

Land Suitability Evaluation for Biosaline Paddy Rice Cultivation in Coastal Areas of Sayung District, Demak Regency, Indonesia

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ABSTRACT

This study evaluated the suitability of land for biosaline paddy rice cultivation in Sayung District, Demak Regency, Indonesia, and identified major limiting factors and potential improvement measures. Field surveys and laboratory analyses were conducted to assess climatic conditions, soil physical properties, soil chemical characteristics, salinity levels, and slope conditions. Land suitability was determined using a matching method by comparing observed land characteristics with the land requirements of irrigated paddy rice. Suitability classes were categorized as highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N). The results showed that climatic factors, including temperature, rainfall, and relative humidity, as well as most soil physical characteristics, were generally favorable for paddy rice cultivation and fell within the S1–S2 suitability classes. However, several soil-related constraints limited overall land suitability. The main limiting factors were low nitrogen (N), phosphorus (P), and potassium (K) availability, elevated soil salinity, and deficiencies of calcium (Ca) and magnesium (Mg) in certain areas. Consequently, several land units were classified as S3-na and S3-xc. Potential land improvement was evaluated through the application of P_2O_5 and K_2O fertilizers and Ca–Mg-based soil amendments. These treatments improved nutrient availability, reduced salinity-related constraints, and increased land suitability from S3 to S2 classes. The findings indicate that appropriate nutrient management and soil amelioration practices can significantly enhance land quality and support sustainable biosaline paddy rice production in coastal areas affected by salinity.

Keywords: biosaline paddy rice; land amelioration; land suitability evaluation; Sayung District; soil fertility

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a strategic commodity and the primary staple food for more than 95% of Indonesia's population. Consequently, efforts to increase rice production continue to be prioritized to meet the growing food demand driven by population growth, increasing per capita consumption, and Indonesia's commitment to achieving food security and self-sufficiency under the Indonesia Emas 2045 agenda (Masganti et al., 2020). According to data from the Indonesian Central Bureau of Statistics (BPS), national rice production reached approximately 53.14 million tons of milled dry grain in 2024, harvested from about 10.05 million hectares. Nevertheless, this production level declined compared to the previous year due to reductions in harvested area and the increasing impacts of climate change on agricultural systems.

One of the major challenges to sustaining rice production is the degradation of agricultural land quality in coastal regions caused by seawater intrusion, which leads to soil salinization. Soil salinity is a global issue affecting more than 800 million hectares of agricultural land worldwide (FAO, 2005). In Indonesia, saline-affected land is estimated to cover approximately 440,300 hectares,

consisting of 304,000 hectares of moderately saline land and 140,300 hectares of saline land (Usnawiyah et al., 2021). The expansion of saline areas is closely associated with sea-level rise resulting from climate change and global warming, which accelerates seawater intrusion into coastal zones (Shukla et al., 2021).

Soil salinity is one of the primary constraints to rice cultivation because it reduces the availability of water and essential nutrients for plant growth. This condition results from increased concentrations of dissolved salts, particularly Na^+ and Cl^- ions, which induce osmotic stress, nutrient imbalance, and ionic toxicity in plants (Munns & Tester, 2008; Fahmi et al., 2023). In addition, saline soils are often characterized by low nitrogen and potassium availability and relatively high pH levels, which further limit nutrient uptake by crops (Machado & Serralheiro, 2017; Rengasamy, 2010). At salinity levels corresponding to an electrical conductivity (EC) of 6–12 dS m^{-1} , rice growth and productivity can be substantially reduced, as indicated by decreases in tiller number, chlorophyll content, photosynthetic rate, and grain yield (Mondal et al., 2013). Therefore, increasing soil salinity poses a serious threat to sustainable rice production and food security in coastal agricultural regions.

Sayung District, located in Demak Regency, Central Java, is one of the coastal areas in Indonesia experiencing significant environmental pressures due to tidal flooding, land subsidence, and increasing seawater intrusion. The relatively low topography of the area facilitates the movement of seawater inland, affecting surrounding agricultural lands. Previous studies have reported increasing soil and groundwater salinity in the coastal areas of Demak, resulting in declining land quality and reduced rice productivity (Marfai & King, 2008; Darmanto & Cahyadi, 2013; Sarah & Soebowo, 2018). However, information regarding the suitability of saline-affected land for rice cultivation in Sayung District remains limited, particularly studies integrating physical, chemical, and salinity-related soil characteristics within a comprehensive land evaluation framework.

