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Properties of soils on fluvio-marin landform and their land management strategy for paddy field in Bataguh swampy area, Kapuas Regency, Central Kalimantan Province, Indonesia

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Abstract. Tidal swamp land has strategic and prospective value in sustaining national food resiliency and reserves. This land has the potential for the development of commodity paddy fields. However, this type of tidal swamp has a unique character and influences land management. This research aims to determine soil properties on landform fluvio-marine and its potential for developing lowland rice in Bataguh District, Kapuas Regency, Central Kalimantan. A total of 4 representative soil profiles were identified and characterized in the field and laboratory. Research results show that the lands under study have fine texture. Soils in the surface layer are classified as very acidic to acidic (soil pH 3.3-4.7), has very high organic C levels (5.46-9.37%), potential P moderate (21-40 $mg.100g^{-1}$), K potential low until moderate (16-21 $mg.100g^{-1}$), exchangeable Ca low (2.24-3.17 $cmol_c kg^{-1}$), exchangeable Mg medium (5.11-8.30 $cmol_c kg^{-1}$), soil CEC medium until high (19.63-38.09 $cmol_c kg^{-1}$), and base saturation low until high (37-63%). The depth of sulfidic materials or pyrite layer is shallow until deep within 50-85 cm. The sand mineral fraction is dominated by quartz, while the mineral fraction of clay is dominated by kaolinite, followed by vermiculite and illite. The land studied is classified as marginally suitable (S3) for the development of tidal rice fields with a limiting factor for acid to very acid soil reactions (soil $pH < 5$). Balanced fertilization, liming, and micro water management can be done to increase the productivity of this land.

1 Introduction

Indonesia, an agricultural nation, relies heavily on its agricultural sector, with most of its population employed in agriculture, forestry, and fisheries. Approximately 38,703,996 people, constituting around 26.9% of the total workforce, are engaged in these sectors. However, Indonesia's vast population, totaling 275,738,800 people, results in a high national

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demand for food. This demand continues to rise annually due to the country's population growth, which averaged 1.25% per year between 2010 and 2020, as per statistical data [1].

Data regarding the national agricultural land area between 2014 and 2020 indicates a decline in the use of agricultural land for food production. In 2014, the area of food agricultural land was 453,060 km², reduced to 423,341 km² in 2020 [2]. This decrease in agricultural land area, particularly for food production, is attributed to land conversion for other purposes like plantations, industry, and residential areas. This situation intensifies the challenge of ensuring food security, especially in meeting the nation's food requirements. According to the decree issued by the Minister of Agrarian Affairs and Spatial Planning/Head of BPN-RI No.686/SK-PG.03.03/XII/2019, the standardized area for Indonesian rice fields is set at 74,639.48 km². Despite Java Island covering only around 6.75% of Indonesia's land area, it plays a pivotal role in national agricultural production. The rice fields on Java Island cover 34,738.10 km², approximately 46.54% of the national rice field area, producing 31,246,602 tons or roughly 56.13% of the country's total rice production. To ensure the Indonesian population's food needs are met, the existing rice fields must be optimized to their fullest potential.

Efforts have been made to address this food demand through both agricultural expansion and intensification. One area with significant developmental potential is swamp land, characterized by its transitional position between terrestrial and aquatic systems, remaining flooded or inundated for a considerable part of the year. The total expanse of swamp land in Indonesia covers approximately 34.12 million hectares. This category encompasses tidal swamp land, which spans 8.92 million hectares, while the remainder is comprised of lowland swamp land. Tidal swamps are widespread across Sumatra, Kalimantan, and Papua. Among these, 7.55 million hectares of tidal swamp land are mineral soil, and the remaining 1.37 million hectares consist of peat soil [3].

Tidal swamp land is land that is influenced by the tides of sea or river water. This tidal swamp land is generally located on the Fluvio-marine landform. The soils formed on this landform are influenced by marine sediments and river sediments at different levels, where some of the soil-forming materials can come from marine sediments and others come from river sediments. Common challenges in land use within Fluvio-marine landforms involve the presence of sulfide or pyrite (FeS2) mineral layers. The detrimental impacts of pyrite oxidation include decreased plant growth, corrosion of engineering infrastructures, massive fish kills and fish diseases, and dramatic changes to stream ecology [4]. Pyrite forms in soil originating from marine sediments in marine environments or brackish water containing organic matter and sulfate-reducing bacteria, which convert sulfate $(SO_4)^{2-}$ to sulfide in anaerobic conditions [5]. Pyrite becomes hazardous upon oxidation, generating sulfuric acid and the mineral jarosite, leading to high acidity that can impede plant growth [6]. Pyrite oxidation occurs when the soil dries out; as the groundwater level decreases, oxygen enters the soil layer, causing pyrite to oxidize, resulting in the production of iron, sulfate, and hydrogen [7]. The release of numerous H^+ ions during this reaction acidifies the soil pH, increasing the availability of Fe and Al in the soil.

