Research Article

Soil fertility status and land suitability evaluation for rice crops on former shrimp ponds

Evaluasi status kesuburan tanah dan kesesuaian lahan untuk tanaman padi pada lahan bekas tambak udang

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Abstract: Undertaking suitable land, including former shrimp ponds for rice, is required to cope with future rice shortages. The purpose of this study was to identify the soil morphology and physicochemical properties, determine soil fertility status and assess irrigated rice suitability of ex-shrimp ponds. Soil morpho-physicochemical properties such as soil color, structure, texture, pH, organic-C, P_2O_5, K_2O, base saturation, and cation exchange capacity were determined. The resulting data was then matched into the criteria for BSCR and SLAN/CCDS, five major soil fertility criteria, and ICALRRD land suitability. Soil physiographical, morphological, and physicochemical analysis suggested that the soil developed from the alluvial site of calcareous-marl parent material located at saturated backswamp, then permanently drained. ESP, SAR, and salinity values were detected relatively lower than saline, sodic, and saline-sodic soil. The entire cations fell below BCSR ideal ratios, whereas all exchangeable K were detected below the CCDS/SLAN thresholds. Actual suitability for land units of A, B, and C were S3-rc,na, S3-na and S3-rc,nr,na,eh, respectively. The improvement such as fertilization, amelioration, slope flattening/cut-filling, and irrigation management increases all land units to S1. This study pinpointed the importance of former shrimp pond soil to provide suitable land for rice crop cultivation. Also, encouraging further research to identify the origin of alluvial parent material from the soil at the study site.

Keywords: BSCR, land-suitability, ex-shrimp-pond, SLAN, soil-fertility

Abstrak: Pengadaan lahan yang sesuai untuk sawah termasuk bekas tambak udang diperlukan untuk mengatasi kekurangan beras di masa depan. Tujuan dari penelitian ini adalah mengidentifikasi morfologi dan sifat fisikokimia tanah, menentukan status kesuburan tanah dan menilai kesesuaian lahan padi irigasi pada lahan bekas tambak udang. Sifat morfo-fisikokimia tanah yang ditentukan meliputi warna, struktur, tekstur, pH, C-organik, P_2O_5, K_2O, kejenuhan basa, dan kapasitas tukar kation. Data yang dihasilkan kemudian dicocokkan dengan kriteria BSCR dan SLAN/CCDS, lima kriteria kesuburan tanah utama, dan kesesuaian lahan BBSDLP. Analisis fisiografi, morfologi, dan fisikokimia tanah menunjukkan bahwa tanah berkembang pada bahan induk aluvial berkapur-marl yang terletak di rawa belakang jenuh air, kemudian dikeringkan secara permanen. Nilai ESP, SAR, dan salinitas yang terdeteksi relatif lebih rendah dibandingkan dengan tanah salin, sodik dan salin-sodik. Seluruh kation yang diamati berada di bawah rasio ideal BCSR, sedangkan semua K dapat dipertukarkan terdeteksi di bawah ambang batas CCDS/SLAN. Kesesuaian aktual satuan lahan A, B, dan C berturut-turut adalah S3-rc,na, S3-na dan S3-rc,nr,na,eh. Upaya perbaikan seperti pemupukan, ameliorasi, pendataran lereng/gali-uruk dan manajemen erosi dapat meningkatkan kelas semua satuan lahan menjadi S1. Studi ini menunjukkan pentingnya peran tanah bekas tambak udang dalam upaya penyediaan lahan yang sesuai untuk budidaya tanaman padi. Penelitian ini juga mendorong penelitian lebih lanjut untuk mengidentifikasi asal bahan induk aluvial yang menjadi tempat berkembangnya tanah di lokasi studi.

Kata kunci: BSCR, kesuburan-tanah, kesesuaian-lahan, SLAN, tambak udang

Citation:

INTRODUCTION

Nowadays, rice stood as the primary source of staple food in the Banggai Regency. According to the latest land use map published by the Indonesian Ministry of Environment and Forestry (KLHK, 2019) and BPS-Statistics Indonesia of Banggai Regency (BPS Banggai, 2021), Banggai Regency is estimated to have about 129,753.23 ha of paddy field and produced 271,371 tonnes of rice in 2019. This region was also the subject of the transmigration program designating to depreciate overpopulated areas and achieve national food security (Whitten, 1987). Although the supply interestingly has an increasing pattern, the rapid development and population growth in this area result in high rice demand in the future (BPS Banggai, 2010-2021). To sufficiently cope with future rice shortage, undertaking suitable land for rice field become inevitably necessary.

An abandoned shrimp pond located in Batui District provides a valuable area that can be fulfilled the land required for rice field expansion. This shrimps pond was formerly managed by PT BSS (Banggai Sentral Shrimp) from 1989 (Kalesaran, 2010) until it collapsed around the middle of 2010 – 2020. Similar to the salt-affected coastal area, soil pH and base saturation/KB level at the former shrimp pond soil is typically moderated to high. This soil also exhibits high sodium adsorption ratio/SAR and exchangeable sodium percentage/ESP. However, many researchers revealed that such value, particularly for pH and KB, emanates from excessive sodium (Na) rather than a balanced composition of K, Ca, Mg and Na. The reason is attributed to periodically saturation by brackish and saltwater during operation time, which contributes to Na and Cl accumulation in soil solution and exchange complex (Boyd et al. 1994; Sonnenholzner & Boyd, 2007; Chi et al. 2012; Yan & Marchner 2012; Wu et al. 2013; Van Tan & Thanh, 2021). Oppositely, the high precipitation that occurs in this area is an essential source of freshwater adequate to leach Na and Cl. Moreover, this soil is also occasionally obtained freshwater during high flooding that possibly contains abundant nutrients from rice fields located in an elevated area. Determining exchangeable base cations, SAR, and ESP is crucial before the initiation of rice cultivation since no current reports of soil chemical data are recorded in this area.

As stated before, the former shrimp pond soil suffers cation imbalance that chemically and physically affects its capability to support plant growth and development. Due to its similar type of charge and analogous root's influx channel, elevated Na concentration in the soil can compete and interfere with K and Ca absorption in soil and root exchange complex (Qi & Spalding, 2004; Tavakkoli et al. 2010; Coskun et al. 2013; Kronzucker et al. 2013; Wakeel, 2013). Furthermore, high Na content in soil is reported to be detrimental for soil aggregate stability due to its effectiveness in dispering soil particles (Agassi et al. 1981; Abu-Sharar et al. 1987; Tajik et al. 2003). This condition could lead to particle and cation leaching from the soil system, physicological dehydration, and plant deficiency problems from a long-term perspective. On the other hand, a high concentration of Cl can reduce photosynthesis capacity and quantum yield (Tavakkoli et al. 2010). Consequently, the evaluation of soil fertility status of this area study must be conducted.