Land suitability evaluation is an important approach for assessing the capability of land to support optimal crop growth and production. Through land evaluation, limiting factors such as salinity, soil pH, sodium content, nutrient availability, and soil physical characteristics can be identified, enabling the development of appropriate land management recommendations (Sys et al., 1991; Ritung et al., 2011). Furthermore, the results of land suitability assessment can provide a scientific basis for selecting salt-tolerant rice varieties, implementing suitable cultivation practices, and applying soil amendments and management strategies to mitigate the adverse effects of salinity (FAO, 2007; Machado & Serralheiro, 2017).

Given these circumstances, this study aims to evaluate the suitability of land for biosaline paddy rice cultivation in Sayung District, Demak Regency, identify the major limiting factors affecting land suitability, and propose potential improvement measures to enhance land suitability classes. The findings are expected to provide a scientific basis for the management of saline-affected lands and the development of adaptive rice cultivation systems in coastal environments, thereby supporting sustainable rice production and national food security.

2. MATERIAL AND METHODS

2.1 Research area

This study was conducted from September to December 2025 in Demak Regency, Central Java, Indonesia. Sayung District, located in Demak Regency, is one of the coastal areas along the northern coast of Java Island, situated between $6^{\circ}43'26''$ – $7^{\circ}09'43''$ S and $110^{\circ}27'58''$ – $110^{\circ}48'47''$ E. The district is bordered by Jepara Regency to the east, Kudus Regency to the south, Semarang City to the southwest, and the Java Sea to the north. Sayung District is widely recognized as one of the coastal regions affected by saline land problems resulting from seawater intrusion and frequent tidal flooding (*rob*), which have significantly influenced the physical and chemical properties of agricultural soils (BPS Demak Regency, 2024; Kurniawan et al., 2022).

Based on information provided by the Agricultural Extension Service Center of Sayung District, five villages were selected as study sites: Perampelan, Tambakroto, Pilangsari, Sidorejo, and

Banjarsari. These villages were chosen because they represent saline-affected agricultural areas with varying levels of soil salinity, making them suitable for evaluating land suitability for biosaline paddy rice cultivation. The variation in salinity conditions among the selected villages provided a representative basis for assessing land characteristics, identifying limiting factors, and developing appropriate land management recommendations.

2.2 Data Collection

This study employed a survey-based research method involving direct field observations and the collection of both primary and secondary data. Survey methods are widely used to obtain information and document existing conditions by observing phenomena directly within the study area and collecting factual data related to the environmental and socio-agricultural context of the research (Nazir, 1983; Doyle, 2020). Primary data collected in this study included soil texture, soil pH (H₂O), cation exchange capacity (CEC), organic carbon (C-organic), total nitrogen (N-total), available phosphorus (P-available), available potassium (K-available), and soil salinity (Done & Topp, 2000). Secondary data consisted of climatic variables, including air temperature, rainfall, and relative humidity (Marleila, 2005).

A total of ten agricultural land units were selected and evaluated. Each land unit exhibited distinct characteristics that could influence land suitability for rice cultivation, including water availability represented by annual rainfall (wa), oxygen availability reflected by drainage conditions (oa), temperature regime (tc), rooting media characteristics such as soil texture and effective soil depth (rc), nutrient retention capacity (nr) represented by cation exchange capacity (CEC), base saturation, soil pH, and organic carbon content, as well as erosion hazard (eh) and flood hazard (fh). All collected data were compiled and analyzed to assess land suitability. The evaluation was conducted by comparing the observed land characteristics with the land suitability criteria for agricultural crops published by the Indonesian Center for Soil and Agroclimate Research (*Pusat Penelitian Tanah dan Agroklimat*) (Ritung et al., 2011). This approach enabled the identification of limiting factors and the determination of land suitability classes for biosaline paddy rice cultivation in the study area.

2.3 Data analysis

The research process was divided into three main stages: data collection, parameter-based data classification, and presentation of the evaluation results. During the data collection stage, additional attributes were incorporated into the land unit maps to provide a clearer representation of the land characteristics associated with each evaluated parameter. These attributes served as the basis for assessing land suitability and identifying factors that influence crop growth and productivity.

Land suitability for biosaline paddy rice cultivation was determined using the matching method, which involves comparing observed land characteristics with the crop growth requirements. The evaluation adopted the Law of the Minimum proposed by Liebig, whereby the overall suitability class is determined by the most limiting factor affecting plant growth and development (Ritung et al., 2011). Laboratory analysis results and field observation data were matched against the land-use requirements specified in the land suitability evaluation criteria.

Based on this assessment, land suitability was classified into four categories: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) (Rendana et al., 2022).