This research aims to determine the properties of soil on Fluvio-marine landforms and its potential for developing lowland rice in Bataguh District, Kapuas Regency, Central Kalimantan Province.

2 Materials and methods

2.1 Description of the study area

The research location is in Swampy Area of Bataguh District, Kapuas Regency, Central Kalimantan Province (Fig. 1) covering an area of 6,102 ha. Geographically the research location is located at coordinates 03° 01' 40"- 03° 23' 36" South Latitude and 114° 08' 39"- 114° 25' 29" East Longitude. The research location is geologically included in the River and Swamp Sediment Formation (Qa) which is composed of mud, silt, sand and clay sediments. This formation is relatively young and formed during the Holocene. Observations in the field showed that the parent material of the soil at the study site consisted of clay deposits, both from river depositional materials and marine materials. The land use in the research location is generally tidal rice fields [8].

The study area had an average annual rainfall of 2,476 mm over the last 10 years. The highest rainfall occurs in January (309 mm), while the lowest is in August (102 mm). Climatic zoning at the study site is based on the number of wet months and dry months. Wet months are months with rainfall >200 mm/month and dry months are months with rainfall <100 mm/month [9]. Based on the analysis of rainfall data, the study area has an agro-climatic zone B1. Zone B1 illustrates that in the study area, the wet months occur for 7 consecutive months and the dry months for 0-1 month. The study area has 7 wet months (November-May) varying from 201 to 309 mm, moist months (June-October) 102 to 1456 mm and no dry months.

2.2 Soil sampling and laboratory analyses

Four representative soil profiles (GM 15, RA 25, TQ 17, YP 28) (Fig. 1) were sampled from each layer for chemical, mineralogical, and pyrite analyses. Soils were sampled by horizon from the surface down to 150 cm using a hand-operated Eijkelkamp auger. Field observation for pyrite was determined by treating the soil with 30% Hydrogen peroxide (H_2O_2). The soil effervescence after peroxide treatment and the drop in the field soil pH to less than 2.5 or lower, indicated the presence of pyrite [10]. Observations made in the field refer to the Soil Observation Guidelines in the Field [11, 12], while soil classification refers to Keys to Soil Taxonomy [13].

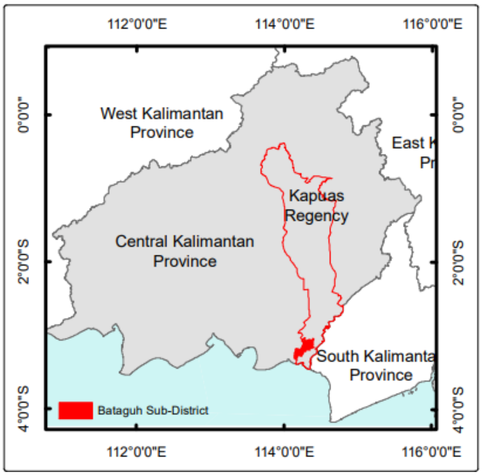

Fig. 1. Location of the study area.

Laboratory analysis consists of soil's physicochemical and mineralogical properties. All laboratory determinations were made on air-dried materials passing a 2-mm sieve. Particle size distribution was determined by a pipette method after dispersion. Soil pH was measured with a glass electrode in water using a soil: solution ratio of 1: 5. Organic carbon was determined by the Walkley-Black wet combustion method, while total N was determined by the Kjeldahl method. Available P_2O_5 was determined by the Bray 1 extraction method, while potential P_2O_5 and K_2O contents were determined by the HCl 25% extraction 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 (Al^{3+} and H^+) is extracted with 1 M KCl and measured by titration. Sulfidic or pyrite materials are determined by carrying out oxidation using nitric acid before being reacted with HCl [14].

Soil mineralogy analysis consists of the mineral analysis of sand and clay fractions. The mineral composition of the sand fraction (50-500 µm) was identified on a glass slide using a polarizing microscope and the minerals were determined based on the line counting method [15]. Analysis of the sand fraction minerals is intended to determine the composition and primary mineral reserves.