Several sets of criteria based on basic soil-plant relationship phenomena were developed separately by soil scientists under different interpretation philosophies to assess soil fertility status (Eckert, 1987). These approaches including the basic cation saturation ratio/BCSR and sufficiency level of available nutrients/SLAN. The BCSR's approach was based on "balancing theory," which recommends the fertilization to adjust the cation saturation ratios to an optimum or ideal level, irrespective of their actual concentration (Chaganti & Culman, 2017). On the other hand, the SLAN approach stood on the law of diminishing returns. This concept

theorized that the decrease of crops yield response occurs while the soil nutrients concentration is approaching sufficient level (McLean, 1977). Several researchers have reported the BSCR and SLAN study in subtropical soil (Eckert & McLean, 1981; Liebhardt, 1981; Favaretto *et al*. 2008; Brock *et al*. 2020; Culman *et al*. 2021). However, the research conducted in tropical soils, especially in the study area were found scarce (Hikmatullah & Al-Jabri, 2007; Anda, 2012; Assefa *et al*. 2020; Kasno *et al*. 2021).

However, after appropriate management, the small marginal area of the ex-shrimp pond could act as potential farmland capable of producing considerable amounts of rice. In order to attain optimum yield and avoid mismanagement, the land must be evaluated to identify its soil-climate constraints dealing with rice paddy requirements. Currently, many suitability studies were conducted not only based on field data (Suheri *et al*. 2018), meanwhile, also incorporated remote sensing data (Kihoro *et al*. 2013; Widiatmaka *et al*. 2016; Baroudy *et al*. 2020; Taghizadeh-Mehrjardi *et al*. 2020; Al Taani *et al*. 2021). The advanced development of remote sensing technology provides spatial product up to medium-detail scale with broad coverages (e.g., Sentinel-1 SAR, Sentinel-2 MSI, Landsat-8 OLI, MODIS, IFSAR, TerraSAR-X, DEMNAS, SRTM, etc.) that supports detailed small-scale mapping study (Lima *et al*. 2019; Ge *et al*. 2020; Nurtyawan & Fiscarina, 2020). This paper presented several field data of formerly shrimp pond soil consisting of chemical and physical soil surface properties, combining with current and legacy of remote sensing and GIS data to assess their fertility status and suitability for irrigated rice.

MATERIALS AND METHODS

Study Area

The study area is located at ex-shrimp pond formerly operated by PT BSS (Banggai Sentral Shrimp), Sisipan Subdistrict, Batui District, Banggai Regency, Central Sulawesi Province, Indonesia, as shown in Figure 1. Astronomically located at 51S UTM Zone, $1^o18'2.76''$ – $1^o32'43.97''$ S and $122^o32'18.32''$ – $122^o33'32.56''$ E, the study site covers an area of about 151.76 hectares. Geographically, the study area is located between Batui and Bakung River, occupying the backswamp area about 500 meters from The Makakata Coast.
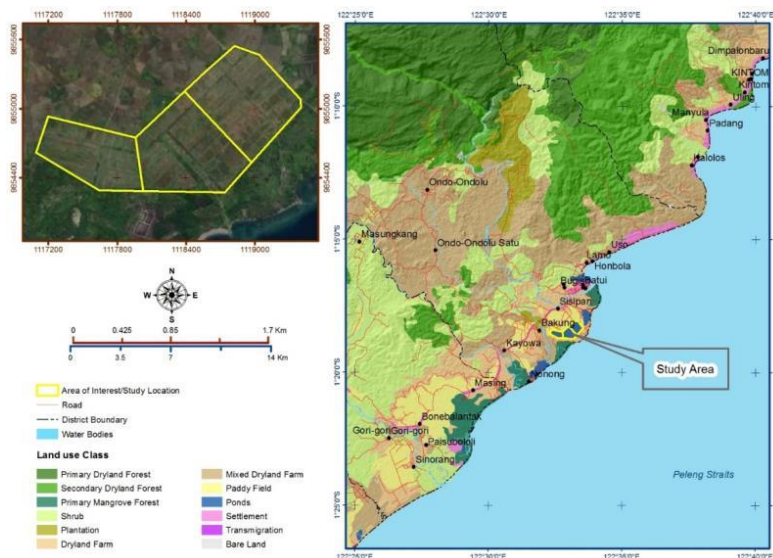

Figure 1. Study location of former shrimp pond area

Remote Sensing and GIS Database

A wide range of the legacy and current remote sensing and geographic information system/GIS data were surveyed, then collected to develop a spatial database, presented in Table 1. The remote sensing data were retrieved using cloud computing Google Earth Engine (Gorelick *et al*. 2016). Furthermore, all spatial datasets were computed and modeled using model builder in ArcGIS 10.5. The entire collected spatial data were digitally georeferenced and projected to World Geodetic System (WGS) 1984., Lastly, all datasets were reprojected to Transverse Mercator (TM)-3 zone 51.1 S based on Indonesian horizontal datum DGN-95 to obtain a more accurate area.

Considering the mapping scale variation among each dataset, all of the vector-based data were standardized to the scale of 1:50,000. The land system and geological map were smoothed based on the latest digital elevation model, supporting more detailed scale mapping. On the other hand, remote sensing data based on raster/grid cells were resampled to 10-meter horizontal resolution with different kernel algorithms regarding their distinct spatial characteristic. The cubic convolution algorithm was applied to reduce artifacts while the data varied continuously across spatial space, such as elevation (Kidner, 2003; Her *et al*. 2015). However, the nearest neighbor algorithm was performed while the data exhibited a clear border (e.g., land use; discrete, categorical data), owing to its robustness in resampling the high-resolution raster dataset (Porwal & Katiyar, 2014).

Table 1. Spatial datasets used in this study

Datasets	Use	Scale/ resolution	Source
Topographic Map			
National Digital Elevation Model (DEMNAS)	Altitude/elevation, slope, relief, watersheed	Spatial: ~8.3 m	GIA (2021a)
Shuttle Radar Topography Mission/SRTM	Additional topographical data	Spatial: ~30 m	Farr *et al.* (2007); USGS (2021a)
Advanced Spaceborne Thermal Emission and Reflection Radiometer/ASTER	Additional topographical data	Spatial: ~30 m	Abrams *et al* (2020); USGS (2021b)
Soil Map			
National Reconnaissance Soil Map	Nutrient retention Nutrients available	1:50,000	BBSDLP (2020)
Land System Map	Physiography and geomorphology	1:250,000	RePPProT (1987)
Geological Map	Lithology	1:250,000	Surono *et al.* (1993)
Local Map			
Regional Topographical Map (RBI)	General description	1:50,000	GIA (2021b)
Land Use Map			
KLHK-2019 Land Use Map	Land use	1:50,000	KLHK (2020)
Sentinel-2 Surface Reflectance	Land use	Spatial: 10 m	Google Earth Engine (Gorelick *et al*. 2016)

Fieldwork: Soil Sampling , Land Observation, and Secondary Data Collection

A fieldwork study was conducted in December 2020 to collect soil samples and assess field data regarding the information obtained through the spatial data. The soil samples (± 2 kg)

from the surface horizon (0 – 25 cm) were compositely collected using the soil auger. According to the present ex-shrimp pond condition, all of the remaining natural soil and landscape bodies had been eradicated. Hence, we divided the study site into three land units separated by a relatively large canal. The morphological observation was also performed through soil color, structure, and surface rock fragments. The soil color interpretation was visually referred to Munsell's Soil Color Chart (Pendleton & Nickerson, 1951; Simonson, 1993; Munsell Soil Color Chart 1994). Otherwise, soil structure and surface rock fragments were qualitatively determined according to Technical Guidelines for Soil Surveying and Mapping at Semi-Detailed Scale of 1:50.000 (Wahyunto *et al*. 2016), FAO-Guidelines for Soil Description (FAO, 2006), and Field Book for Describing and Sampling Soils (Schoeneberger *et al*. 2012).