The suitability class and subclass for each land unit were determined according to the identified limiting factors. Subsequently, spatial analysis was performed by integrating all evaluated land parameters within a geographic information system (GIS) environment. The resulting suitability data were overlaid with administrative maps and processed using ArcGIS software to generate spatial distribution maps of land suitability classes for paddy rice cultivation (Rahmawaty et al., 2011). These maps provided a visual representation of the spatial variability of land suitability across the study area and facilitated the identification of areas requiring specific land management interventions.

2.4 Observation and soil sampling

The study was conducted through five main stages: (1) determining the geographic coordinates of the observation sites, (2) conducting field observations and soil sampling, (3) performing laboratory analyses, (4) evaluating actual land suitability, and (5) assessing potential land suitability. Soil sampling was carried out at five observation points within each study area. At each observation point, three soil samples were collected to ensure representative characterization of soil conditions. Samples were obtained using a soil ring sampler at a depth of approximately 5–10 cm below the soil surface. This sampling depth was selected to represent the soil layer most directly influenced by cultivation practices and salinity conditions.

Prior to laboratory analysis, all soil samples were carefully prepared and handled to maintain their original properties. Plant residues and surface litter were removed to prevent contamination, and the samples were protected from direct sunlight during storage and transportation. These procedures were implemented to preserve sample integrity and ensure the reliability of laboratory measurements (Hardjowigeno, 2015; Indonesian Soil Research Institute, 2009).

The collected samples were subsequently analyzed to determine key soil physical and chemical properties relevant to land suitability evaluation, including soil texture, pH, cation exchange capacity (CEC), organic carbon content, nutrient availability, and salinity status. The analytical results were then used as the basis for determining both actual and potential land suitability classes for biosaline paddy rice cultivation in the study area.

Table 1. Location of land use evaluation area

No Village	Coordinates
1 Prampelan	6°57'28.64" S, 110°31'57.32" E
2 Tambakroto	6°57'14.86" S, 110°31'50.91" E
3 Pilangsari	6°57'18.38" S, 110°33'19.63" E
4 Sidorejo	6°53'46.17" S, 110°33'26.05" E
5 Banjarsari	6°52'37.03"S, 110°32'49.13" E

Note: S = South Latitude; E = East Longitude

Table 2. Land characteristics and land suitability characteristics of paddy rice

Land qualities/land characteristic	Land suitability class			
	Highly suitable	Moderately suitable	Marginally suitable	Not suitable
	S1	S2	S3	N
Temperature (C)	22-29	29-32	32-35	>35
Rainfall (mm/year ⁻¹)	1.500–2.500	1.000–1.500 ; 2.500–3.000	800–1.000 ; 3.000–4.000	<800 >4.000
Humidity (%)	70–80	80–85	85–90	>90
Drainage	Slightly impeded, moderate	Well drained	Poorly drained	Excessively drained
Soil texture	Fine, moderately fine	Medium	Moderately coarse	Coarse
Rough material (%)	<15	15-30	35-55	>55
Adequate depth (Cm)	>100	75-100	50-75	<50
Clay CEC (cmo/kg)	>16	5–16	<5	<20
pH H ₂ O	5.5–7.0	5.0–5.5 7.0–7.5	4.5–5.0 7.5–8.0	<4.5 >8.0
C-Organic (%)	> 1,2	0,8-1,2	<0,8	
N Total (%)	High	Moderate	Low	Very Low
P2O5 Olsen (ppm)	High	Moderate	Low	Very Low
K20 (ppm)	High	Moderate	Low	Very Low
Slope (%)	<3	3–8	8–15	>15
Erosion hazard	Very low	Low	Moderate	Heavy
Flooding	None	Rarely	Occasionally	Frequently
Surface rock (%)	<5	5-15	15-40	>40
Outcrop rock (%)	<5	5-15	15-25	>25

3. RESULTS

3.1 Study Area Description

Sayung District is located in Demak Regency, Central Java Province, Indonesia, along the northern coastal region of Java Island, between 6°43'26"–7°09'43" S and 110°27'58"–110°48'47" E. Demak Regency is bordered by Jepara Regency to the east, Kudus Regency to the south, Semarang City to the southwest, and the Java Sea to the north. The regency covers an area of approximately 996.94 km² and has a population of about 1.2 million inhabitants. Administratively, Demak Regency consists of 14 districts (*kecamatan*) and 249 villages/urban villages (*desa/keurahan*). Sayung District comprises 14 villages, namely Banjarsari, Bedono, Bintoro, Karangasem, Karangturi,

Kedungwaru, Klaling, Krandon, Ngemplak, Sayung, Sidorejo, Surodadi, Tugu, and Wonosari (BPS Demak Regency, 2025). Due to its location in the low-lying coastal zone of northern Java, Sayung District is highly vulnerable to seawater intrusion, tidal flooding (*rob*), and land subsidence. These environmental pressures have contributed to increasing soil salinity and land degradation, particularly in agricultural areas, making the district an important site for evaluating land suitability for biosaline paddy rice cultivation.