The clay mineral fraction (< 2µm) was determined using an X-ray diffractometer by a Rigaku instrument (SmartLab, Rigaku, Tokyo, Japan) with Cu-Kα radiation at 40 kV and 30 mA. The specimens were oriented on a ceramic sample holder and treated using standard procedures [16], which included Mg-saturation, Mg-saturation with glycerol solvation, K-saturation, and heat treatment of K-saturated slides at 550°C. The oriented specimens were then scanned from 3 to 40° 2θ at 1°/min. The identification of clay minerals is based on their basal distance (d spacing) from each diffraction peak [17]. Analysis of clay mineral fraction aims to determine the composition of clay minerals and for soil classification purposes.

Land suitability assessment was carried out using the matching method, namely comparing soil characteristics and land requirements for the development of tidal rice fields referring to land suitability criteria [18]. Land evaluation results are expressed in land suitability classes: very suitable (S1), suitable (S2), marginally suitable (S3), or not suitable (N) including the limiting factors.

3 Results and discussion

3.1 Soils morphological characteristics

In the upper part, the soil color at the research location is predominantly black to grayish brown (10YR 2/1 to 2.5Y 5/2), while in the lower part, the color is gray (2.5Y 5/1 to N 5 /1) which is influenced by the results of sedimentation of marine material. The texture of mineral soils based on field observations is generally silty clay loam to clay in the upper layers and clay in the lower layers (Table 1).

This marine sediment material contains sulfide or pyrite material at different depths in each location. The pyrite surface in the profile studied is quite deep (50 cm at RA 25 and 52 cm at TQ 17) and deep (85 cm at YP 28 and 95 cm at GM 15) (Table 1). The presence of moderate to high levels of sulfide or pyrite material in the soil layer is indicated by a moderate to strong soil reaction when treated with H_2O_2 solution, causing the soil pH to drop drastically to 1-2 (Table 1).

Based on field observation, the soil reaction (pH) in the research location is generally acidic (pH 4.5-5.5) in horizon A and Bg, whereas acidic to slightly acidic (pH 5.0-6.0) in horizon Cg that comes from marine/coastal sediments. The high pH of the soil in the Cg horizon is because its condition is always reductive, in contrast to the top layer which has undergone oxidation. The consistency class of the soil studied was generally slightly sticky to sticky and slightly plastic to plastic in the upper soil layers, becoming stickier to plastic in the lower layers. The level of soil maturity based on field observations varies from half-mature to almost mature and mature (Table 1).

Table 1. Soil morphological properties of the studied soils.

Profile/ Horizon	Depth (cm)	Color (Wet)	pH-field*		Field texture	Consistency	Field** Ripeness
			water	H_2O_2			
GM 15 Sulfic Endoaquepts							
Ap	0-25	10YR 3/1	5.0	4.0	clay	sticky, plastic	ripe
Bg1	25-53	10YR 4/2	5.0	4.0	clay	sticky, plastic	ripe
Bg2	53-95	2.5Y 4/2	5.0	2.0	clay	sticky, plastic	ripe
2Cg	95-150	2.5Y 4/1	5.0	1.0	clay	sticky, plastic	ripe
RA 25 Sulfic Endoaquepts							
Ap	0-15	10YR 2/1	5.5	4.0	silty clay loam	slightly sticky, slightly plastic	ripe
Bg	15-52	2.5Y 3/1	5.0	4.0	clay loam	slightly sticky, slightly plastic	ripe
2Cg1	52-84	5Y 4/1	5.0	1.0	clay	sticky, plastic	ripe
2Cg2	84-150	5Y 3/1	6.0	1.0	clay	sticky, plastic	ripe
TQ 17 Sulfic Endoaquepts							
Ap	0-15	10YR 4/2	4.5	4.0	clay loam	slightly sticky, slightly plastic	ripe
Bg	15-50	10YR 5/2	4.5	4.0	clay	sticky, plastic	ripe
2Cg1	50-70	2.5Y 5/2	5.5	2.0	clay	sticky, plastic	ripe
2Cg2	70-150	N 5/1	5.5	1.0	clay	sticky, plastic	ripe
YP 28 Sulfic Endoaquepts							
Ap	0-25	2.5Y 3/2	5.0	4.0	silty clay loam	slightly sticky, slightly plastic	nearly ripe
Bg1	25-55	2.5Y 4/2	5.0	4.0	clay loam	slightly sticky, slightly plastic	ripe
Bg2	55-85	2.5Y 5/2	5.0	4.0	clay loam	sticky, plastic	ripe
2Cg	85-150	2.5Y 5/1	5.0	2.0	clay loam	sticky, plastic	half ripe

