or *Andosol Distrik*. They have no specific properties for subgroup differentiation other than udic moisture regimes. Profile P4 is classified as Vitrandic Eutrudepts or *Kambisol Eutrik*, because it has low water retention (< 15%) at 1,500 kPa, weak to moderate structure development with cambic horizon and high base saturation (> 60%), while profile P2 is classified as Vitrandic Udipsamments or *Regosol Eutrik*, since this profile has weak structure development, coarse texture and low water retention (< 15%) at 1,500 kPa.

Soil management implication for agricultural use

The volcanic ash soils in North Sulawesi have good physical, chemical, and mineralogical characteristics. This is reflected by deep solum and friable to very friable consistency that are favorable for soil tillage and root

Table 7. Selective dissolution analysis of the studied profiles

Tabel 7. Analisis pelarutan selektif dari profil tanah yang diteliti

Profile	Horizon	Dithionite		Oxalate			Pyrophosphate		allophane[1)]	ferrihydrite[2)]	Al_p/Al_o	Fe_o/Fe_d	Fe_p/Fe_o
		Fe_d	Al_d	Fe_o	Al_o	Si_o	Fe_p	Al_p					
		………………	………………	………………	………………	………………	%	………………	………………	………………			
P1	Ap	1.44	0.43	2.09	1.15	0.36	0.16	0.21	3.6	3.6	0.18	1.46	0.08
	Bw	1.12	0.29	2.04	1.13	0.49	0.09	0.11	3.8	3.5	0.10	1.81	0.04
	C	0.57	0.19	1.29	0.84	0.40	0.05	0.05	3.0	2.2	0.06	2.25	0.04
	2Ab	2.79	0.11	0.61	0.46	0.24	0.18	0.22	1.3	1.0	0.48	0.22	0.29
	2Bw	5.26	0.45	2.81	1.31	0.03	0.38	0.69	0.2	4.8	0.53	0.53	0.13
P2	Ap	0.18	0.26	2.23	1.35	0.61	0.22	0.29	4.2	3.8	0.22	12.22	0.10
	2A1	0.03	0.05	0.85	0.32	0.22	0.05	0.04	1.3	1.4	0.13	24.40	0.06
	2A2	0.04	0.07	1.34	0.41	0.24	0.05	0.06	1.5	2.3	0.14	33.83	0.04
	3Bw1	0.15	0.39	2.20	3.88	2.32	0.12	0.35	14.8	3.7	0.09	14.40	0.05
	3Bw2	0.22	0.28	2.24	2.40	1.39	0.21	0.38	8.7	3.8	0.16	10.25	0.09
P3	Ap	nd	nd	1.10	3.10	1.79	0.35	0.57	11.1	1.9	0.18	nd	0.32
	Bw	nd	nd	1.18	4.31	2.67	0.58	1.06	15.5	2.0	0.25	nd	0.49
	2Bw1	nd	nd	1.05	2.66	1.65	0.31	0.47	9.9	1.8	0.18	nd	0.30
P4	Ap	0.08	0.06	1.67	0.51	0.36	0.64	0.17	1.9	2.8	0.33	19.83	0.38
	AB	0.18	0.06	2.22	0.51	0.38	0.17	0.18	2.0	3.8	0.36	12.36	0.08
	Bw	0.16	0.06	2.12	0.61	0.37	0.74	2.08	0.8	3.6	3.44	13.21	0.35
	2Bw1	0.12	0.06	2.17	0.63	0.38	0.51	1.09	1.3	3.7	1.72	18.54	0.24
	2Bw2	0.16	0.08	1.49	0.62	0.37	0.58	1.54	1.0	2.5	2.50	9.56	0.39
	2Bw3	0.13	0.11	1.06	0.63	0.37	0.27	0.52	1.7	1.8	0.83	8.01	0.25
	3BC	0.02	0.03	0.25	0.47	0.19	0.02	0.02	1.7	0.4	0.05	12.51	0.08

[1)] According to Parfitt and Wilson (1985)

[2)] According to Child *et al.*(1991); Dahlgren *et al.* (1997)

nd = not determined; Al_o, Fe_o, Si_o = Al, Fe and Si extracted by acid ammonium oxalate; Al_p, Fe_p = Al and Fe extracted by sodium pyrophosphate; Al_d, Fe_d = Al and Fe extracted by dithionite-citrate bicarbonate

growth. The relatively high organic matter contents in the upper horizons, medium acid soil reaction, and high exchangeable cations are beneficial to nutrient availability for crops. In addition, the high reserves of weatherable minerals warrant long term nutrient supply.

Most of the soils are intensively cultivated for highland vegetable crops, annual and perennial crops. One of the main environmental problems is slope steepness that contributes to erosion and slumping hazards, especially for annual and vegetables crops. To solve the problem, implementation of proper soil conservation is suggested. The management practices include contour planting and a contour hedgerow system. Some soils (P1 and P3 profiles) have a high P retention limiting P availability for crops, while the other soils (P2 and P4 profiles) exibit low to medium P retention. Hence, P fertilizers should be applied based on the availability of P and the values of P retention.

All profiles have high sand contents. The high sand contents may cause low capacity of soils to hold water. Soils dominated by sand are prone to drought. Therefore, it is important to maintain organic matter status by incorporating organic matters originated from green manure, farmyards, and other sources.

Conclusions

The volcanic ash soils in the study area show a wide variation of properties and were at the first stage of soil development as indicated by formation of non-crystalline minerals (allophane) and hydrated-halloysite. Two profiles met the criteria for andic soil properties and were classified as Andisols, while the other two profiles meet the criteria for vitrandic soil properties at subgroup level of Inceptisols and Entisols.

These soils are characterized by deep solum, coarse to medium texture, acid to slightly acid reaction, and low to high organic carbon and CEC. They are developed from andesitic to basaltic volcanic materials, dominated by volcanic glass and weatherable minerals (labradorite, augite, hypersthene, horblende, and olivine) with high nutrient reserves for long term soil fertility maintenance. However, intensive agriculture on these soils will still require fertilization.

The volcanic ash soils are highly potential for agricultural production, especially for food and vegetable crops. Land management should be directed to maintaining of organic matter content and availability of P. Proper soil conservation technique should be applied to minimize erosion and slumping hazards.

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