Climate and weather data (2019 – 2020) were obtained from the Meteorological Station Class III Syukuran Aminudin Amir – Banggai through the Meteorological, Climatological, and Geophysical Agency/BMKG website (BMKG, 2021). Due to websites constraints, daily temperature and humidity data from January 2019 to December 2020 were collected separately in monthly report forms, then compiled using the Microsoft Excel software program.

Laboratory Analyses

Soil physical and chemical analyses were carried out at the Soil Chemistry and Fertility Laboratory, Agrotechnology Department, Faculty of Agriculture, Hasanuddin University. Soil samples were dried, ground, and then passed through a 2-mm sieve, resulting in fine air-dried soil. Soil texture was assessed using the pipette method. Soil sub-samples were digested using a combination of $K_2Cr_2O_7$ and H_2SO_4 to obtain organic-C according to Walkley and Black wet oxidation method (Walkey & Black, 1934). Soil pH and salinity were determined in a 1:2.5 soil to water mixture (Rayment & Higginson 1992). Phosphorus (P) was extracted following the Olsen method using 0.5 mol/L $NaHCO_3$ (Olsen *et al*. 1954). Total potassium (K) was extracted with HCl 25%. Nitrogen (N) was digested using according to the Kjeldahl method (Kjeldahl, 1883). Exchangeable cations (Na, K, Ca, and Mg) and cation exchange capacity/CEC were extracted and determined with NH_4OAc pH7 (Schollenberger and Simon, 1945; Chapman, 1965; Thomas, 1965). The final solution for P was measured using the PerkinElmer LAMBDA 25 UV-VIS spectrophotometer. The exchangeable cations of K and Na were determined using BK-FP640 Biobase flame emission spectrophotometer, meanwhile Ca and Mg were calculated through the titration method.

The effective CEC (ECEC) is considered equal to CEC extracted by NH4OAc since the soil pH reaching near pH 7. Clay to CEC ratio/CCR is calculated as CEC divided by clay percentage. The base saturation is obtained through the percentage value of the sum of all base cations (K, Na, Ca, and Mg) after being divided by CEC. The saturation of individual base cations is calculated from their value divided by CEC and expressed as a percentage. The exchangeable sodium percentage (ESP) is expressed as the percentage of exchangeable Na after being divided by CEC. Meanwhile, sodium absorption ratio (SAR) is calculated as exchangeable Na divided by the square roots of the half of summed Ca and Mg (Sparks, 2003).

Data Interpretation, Soil Fertility and Land Suitability Evaluation

The soil chemical properties were interpreted referring to the Technical Guidelines for Soil, Plant, and Fertilizer Chemical Analysis, Indonesian Soil Research Institute/ISRI (Eviati & Sulaeman 2009) as presented in Table 2. Clay to CEC ratio/CCR value was interpreted in relation to soil mineralogical composition described by Shaw *et al*. (1998) and Eldrigde (2003).

Concerning the concept of "ideal soil" proposed by Liebhardt (1981), the study also employed the base cation saturation ratio/BCSR approach (reviewed by Kopittke & Menzies, 2007; Chaganti & Culman, 2017) as well as the critical cation deficiency status/CCDS or sufficiency level of available nutrients/SLAN developed regionally by ISRI (Pusat Penelitian Tanah, 1983) and generally accepted criteria based on Australian Soil (Aitken & Scott, 1999; Bruce, 1999; Gourley, 1999).

Soil fertility status was determined according to Soil Fertility Assessment based on the Five Major Soil Chemical Properties, TOR P3MT Type B: Capability Survey for Land Suitability (Pusat Penelitian Tanah, 1983). The land suitability evaluation was performed through matching land-climatic properties to the required condition for irrigated rice crops following the Food and Agriculture Organization/FAO Land Suitability Evaluation 1976 (FAO, 1976) modified by the Indonesian Center for Agricultural Land Resources Research and Development/ICALRRD (Ritung *et al.* 2011) as shown in Table 3.

Table 2. ISRI's soil chemical properties criteria

Soil Chemical Properties	VL	L	M	H	VH
C (%)	<1.00	1.00-2.00	2.01-3.00	3.01-5.00	>5.00
N (%)	<0.1	0.1-0.2	0.21-0.5	0.51-0.75	>0.75
C/N	<5	5-10.	11-15.	16-25	>25
P_2O_5 Olsen (ppm)	<4.5	4.5-16.5	16.6-22.8	>22.8	-
K_2O HCl 25% (mg/100 g)	<10	10-20.	21-40	41-60	>60
CEC (me/100 g)	<5	5-16.	17-24	25-40	>40
Exchangeable base:					
K (me/100 g)	<0.2	0.2-0.3	0.4-0.5	0.6-1.0	>1.0
Na (me/100 g)	<0.1	0.1-0.3	0.4-0.7	0.8-1.0	>1.0
Mg (me/100 g)	<0.4	0.4-1.1	1.2-2.0	2.1-8.0	>8.0
Ca (me/100 g)	<2	2-5.	6-10.	11-20.	>20
Base Saturation (%)	<20	20-35	36-50	51-75	>75
pH H_2O:					
SA$_c$	A$_c$	MA$_c$	N	MA$_l$	A$_l$
<4.5	4.5-5.5	5.6-6.5	6.6-7.5	7.6-8.5	>8.5

Note: VL: very low, L: low, M: medium, H: high, VH: very high, SA$_c$: strong acidity, A$_c$: acid, MA$_c$: moderately acid, N: neutral, MA$_l$: moderate alkaline, A$_l$: alkaline

Table 3. Land suitability for irrigated rice based on ICALRRD criteria

Requirements for land use/characteristics	Land suitability class			
	S1	S2	S3	N
Temperature (tc)				
Average temperature (°C)	26 – 29	22 – 24 29 – 32	18 – 22 32 – 35	< 18 > 35
Water availability (wa)				
Humidity (%)	33 – 90	30 – 33	< 30 > 90	-
Root media (rc)				
Texture	smooth, moderately smooth	medium	moderately rough	Rough
Drainage	moderately drained, moderate	poorly drained, good	very poorly drained, moderately well-drained	excessively drained
Soil Depth (cm)	>50	40 – 50	25 – 40	<25

| Requirements for land use/characteristics	Land suitability class			
	S1	S2	S3	N
Nutrient retention (nr)				
CEC ~~land~~ (cmol/kg)	> 16	5 – 16	< 5	-
Base saturation (%)	> 50	35 – 50	< 35	-
pH H$_2$O	5.5 – 7.0	4.5 – 5.5	< 4.5	-
		7.0 – 8.0	>8.0	
C-organic (%)	> 2.0	0.8 – 2.0	< 0.8	-
Sodicity (xn)				
ESP (%)	< 20	20 – 30	30 – 40	> 40
Toxicity (xc)				
Salinity (dS/m)	< 2	2 – 4	4 – 6	> 6
Nutrients Available (na)				
N total (%)	medium	low	very low	-
P$_2$O$_5$ (mg/100 g)	high	medium	low – very low	-
K$_2$O (mg/100 g)	medium	low	very low	-
Erosion hazard (eh)				
Slope (%)	< 3	3 – 5	5 – 8	> 8
Flood/inundation hazard (fh)				
Water level (cm)	25	25 – 50	50 – 75	> 75