Notes: *Field pH was determined using a pH indicator strip (Merk, Germany); **the field ripeness estimate by a simple test of squeezing a soil sample in the palm of a hand

3.2 Soil mineralogical properties

The mineralogy of the sand fraction of all the profiles was dominated by quartz (32-93%). Weathered mineral, rock fragments, volcanic glass, and organic SiO_2 was found in low amounts (<10%). The mineral composition of the sand fraction in the upper layers (Ap and Bg) which is developed from fluvial parent material and in the lower layers (Cg) is not significantly different. This indicates that the soil materials are formed from the same material. The total mineral fraction of easily weathered sand (andesine, orthoclase, sanidine, hornblende, augite, hypersthene, epidote, glaucophane) and zircon from all soil profiles studied was relatively low (<6%) (Table 2). The amounts of opaque minerals are varied between 1 to 61%. The low amount of weatherable minerals and high amounts of quartz indicate that all the soils formed from felsic parent materials.

The mineral composition of the clay fraction of the studied profiles was dominated by kaolinite, followed by vermiculite and illite in medium amounts (Fig. 2). The presence of kaolinite was indicated by XRD peaks with a d-spacing of 7.13 to 7.19 Å (order 1) and 3.55 to 3.56 Å (order 2) after Mg^{2+} treatment, Mg^{2+} + glycerol, and K^+ treatment, and further the peaks collapsed after of K^+ plus heating at 550ºC treatment [19]. Vermiculite has a d-spacing of 14.05 to 14.54 Å after Mg^{2+}, Mg^{2+} + glycerol, and K^+ treatments, and further, the peaks collapsed after K^+ plus heating at 550 ºC treatment with a d-spacing of 9.88 to 10.05 Å. The presence of Illite was indicated by XRD peaks with a d-spacing of 10.08 to 10.40 Å (order 1), 4.88 to 5.01 Å (order 2), and 3.32-3.35 Å after all treatments [20].

Table 2. Mineral composition of soil sand fraction in the studied area.

Profile/ Horizon	Depth (cm)	Type of minerals (%)															Total
		Os	Wm	Rf	Vg	An	Or	Sn	Hb	Au	Hp	Ep	Gl	Op	Zr	Qz	
GM 15 Sulfic Endoaquepts																	
Ap	0-25	tr	6	3	2	tr	tr	1	3	tr	1	-	-	5	-	79	100
Bg1	25-53	tr	3	3	1	tr	tr	tr	2	-	tr	-	-	7	-	84	100
Bg2	53-95	-	2	2	1	tr	tr	tr	1	-	tr	-	-	10	-	84	100
2Cg	95-150	-	5	1	1	tr	-	-	-	-	-	-	-	61	-	32	100
RA 25 Sulfic Endoaquepts																	
Ap	0-15	2	6	8	1	3	-	1	2	1	5	1	2	14	1	53	100
Bg	15-52	3	4	5	tr	2	-	tr	2	2	3	1	1	15	tr	62	100
2Cg1	52-84	2	3	6	1	1	-	tr	1	2	4	1	tr	10	tr	69	100
2Cg2	84-150	1	4	9	tr	1	-	tr	1	1	4	tr	tr	12	tr	67	100
TQ 17 Sulfic Endoaquepts																	
Ap	0-15	-	tr	4	1	-	tr	1	tr	tr	tr	tr	tr	tr	1	93	100
Bg	15-50	-	tr	2	1	-	tr	2	-	tr	-	-	tr	1	2	92	100
2Cg1	50-70	-	1	1	1	-	1	2	tr	-	-	-	-	tr	3	91	100
2Cg2	70-150	-	tr	2	tr	-	1	3	-	-	-	tr	-	1	3	90	100
YP 28 Sulfic Endoaquepts																	
Ap	0-25	-	5	4	1	1	1	3	-	tr	1	tr	-	6	1	77	100
Bg1	25-55	-	4	5	1	tr	2	1	-	-	tr	1	-	4	tr	82	100
Bg2	55-85	tr	2	4	tr	tr	tr	tr	-	-	-	tr	-	3	-	91	100
2Cg	85-150	-	3	3	tr	-	1	1	-	-	-	tr	-	3	tr	89	100

Notes: Os=organic SiO_2, Wm=weathered mineral, Rf=Rock fragment, Vg=volcanic glass, An=andesine, Or=orthoclase, Sn=sanidine, Hb=hornblende, Au=augite, Hp= hypersthene, Ep=epidote, Gl=glaucophane, Op=opaque, Zr=zircon, Qz=quartz, tr=trace (<1%),

The low amount of weatherable minerals, the high amount of quartz, and the high amount of kaolinite indicated that the soils in the transect area have low fertility status due to the low amount of nutrient reserves. Few easily weathered minerals and high kaolinite indicate that the parent material that forms this soil is mostly derived from weathered acid sedimentary rock materials in the surrounding area with higher topography and low nutrient elements. The potential for natural soil fertility in the long term is quite low because it is not supported by adequate nutrient reserves due to low perishable minerals in the soil. However, the presence of vermiculite and illite contributes to moderate soil cation exchange capacity.

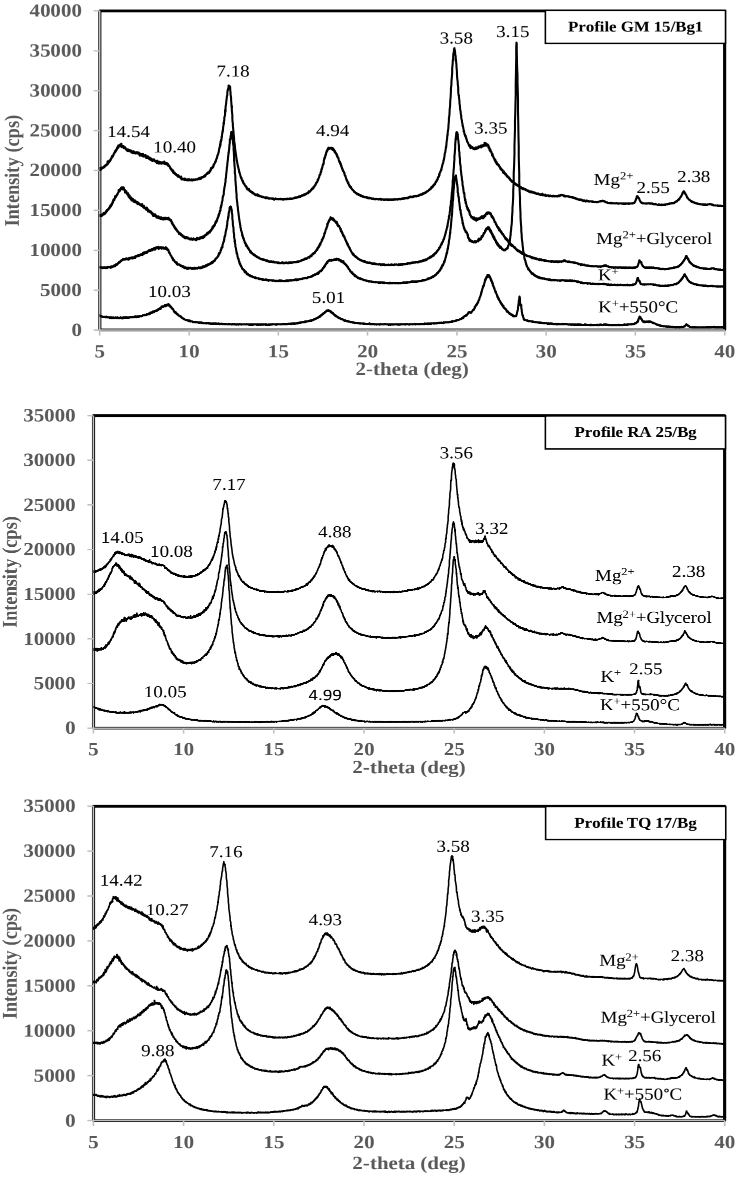

Fig. 2. X-ray diffractogram of the studied soils with Mg^{2+}, Mg^{2+}+glycerol, and K^{+}+heating 550°C treatments.

3.3 Soil chemical properties

The soils at the research location have a relatively fine texture. These soils predominantly consist of silt and clay fractions (Table 2). The GM 15, RA 25, and YP 8 soil profiles exhibit a silty clay texture, with clay content ranging from 43-58% and silt content from 47-69%, except for the top layer of YP 8, which has a clay texture. In contrast, the TQ17 profile displays a consistent silty clay texture throughout, with clay content ranging from 31-39% and silt content from 61-69%, devoid of any sand fractions.