RESULTS AND DISCUSSIONS

General Overview of Study Area: Geological Settings, Physiography, and Soil Formation

The development of soils and their properties located downstream of the river, about the pedogenetic process, is influenced by the characteristic of soil and rock at an elevated upstream location. The geological, land system and soil map of the study location are presented in Figure 2. The soil in the study site developed adjacent to the estuary of Batui and Bakung rivers in Qa/Quarternary alluvium formation consisting of mud, sand, and cobbles that overlying Bongka/Tmpa formation. From a physiographical perspective (RePPProt, 1987; Figure 2; Table 4), the study site is located at relatively flat alluvial plains on the form of coalescent estuarine or riverine plains. According to the combination of the topographic and geological map, Batui and Bakung river is originated along with the old cretaceous-palaeocene mafic and ultramafic complexes (Ku formation) and passing through tertiary sediments including Salodik/Tems, Poh/Tomp, Kintom/Tmpk, and Tmpb formation (Silver *et al.* 1983; Surono *et al.* 1993; Parkinson, 1998). The mafic and ultramafic formations which are the part of East Sulawesi Ophiolite Belt (Circum Pacific Phanerozoic multiple ophiolite belts) contain mostly of lherzolite and harzburgite. Olivine was found to appear as the prime mineral, combined with a lesser amount of orthopyroxene, clinopyroxene, and minor spinel (Silver *et al.* 1983; Hall & Wilson, 2000; Kadarusman *et al.* 2004). On the other hand, Surono *et al.* (1993), Hall & Wilson (2000), and Martosuwito (2012) reported that the tertiary sediments as the constituent of Banggai-Sula and Tukang Besi Continental Fragments constituted primarily of limestone with marl intercalation (Tems), marl with limestone intercalation (Tomp), sandy marl and sandstone (Tmpk), and conglomerate, sandstone, silt, marl, and limestone (Tmpb).

At the upper range, mafic and ultramafic parent rocks gave rise to the high Fe and Mg soil (Anda, 2012; Fu *et al.* 2012). Excessive Fe-bearing minerals released from weathered parent material in the tropical region lead to the formation and accumulation of low activity clay in the form of cambic (Van der Ent *et al.* 2016), kandic (Tufaila *et al.* 2011), or oxic horizon (Tashakor *et al.* 2018; Becquer *et al.* 2001). Meanwhile, soil containing high Ca developed from marine

calcareous material such as limestone and marl (Sağlam & Dengiz, 2015). Besides their difference in the diagnostic horizon (argillic for alfisols, cambic for inceptisols), the typical hapludalfs and eutrudepts soils at the higher location shown high base saturation, which might represent elevated Ca (and/or Mg) content at the soil horizon (Zilioli et al. 2011; Mulyani et al. 2015; Sağlam & Dengiz, 2015; Graham et al. 2017).
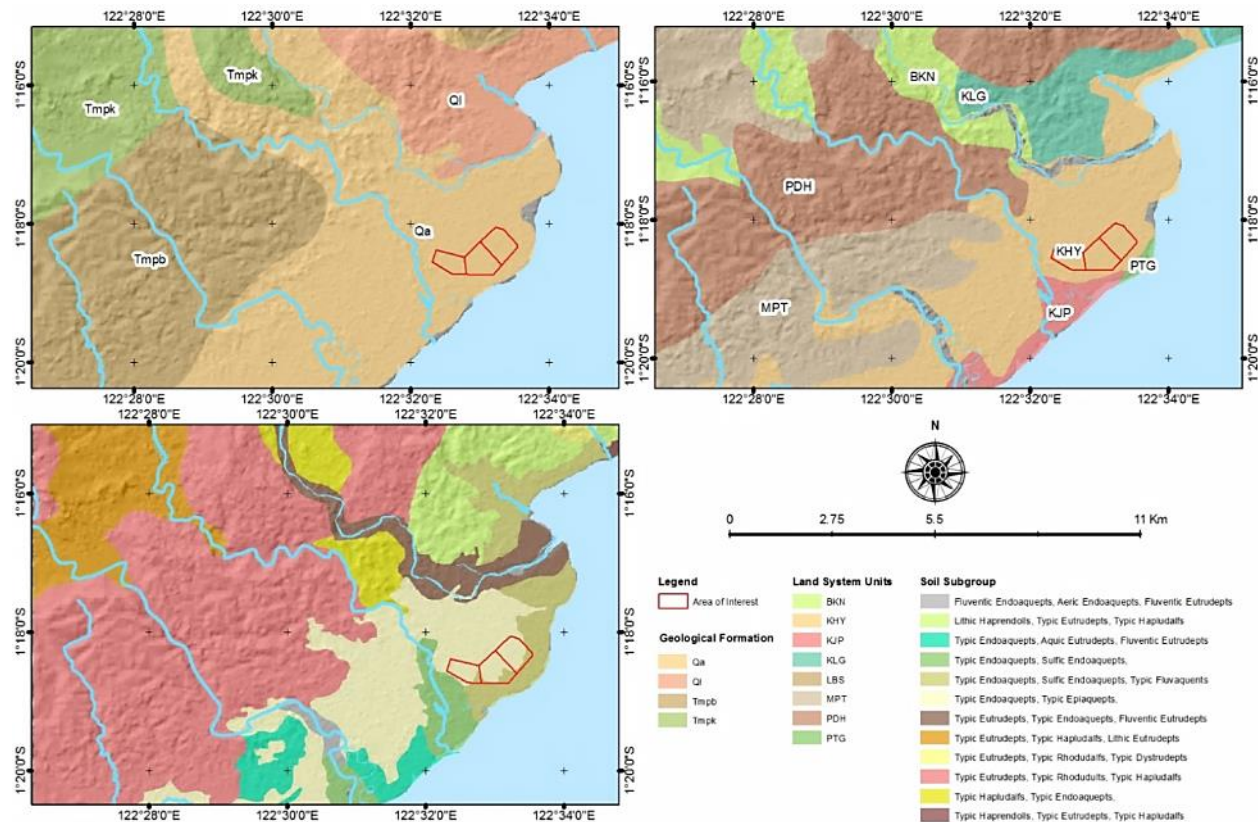
Figure 2. The geological formation, land system, and soil map of the study location