Laboratory analyses revealed that the soil acidity is highly acidic to slightly acidic, with pH values ranging from 3.0 to 5.1 (Table 3). These values are lower than those recorded in the field. Field measurements indicated slightly acidic to moderately acidic soil reactions, ranging from 4.5 to 6.0. A significant decrease in pH occurred in the C horizon layer, where field measurements showed a pH range of 5-6, whereas laboratory analysis yielded pH values between 2.8-4.4. This phenomenon suggests the presence of sulfidic materials in the soil, which oxidize and generate sulfuric acid [21]. This oxidation occurs during soil drying before laboratory analysis. The consistent decline in soil pH in laboratory measurements corresponds to the rise in concentrations of Al^{3+} and H^+. Al^{3+} concentrations in the surface and subsurface layers were 3.40-13.21 and 0.38-18.57 $cmol_c kg^{-1}$, respectively, while H^+ concentrations ranged from 0.73-4.98 in the surface layer and 0.60-16.87 $cmol_c kg^{-1}$ in the subsurface layer. These findings align with research on tidal swamp lands in Banyuasin, indicating that lower soil pH levels enhance the availability of Fe and Al [22]. Elevated levels of Fe and Al can be harmful to plants and can also sequester phosphorus in the soil, rendering it inaccessible to plants.

The soil exhibits a relatively high organic carbon (C-organic) content. Typically, the C-organic content is higher at the soil surface than in the underlying layers. In the uppermost layer, C-organic content ranged between 5.46% and 9.37%. However, in the lower soil layers, the C-organic content tends to be lower, except in the second layer of RA25 soil, where it reaches 12.535%. According to the Soil Taxonomy classification system [13], soil material containing over 12% organic matter is categorized as organic soil material.

The potential P_2O_5 levels are classified as ranging from low to high. Generally, the surface layer of soil has higher potential P_2O_5 levels than the layers below. Surface potential P_2O_5 levels range from medium to high, varying between 21 and 40 mg per 100g, while sub-surface potential P_2O_5 levels vary from 7 to 41 mg per 100g. The available P_2O_5 levels are also categorized as low to high. At the soil surface, available P_2O_5 levels range from 9.6 to 37.0 ppm, while in the lower layers, they range from 6.4 to 33.8 ppm. Typically, the top layer contains more available P_2O_5 than the lower layer, except in TQ-17, where the second layer boasts an available P_2O_5 content of 19.4 ppm, surpassing the top layer. The potential K_2O content is generally low to medium in all soil layers, ranging from 16 to 29 mg per 100g. This indicates the need for P and K fertilizer application to the soil.

The cation exchange capacity (CEC) of the topsoil is classified as moderate, ranging from 19.63 to 38.69 $cmol_c kg^{-1}$. This value is nearly consistent with the CEC value in the lower layer, which ranges between 12.63 and 37.43 $cmol_c kg^{-1}$ (Table 4). The base saturation of these soils varies from medium to high, with surface layer values ranging from 37% to 63%, while sub-surface layer values vary from 52% to over 100%. The concentration of exchangeable cations, both in the top layer and beneath the soil surface, follows this sequence: Mg > Ca > Na > K. On average, the ratio of Ca : Mg : K : Na is approximately 0.37 : 1 : 0.03 : 0.34. This differs from the base cation saturation ratio (BCSR) concept, which suggests an ideal ratio of Ca : Mg : K : Na as 6.5 : 1.0 : 0.5 : 0.5 [23]. The higher levels of Mg compared to Ca are indicative of the influence of marine deposits, as supported by previous studies [10, 24]. High levels of Mg^{2+} and Ca^{2+} can be caused by the presence of type 2:1 clay minerals [25]. In all soil layers studied, Mg levels were greater than Ca. This is different when compared with the results of other research in different places. In some soils found in fluvio-marine landforms in Indramayu, the top layer exhibited Ca levels > Mg, whereas in the lower layer, Mg levels > Ca. This observation highlights the composite nature of the soil, formed through a combination of marine and river sedimentation processes [26].

Table 3. Particle size distribution, soil pH, organic C and N, potential P_2O_5 and K_2O, available P_2O_5 of the soils in the study area.