**Table 4.** Physiographical description of study location and its surrounding areas (RePPProT 1987)

Land Unit Symbol	Land Unit Name	Landform	General Description	Lithology
PTG	Puting	Beaches	Coastal beach ridges and swales	Alluvium, recent marine
KJP	Kajapah	Tidal Swamps	Inter-tidal mudflats under halophytes	Alluvium, recent estuarine-marine
KHY	Kahayan	Alluvial Plains	Coalescent estuarine/riverine plains	Alluvium, recent estuarine-marine; alluvium, recent riverine; peat
BKN	Bakunan	Alluvial Valleys	Minor valley floors within hills	Alluvium-recent riverine
MPT	Maput	Hills	Asymmetric non-orientated sedimentary ridges	Sandstone; conglomerate; mudstone; shale
KLG	Kalung	Hills	Karstic hills over marble and limestone	Marble; limestone
PDH	Pendreh	Mountains	Asymmetric broadly dissected sedimentary ridges	Sandstone; siltstone; mudstone; shale; conglomerate

The soil at the study site is classified as typic endoaquepts and typic epiaquepts based on USDA soil taxonomy (Soil Survey Staff, 2014; BBSDLP, 2020; Figure 2). This type of soil has a

cambic horizon and developed at a seasonally waterlogged (classified as epiaquepts) and permanently inundated (classified as endoaquepts), in this case, it is located on the estuary or riverine alluvial parent material (RePPProT, 1987; Soil Survey Staff, 2014; Figure 2; Table 4).

The elevation profile presented in Figure 3 supports the data stated above, which indicates the study site is located at the river and coastal backswamps. In this area, the particles and ions consisted of heterogeneous parent materials transported periodically from the upper range by river stream and flood also converged with marine sediment deposited by tidal fluctuation. Under continuous litterfall production from the mangrove ecosystem, providing organic material and maintaining redox interface, resulting in sedimentary pyrite occurrence (Aragon & Miguens 2001; Souza-Júnior et al. 2008; Ding et al. 2018) as indicated by the presence of sulfic endoaquepts in Figure 2.
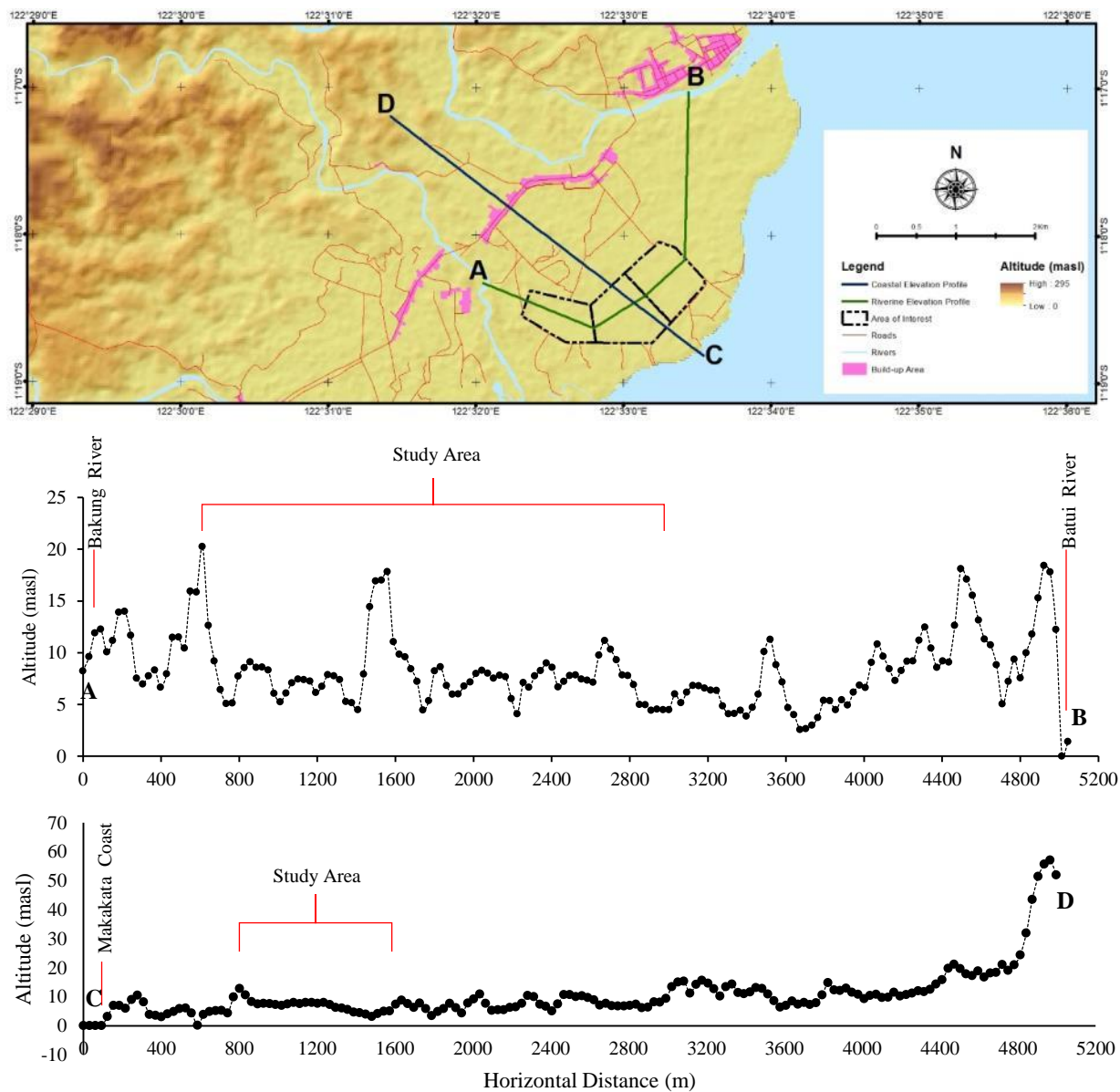
Figure 3. Elevation profile (derived from ASTER) of the study area observed from (A-B) riverine and (C-D) coastal transects

Although the suborder and great group prefix-name only concern the aspect of saturation (Soil Survey Staff, 2014), the chemical composition approximation of this alluvial soil can be deduced back either from ultramafic or calcareous outcrops in the upstream as a source of their parent material. Through the process of erosion and leaching, soil particles and rock fragments, and the individual cations/anions were loaded and deposited adjacent downstream to the river and flooding pathways. Regarding the plant requirements, mafic/ultramafic derived soils are often experiencing the lack of available K since their parent materials did not contain a considerable amount of K-bearing minerals (Ecchevarria, 2017; Kadarusman *et al.* 2004). On the other hand, calcareous derived soil exhibited a relatively higher K content (Moraetis *et al.* 2016). Thus, soil chemical properties such as total and exchangeable K content can be sufficient not only to assess the fertility status required by plants but also to differentiate the origins of the soil parent material.

Soil Morphological and Physicochemical Properties

Table 5 presents the soil's morphological, physical, and chemical properties. The hue of 2.5, especially for land unit B, indicates the gley soil with poor drainage, which was possibly saturated for an extended period (Fiedler & Sommer, 2004). During inundation, the decrease in oxygen content will cause the reduction of oxidized iron (Fe^{3+}) and appearing bluish or grayish color (DeLaune & Reddy, 2005; Craft, 2016). Furthermore, after the company management collapsed, the site was abandoned and drained permanently. This cause the gley color did not reach the soil color of 5/1 to 7/2. The variability of Munsell's value and chroma shown in each observed soil denoting the alteration of gley color simultaneously with the increasing of redness/oxidized Fe, masked by a diverse content of organic matter (Torrent *et al.* 1983; Gunal *et al.* 2008; Viscara Rossel *et al.* 2010; Moritsuka *et al.* 2014).

The soil structure was shown as massive to prismatic forms. Even though the structure was observed at the soil surface, their exhibited pattern also interestingly in accordance with the model of subsoil structure development proposed by Vervoort *et al.* (1999), particularly for saturated and frequently saturated horizons.

The shrimp pond requires prolonged saline or brackish water saturation to sustain its production, consequently accumulating elevated Na in soil sediment (Flaherty *et al.* 2000; Hossain *et al.* 2013; Kabir *et al.* 2015). High exchangeable Na and salinity have still existed in the soil after the shrimp pond abandonment, for instance, reported by Towatana *et al.* (2003) and Tanavud *et al.* (2010). Although the study area was formerly operated as a shrimp pond, the exchangeable Na was classified as medium in land units of A and B. Surprisingly, low level of the exchangeable Na was observed in land unit C. The Na saturation is averaging at 1.80±0.60 percent. Combined ESP, SAR, and salinity value were also detected outside the saline, sodic, and saline-sodic soil range (Abrol *et al.* 1988; Spark, 2003). This condition suggested that the entire soils at the study site undegoes sufficient leaching since its abandonment.

Soil pH is classified as moderately acid (land unit A and C) to neutral (land unit B) with an average of 6.33±0.31. Soil CEC was observed as a medium in entire land units. The total K content (K_2O 25% HCl) is classified as medium. Meanwhile, exchangeable K observed in this study was below the detection level. All exchangeable Mg were recorded very low; oppositely, the exchangeable Ca's saturation was immensely larger than other cations. Despite the fertilization and amelioration conducted during pond operation (Boyd & Daniels, 1994; Adhikari, 2003; Mustafa *et al.* 2020), this condition indicated that the alluvial material in the study site originated mostly of calcareous than mafic/ultramafic soil material. Devnita (2009)

was also reported similar chemical composition on typic dystropepts developed from volcanic origin and coral reefs.

The clay to CEC ratio (CCR) is detected varying from 0.35 to 0.36 mol_c/kg clay in land units of B and C. This value, according to Shaw (1998), corresponds to mixed clay mineralogies. Land unit A, differently, having the CCR of 0.63 molc/kg clay, attributed to mixed clay mineralogies with a higher proportion of montmorillonite or smectite (Shaw, 1998; Eldrigde, 2003). The occurrence tendency for higher smectite content is also supported by total K possessed by land unit A, which was about 1.4 to 1.5 times higher than other land units. This fact suggested that the area over the land unit A apparently received more marl-derived material than land units of B and C. Further research is needed to ascertain the origin of the alluvial parent material from the soil in the study location.

The importance of soil organic and fine earth fraction composition in relation to the soil exchange capability is partially shown in this study. Land unit A exhibited the highest CEC, N, and sand content compared to others. However, this land unit also had the lowest clay content and CN ratio, also having lower C content than land unit B. This condition suggests the CEC in the land unit A, besides its higher montmorillonite content, is also possibly composed of a relatively larger fraction of mature organic matter than other land units. Grand & Lavkulich (2012) noted that in the mineral soil, higher sand content corresponded to the increase of organic material decomposition susceptibility. The lower protection by clay particles regardless of their nature (high or low clay activity) might lead to higher microbial activity, releasing more C to and available N outside of the organic tissues (Zinn et al. 2005; Zinn et al. 2007).

Table 5.   Soil physical, chemical, and morphological properties

Soil Properties	Land Unit A	Land Unit B	Land Unit C	Average
Morphological Properties				
Munsell's soil color	2.5Y 4/2 Dark grayish brown	2.5Y 5/3 Grayish brown	2.5Y 3/2 Very dark grayish brown	
Structure	Massive	Prism	Prism	
Surface rock fragments	Few	Few	Few	
Physical Properties				
Texture	Clay loam	Clay	Clay	
Sand (%)	30	10	21	
Silt (%)	39	21	21	
Clay (%)	31	68	57	
Chemical Properties				
C (%)	2.19 (M)	2.35 (M)	2.16 (M)	2.23±0.10
N (%)	0.14 (L)	0.06 (VL)	0.09 (VL)	0.10±0.04
C/N	16 (H)	39 (VH)	25 (H)	26.67±11.59
P_2O_5 Olsen (ppm)	15.33 (L)	13.50 (L)	11.04 (L)	13.29±2.15
K_2O HCl 25% (mg/100 g)	40.72 (M)	28.96 (M)	27.62 (M)	32.43±7.21
CEC (me/100 g)	19.47 (M)	23.75 (M)	20.49 (M)	21.24±2.24
Clay to CEC ratio ((mol_c/kg clay)	0.63 (MCM)	0.35 (MC)	0.36 (MC)	0.45±0.16
Exchangeable base ($cmol_c$ kg^{-1}) :				
K	n.d. (VL)	n.d. (VL)	n.d. (VL)	n.d.
Na	0.39 (M)	0.54 (M)	0.23 (L)	0.39±0.16
Mg	1.78 (VL)	1.69 (VL)	0.92 (VL)	1.46±0.47
Ca	8.23 (M)	6.68 (M)	4.63 (L)	6.51±1.81
Base Saturation (%)	53.42 (H)	37.52 (M)	28.21 (L)	39.72±12.75
Individual Base Cation Saturation (%) :				
K	0.00	0.00	0.00	0.00±0.00
Na	2.00	2.27	1.12	1.80±0.60

Soil Properties	Land Unit A	Land Unit B	Land Unit C	Average
Mg	9.14	7.12	4.49	6.92±2.33
Ca	42.27	28.13	22.60	31.00±10.14
Percentage between cation				
Ca/K	~	~	~	~
Ca/Mg	4.6/1	4/1	5/1	4.5/1
Ca/Na	21/1	12/1	20/1	17.7/1
Mg/K	~	~	~	~
Mg/Na	4.6/1	3/1	4/1	4/1
Na/K	~	~	~	~
Exchangeable Sodium Percentage/ESP (%)	2.00	2.27	1.12	1.80±0.60
Sodium Absorption Ratio/SAR	0.17	0.26	0.14	0.19±0.06
Salinity (dS/m)	2.51	2.74	1.21	2.15±0.83
pH H_2O	6.4 (MAc)	6.6 (N)	6.0 (MAc)	6.33±0.31

Note: Letter inside the brackets indicates soil properties status: VL: very low, L: low, M: medium, H: high, VH: very high, SAc: strong acidity, Ac: acid, MAc: moderately acid, N: neutral, MAl: moderate alkaline, Al: alkaline, n.d.: not detected, MC: mixed clay mineralogies; MCM: mixed clay mineralogies with a higher proportion of montmorillonite.