Profile/ Horizon	Depth	Particle size			pH		Organic matter			Potential		Available
		Sand	Silt	clay	H_2O	KCl	C	N	C/N	P_2O_5	K_2O	P_2O_5
	cm	-- % --					-- % -			-mg100g^{-1}-		mg kg^{-1}
GM 15	Sulfic Endoaquepts											
Ap	0-25	0	52	48	4,2	3,6	9,37	0,56	17	40	19	37,0
Bg1	25-53	0	55	45	4,5	3,8	5,02	0,23	22	14	18	33,8
Bg2	53-95	0	52	48	4,3	3,7	5,81	0,24	24	11	18	15,3
2Cg	95-150	0	50	50	3,3	3,1	6,86	0,25	27	7	18	4,9
RA 25	Sulfic Endoaquepts											
Ap	0-15	1	47	52	4,7	3,8	9,28	0,50	19	21	18	9,6
Bg	15-52	0	54	46	3,8	3,5	12,53	0,46	27	14	17	6,5
2Cg1	52-84	0	57	43	2,8	2,6	9,37	0,33	28	15	19	2,2
2Cg2	84-150	0	58	42	3,1	3,0	7,05	0,23	31	16	27	1,3
TQ 17	Sulfic Endoaquepts											
Ap	0-15	0	68	32	3,3	3,2	5,46	0,34	16	28	16	17,5
Bg	15-50	0	69	31	3,8	3,5	3,39	0,20	17	29	18	19,4
2Cg1	50-70	0	68	32	3,6	3,4	3,18	0,19	17	19	15	8,6
2Cg2	70-150	0	61	39	3,0	2,9	4,89	0,26	19	17	29	6,4
YP 28	Sulfic Endoaquepts											
Ap	0-25	0	36	64	4,6	3,9	6,13	0,43	14	35	21	30,0
Bg1	25-55	0	53	47	4,8	4,0	6,58	0,38	17	41	27	28,4
Bg2	55-85	0	51	49	5,1	4,2	4,34	0,24	18	20	22	15,9
2Cg	85-150	0	52	48	4,4	3,8	4,96	0,28	18	21	24	13,7

Table 4. Exchangeable cations, cation exchange capacity, base saturation, exchangeable Al and H, and pyrite content of the soils in the study area.

Profile/ Horizon	Depth	Exchangeable cations				Sum-cat	CEC	BS	Al^{3+}	H^+	Fe	S	Pyrite
		Ca	Mg	K	Na								
	cm	----------- cmol$_c$kg^{-1}---------						%	- cmol$_c$kg^{-1} -		------- % ------		
GM 15	Sulfic Endoaquepts												
Ap	0-25	2,91	7,46	0,32	2,51	13,20	36,03	37	5,59	0,93	-	-	-
Bg1	25-53	3,13	8,62	0,25	2,01	14,01	24,62	57	4,72	0,75	-	-	-
Bg2	53-95	3,44	10,05	0,25	2,11	15,85	26,07	61	5,04	0,90	1,45	0,27	0,50
2Cg	95-150	4,16	11,95	0,17	2,16	18,44	18,01	>100	11,82	4,65	3,00	1,99	3,73
RA 25	Sulfic Endoaquepts												
Ap	0-15	3,17	7,52	0,35	4,03	15,07	38,09	40	4,57	0,78	-	-	-
Bg	15-52	4,17	10,41	0,27	4,53	19,38	37,43	52	6,20	1,77	-	-	-
2Cg1	52-84	4,86	12,26	0,17	2,93	20,22	30,91	65	18,57	16,87	4,78	3,50	6,56
2Cg2	84-150	5,95	16,00	0,16	4,00	26,11	26,05	100	15,04	15,26	6,89	4,08	7,65
TQ 17	Sulfic Endoaquepts												
Ap	0-15	2,24	5,11	0,17	2,14	9,66	19,63	49	13,21	4,98	-	-	-
Bg	15-50	2,02	4,91	0,21	2,83	9,97	13,27	75	7,93	1,36	-	-	-
2Cg1	50-70	2,04	5,39	0,21	3,43	11,07	12,63	88	8,87	1,45	2,06	0,17	0,32
2Cg2	70-150	3,47	10,32	0,10	2,82	16,71	18,07	92	16,37	9,56	4,55	2,86	5,36
YP 28	Sulfic Endoaquepts												
Ap	0-25	3,08	8,30	0,36	3,61	15,35	24,32	63	3,40	0,73	-	-	-
Bg1	25-55	2,74	8,24	0,47	4,09	15,54	21,20	73	2,28	0,77	-	-	-
Bg2	55-85	3,60	11,24	0,29	3,81	18,94	16,26	>100	0,38	0,60	-	-	-
2Cg	85-150	4,20	12,66	0,32	4,37	21,55	17,58	>100	1,83	0,74	2,04	0,21	0,39

CEC = Cation Exchange Capacity, BS = base saturation

The depth of the pyrite layer in the soil at the research site varies from 35 to 85 cm. In the field, the presence of pyrite becomes evident through a moderate to very strong effervescent reaction when the soil is exposed to a peroxide solution (H_2O_2). The formation of foam indicates an accelerated oxidation process, particularly in underground layers originating from marine sediments. Field observations revealed a color change in the soil from brownishgray (freshly exposed surface matrix) to bluish-gray after two minutes of exposure to air when treated with H_2O_2 solution.

In general, the soil fertility level in the study area is categorized as moderate, evaluated within the surface layer down to a depth of 30 cm below the soil surface. The surface layer exhibits high levels of organic carbon and potential phosphorus, along with moderate to high cation exchange capacity (CEC) and base saturation values. However, potential K levels are generally low, representing a limiting factor in soil fertility. To enhance soil fertility, it is necessary to apply potassium fertilizer in addition to nitrogen and phosphorus fertilizers, which are essential for maintaining fertility. Additionally, the application of lime is recommended to improve soil properties by increasing soil pH and enhancing the soil's nutrient availability for plants. Considering the soil's already high levels of exchangeable magnesium, the recommended lime type for application is calcite ($CaCO_3$).

3.4 Land suitability and management

Based on an assessment of soil morphological characteristics and laboratory analysis data, the results of the land suitability assessment for lowland rice cultivation show that the land in the research area is classified as S3 (marginally suitable). A crucial limiting factor in land quality is nutrient retention due to high acidity, reflected in low soil pH. To enhance soil quality, liming is recommended to reduce acidity, with calcite ($CaCO_3$) being the preferred lime type due to the already high levels of Mg in the research location. The addition of lime introduces Ca^{2+} ions, displacing the ions responsible for soil acidity. However, the target pH at which Al saturation will be reduced to 10% can be predicted from the initial pH and initial Al saturation. Effective cation exchange capacity (ECEC) is increased by liming at all sites and additional exchange capacity is occupied by Ca [27]. Fertilization and organic materials also need to be provided to ensure sufficient nutrients for rice growth.

In addition, micro water management is needed to maintain the depth of the groundwater table. Soil drainage on tidal land should not be done excessively. Excessive soil drainage can cause pyrite in the soil to oxidize and produce sulfuric acid which makes the soil very acidic and toxic to plants. The formation of sulfuric acid (H_2SO_4) due to the oxidation of sulfide soil is the main cause of side effects associated with sulfuric acid soil. As a result, the presence of sulfuric acid results in the release of iron (Fe^{2+}, Fe^{3+}), aluminum (Al^{3+}), and various other potentially toxic elements into soil and water systems [28]. When cultivating the land, the cultivating depth must be maintained so that the layer of sulfide material below the soil surface is not lifted so that pyrite oxidation does not occur. Using a tractor or hoe must be done carefully.

Rice cultivation necessitates continuous reducing conditions, such as flooding irrigation, to prevent pyrite oxidation, a leading cause of severe degradation in soil properties and water quality. Cultivating rice effectively reduces subsoil acidity, especially in tropical regions where maintaining high water tables is crucial for preventing sulfide oxidation and environmental acidification [29, 30]. Establishing rice crops in fluviomarine areas is a more environmentally friendly option compared to other land uses. This is because rice crops require standing surface water during their growth period, which inhibits pyrite oxidation [10]. Opting for rice cultivars that tolerate inundation, acidity, and elevated levels of various ions offers an alternative approach to minimize the need for drainage efforts.

4 Conclusion

The mineralogy of the sand fraction of all studied soils was dominated by quartz, while the mineral composition of the clay fraction was dominated by kaolinite, followed by vermiculite and illite. The soils of rice fields at the research site in the Bataguh Sub-District are classified as Sulfic Endoaquepts, where the depth of the pyrite layer that more than 50 cm characterizes the soil types. According to laboratory data, the soil acidity is highly acidic to slightly acidic, with pH values ranging from 3.0 to 5.1. This soil is all poorly drained and fine-textured. The land suitability class for lowland rice development is classified as marginally suitable (S3). The nutrient retention factor due to high soil acidity is the main inhibiting factor in determining this land suitability class. In general, the fertility level of these soils is classified as moderate, where low total K levels are the main determinant. Efforts to improve soil properties to improve soil quality can be carried out by liming, fertilizing, and micro water management. Liming aims to reduce soil acidity and fertilization to ensure sufficient nutrients for rice growth, whereas micro water management aims to maintain surface water to prevent soil damage due to pyrite oxidation.

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