Soil Fertility Status

According to the BCSR approach reviewed by Chaganti & Culman (2017) and Kopittke & Menzies (2007), an ideal soil cation saturation was postulated to having around 60 to 75% for Ca, 10 to 20% for Mg, and 2 to 5% for K. The transformation for cation saturation ratio resulting in Ca:Mg ratio of 6.5:1, Ca:K of 13:1, and Mg:K of 2:1. The entire cations in Table 5 fell below ideal ratios based on the BCSR model. Anda (2012) and Assefa (2021) found a similar result, stating that the BSCR criteria are very limited to implement in tropical soil. They argued that accomplishing the ideal proportion of cation can not guarantee to achieve maximum crop growth. This condition undergoes owing to the lack of knowledge of exact cations concentration to sufficiently fulfilled crop requirements.

Nevertheless, recent reports also recorded perceived positive impacts and long-term use of BCSR among many American farmers (Brock *et al.* 2020; Culman *et al.* 2021) as well as its continuing efficacy studies (Souza *et al.* 2016; Bonomelli *et al.* 2019; Chaganti *et al.* 2021). Some researchers and soil scientists designated that the BCSR approach is also essential in terms of lime, gypsum, soil acidity, and cation competition study (Webster 1985; van Biljon *et al.* 2007; Wood & Litterick, 2017; Culman *et al.* 2021). Biswas *et al.* (2019) suggested that (Ca + Mg)/K ratiogoverned the grain yield of rice. At low salinity conditions, Ca was found to regulate Na, K, and their ratio in rice roots and shoots (Wu & Wang, 2012). In Table 4, Ca/K and Mg/K saturation ratios were very high due to very low exchangeable K concentrations. The (Ca + Mg)/K ratio also can not be calculated due to very low exchangeable K. The imbalance level of cations in soil solution can influence plant growth and development (Hogue *et al.* 1983; Ho & Papadopoulos, 2003; Ding *et al.* 2006). Excessive Ca concentration may compete with other cations in soil and root complex, thus, disrupting their availability (Liu *et al.* 2021) and uptake (Aslam *et al.* 2003; Del Amor & Rubio, 2009). This condition indicated that K and Ca uptake from soil at the study site are also hampered by Ca.

The general CCDS/SLAN based on Australian soil is in the range of 0.5 to 1.5 cmolc kg−1 for Ca, 0.2 to 0.3 cmolc kg−1 for Mg, and 0.2 to 0.5 cmolc kg−1 for K (Aitken & Scott, 1999; Bruce, 1999; Gourley, 1999). Meanwhile, CCDS/SLAN developed by ISRI (Pusat Penelitian Tanah, 1983) is about 6.0 to 10.0 cmolc kg⁻¹ of Ca, 1.1 to 2.0 cmolc kg⁻¹ of Mg, and 0.4 to 0.5 cmolc kg ⁻¹ of K, and 0.4 to 0.7 cmolc kg⁻¹ of Na (classified as medium in ISRI's guidelines; Table 2; Eviati and Sulaeman, 2009). Based on both thresholds ranges, all exchangeable K in the soil at

the study area were detected below the threshold, which requires K fertilization. Without considering exchangeable K, the entire land units satisfied the general sufficiency level, whereas the land units C fell below ISRI's sufficiency level.

Table 6. Soil fertility status of the study area

| Land Unit	CEC	Base Saturation	P_2O_5, K_2O, Organic-C	Soil Fertility Status
A	M	H	Other Combination	Low
B	M	M	Other Combination	Low
C	M	L	Other Combination	Low

Note: Letter inside the brackets indicates soil properties status: VL: very low, L: low, M: medium, H: high, VH: very high.

Using soil fertility assessment based on the five major soil chemical properties (Pusat Penelitian Tanah, 1983) resulted in a low level of soil fertility for entire land units at the study area, as shown in Table 6. Although the CEC, base saturation, K_2O, and organic-C in the land unit of A and B reached medium and high levels, the P_2O_5 content was recorded low. In land unit C, the low status of soil fertility is caused by the combination of low P_2O_5 and base saturation. Thus, phosphate fertilization is required to increase soil fertility in land units of A and B. Meanwhile, a balanced addition of Ca, Mg, and K are critical to enhancing soil fertility in land unit C.

Land Suitability for Irrigated Rice

Temperature and humidity were the main climate factors governing rice growth and development. The changes of both factors are widely discussed influencing rice yield (Julia & Dingkuhn, 2013; Liu *et al*. 2013; Tao & Zhang, 2013; Ghadirnezhad & Fallah, 2014; Yang *et al*. 2017; Mahmood *et al*. 2021). Other researchers reported a significant relation with other physiological parameters and rice agronomic traits, including rice growth (Azuma *et al*. 2007; Sánchez-Reinoso *et al*. 2014; Liu *et al*. 2017; li *et al*. 2019), photosynthesis, leaf area index (Stuerz & Asch, 2019; Mahmood *et al*. 2021), transpiration (Kaushal & Ghosh, 2018), pollen grain germination (Matsui *et al*. 1997), milling and cooking quality (Li *et al*. 2018).

ICALRRD (Ritung *et al*. 2011) formulated optimum temperature and humidity ranges suitable (S1) for cultivating irrigated rice were 26 to 29 °C and 33 to 90 %, respectively (Table 3). Based on Meteorological Station Class III Syukuran Aminudin Amir, Banggai data (Figure 4), the annual average temperature and humidity were 28.16 °C and 77.11 %, respectively, categorized as very suitable (S1). All of the monthly average humidity (Figure 4) were classified as S1 (very suitable). The nine months (February to October) temperatures were very suitable (S1) for irrigated rice cultivation. Meanwhile, three months later (November to January) is considered hotter than the optimum temperature range, thereby classified as moderately suitable (S2).
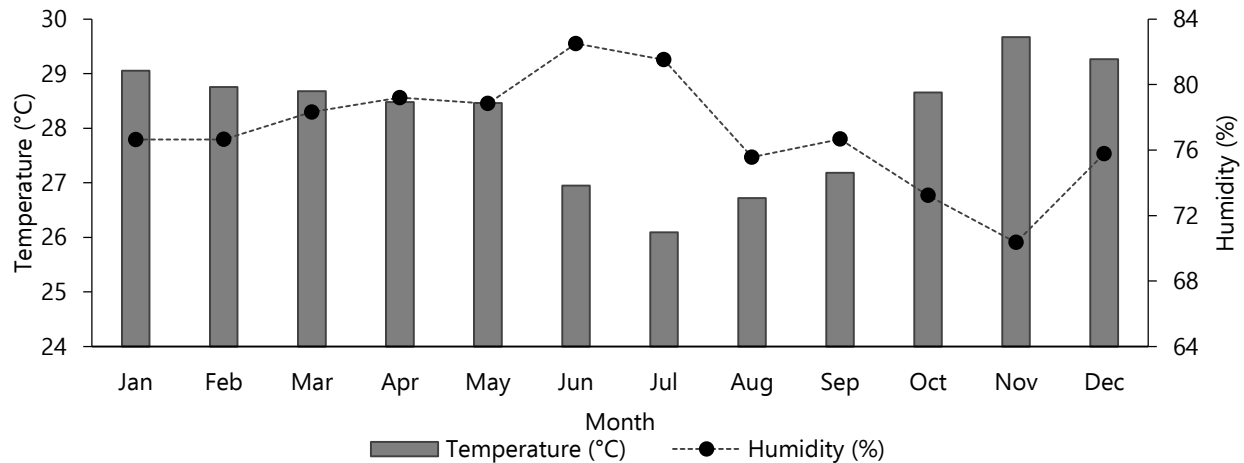
Figure 4. Averaged temperature and humidity (2019 – 2020) of the study site obtained from the Meteorological Station Class III Syukuran Aminudin Amir – Banggai

The nutrients availability (na) is a pivotal factor limiting all land units observed in this study. The entire land units were categorized as marginally suitable (S3) due to low phosphorus content below the threshold required to sustain optimum irrigated rice productivity. The land units of B and C were also recorded possessing very low nitrogen levels, which was classified as similar (S3). Oppositely, all land units exhibited a moderate level of K_2O, which is considered sufficient (S1) to establish sustained cultivation of irrigated rice.

Land units of C and B were also constrained from nutrient retention/nr (S3 and S2, respectively), owing to the low base saturation. CEC, pH (soil reaction), and organic C were classified as very suitable (S1), similar to K_2O content. Regarding all limiting nutrient retention factors, land unit A is considered very suitable (S1) for cultivating irrigated rice without further improvement.

Concerning previous land use management, the study area showed a relatively low ESP and SAR, thereby classified as very suitable (S1) for irrigated rice cultivation. Moreover, more stress must be appointed to toxicity factors in land units of A and B. These land units had a reasonable amount of salt adequate to decrease the actual suitability to S2 level.

Fertilization and amelioration are required to overcome all limiting factors related to nutrient availability and retention possessed by soil in the study site. As discussed before, base saturation did not show the actual levels of each cation available for plant in soil solution and their comparison one to another. Hence, the entire land units require N, P, K and Mg fertilization to counter cation imbalance (Table 8). This action can increase their total and exchangeable content in the soil. For instance, all land units had sufficient K_2O content; however, their exchangeable forms were recorded very low (undetectable through the titration method). K fertilization will recover K available in soil solution, hence also increasing soil-K reserve (Rutkowska, 2013; Sanyal et al. 2019). On the other hand, amelioration could improve the soil chemical and physical properties. In saline conditions, gypsum and organic amendments combination significantly decreased electrical conductivity and SAR of salt affected soil (Jalali & Rajbar, 2009) while also increased rice root length and yield (Shaaban et al. 2013). Two years of organic fertilizer application is reported to alleviate severe saline soil become more suitable for rice growth (Zhang et al. 2021).

Table 7. Actual land suitability classes and subclasses of the study area

Requirements for land use/characteristics	Actual suitability		
	A	**B**	**C**
Temperature (tc)	**S1**	**S1**	**S1**
Average temperature (°C)	S1	S1	S1
Water Availability (wa)	**S1**	**S1**	**S1**
Humidity (%)	S1	S1	S1
Root Media (rc)	**S3**	**S1**	**S3**
Texture	S1	S1	S1
Drainage	S3	S1	S3
Soil Depth (cm)	S1	S1	S1
Nutrient Retention (nr)	**S1**	**S2**	**S3**
CEC land (cmol/kg)	S1	S1	S1
Base saturation (%)	S1	S2	S3
pH H_2O	S1	S1	S1
Organic-C (%)	S1	S1	S1
Nutrients Available (na)	**S3**	**S3**	**S3**
N total (%)	S2	S3	S3
P_2O_5 (mg/100 g)	S3	S3	S3
K_2O (mg/100 g)	S1	S1	S1
Sodicity (xn)	**S1**	**S1**	**S1**
ESP (%)	S1	S1	S1
Toxicity (xc)	**S2**	**S2**	**S1**
Salinity (dS/m)	S2	S2	S1
Erosion Hazard (eh)	**S2**	**S2**	**S3**
Slope (%)	S2	S2	S3
Flood/Inundation Hazard (fh)	**S2**	**S2**	**S2**
Water level (cm)	S2	S2	S2
Subclass	**S3-rc,na**	**S3-na**	**S3-rc,nr,na,eh**

The drainage problems were identified in the land units of A and C, classified as marginally suitable (S3) for rice cultivation. The water levels for the entire land units were recorded as moderately suitable (S2). This condition denoted the saturation that previously occurs in the soil at the study site. Maintaining and regulating water supply is the crucial factor for successful irrigated rice cultivation in this area. The study site is located in an estuary of the Batui and Bakung rivers. Both river's catchment area covering approximately about 67,078.76 hectares (BPDASHL, 2021), supplied with annual precipitation of 4,669.50 mm (BPS Banggai, 2021). Considering the canal established by previous land users, the farmers can improve their irrigation management by building a floodgate/sluice to regulate water in and out. Unlike rainfed rice, the irrigated rice requires an adequate amount of water during its critical stages, such as anthesis and grain filling. Insufficient water supply can cause a decrease in rice yield; otherwise, appropriate water management can increase rice efficiency in utilizing water (Singh et al. 2013; Thakur et al. 2013; Pascual & Wang, 2017). Moreover, irrigation in rice was also critical in governing the leaching process. This process consequently lowered soil salinity and developed the soil to be more appropriate to rice cultivation (Carmona et al. 2010).

Table 8. Potential land suitability classes/subclasses and their improvement regarding their actual limitation factors

Land Unit	Actual Suitability Classess/Subclasses	Improvement	Potential Suitability Classess/Subclasess
A	S3-rc,na	Water irrigation, NPKMg fertilization, gypsum+organic amelioration, slope flattening	S1
B	S3-na	NPKMg fertilization, gypsum+organic amelioration, slope flattening	S1
C	S3-rc,nr,na,eh	Water irrigation, NPKMg fertilization, organic amelioration, slope flattening /cut-filling	S1

CONCLUSION

The soil in the study area formerly utilized for shrimp pond has a great potential to be developed as irrigated rice field. This soil derived from the alluvial site of calcareous-marl parent material located at saturated backswamp, then permanently drained. The soil at the study area is considered marginally suitable for irrigated rice cultivation by assessing its physicochemical properties and land-climate characteristics Prolonged saline/brackish water inundation from previous management had a relatively low influence on soil salinity, SAR, and ESP. Furthermore, nutrient availability acted as the critical factor limiting rice growth and development in the soil in the study area. Further improvements in soil physicochemical properties such as fertilization, amelioration, slope flattening/cut-filling, and water management can maximize its suitability.

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