Area	Actual land suitability		Recovery exertion	Potential land suitability
	Subclass	Unit		
Tambakroto	S3-na	S3na-2	P2O5 Fertilization	S2na
		S3na-3	K2O Fertilization	S2na
Perampelan	S3-na	S3na-2	P2O5 Fertilization	S2na
		S3na-3	K2O Fertilization	S2na
Pilangsari	S3-na	S3na-2	P2O5 Fertilization	S2na
Banjarsari	S3, xc	S3xc-1	Ca and Mg Fertilization	S2xc
Sidorejo	S3-xc	S3xc-1	Ca and Mg Fertilization	S2xc

In contrast, Banjarsari and Sidorejo were classified as S3-xc (marginally suitable with salinity-related limitations), primarily due to elevated salinity levels and insufficient calcium (Ca) and magnesium (Mg) contents. Land improvement measures involved the application of Ca- and Mg-based ameliorants, which increased the suitability class to S2-xc (moderately suitable). Brady and Weil (2008) reported that calcium and magnesium contribute to improved soil structure, increased base saturation, and reduced adverse effects of soil salinity. Furthermore, Zhang et al. (2021) demonstrated that calcium can alleviate Na⁺ toxicity and stabilize cell membrane integrity under

saline conditions, while Liu et al. (2022) found that magnesium enhances photosynthetic performance and water-use efficiency under stress conditions. Consequently, the application of these ameliorants is expected to improve plant growth and support higher rice productivity in saline-affected areas. Overall, the potential land suitability assessment indicates that appropriate nutrient management and soil amelioration practices can substantially reduce the impact of major limiting factors, thereby enhancing the suitability of saline-affected land for sustainable paddy rice cultivation in Sayung District.

Table 4. Potential land recovery for Fosfor, Potassium, Kalsium dan Magnesium

Village	Soil Moisture Level		P available (ppm)	K available (%)	Mg available (cmol(+)/kg)	Ca available (cmol(+)/kg)
	0,5 mm	2 mm				
Tambakroto	25,1	26,3	5,3	6,4	5,7	6,9
Perampelan	30,5	29,5	6,4	8,6	6,7	6,4
Pilangsari	32,7	33,1	7,2	23,5	7,4	6,5
Banjarsari	28,5	28,9	26,3	45	4,1	3,9
Sidorejo	27,3	26,9	32,2	49,4	3,5	4,1

Based on Table 4, the potential land recovery assessment revealed variations in the concentrations of phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) among the observation sites. Soil moisture content within the 0.5 mm and 2 mm aggregate fractions was relatively high, ranging from 25.1% to 33.1%, indicating a favorable soil water-holding capacity capable of supporting paddy rice growth. Adequate soil moisture plays a crucial role in maintaining water availability and enhancing nutrient uptake by plants (Hillel, 2015). Furthermore, optimal moisture conditions facilitate nutrient diffusion and stimulate soil microbial activity, thereby improving nutrient cycling and availability (Brady & Weil, 2016). Lal (2018) also emphasized that appropriate soil moisture enhances the efficiency of P, K, Ca, and Mg utilization in agricultural soils.

Available phosphorus concentrations in Tambakroto, Perampelan, and Pilangsari were classified as low (S3), ranging from 5.3 to 7.2 ppm, indicating a potential limitation to root development and energy metabolism. In contrast, Banjarsari and Sidorejo exhibited considerably higher phosphorus levels (26.3–32.2 ppm), corresponding to the S1 category. Adequate phosphorus availability is essential for ATP formation, root development, and overall crop productivity (Brady & Weil, 2016). These findings suggest that phosphorus management remains a key factor in improving land suitability and sustaining rice production in the study area.

Potassium availability also varied among locations. Tambakroto and Perampelan showed very low potassium concentrations (6.4–8.6 ppm), resulting in an S3 classification, whereas Pilangsari contained 23.5 ppm K and was classified as S2. Higher potassium levels were recorded in Banjarsari and Sidorejo, ranging from 45.0 to 49.4 ppm and corresponding to the S1 category. Potassium plays a fundamental role in regulating cellular osmotic pressure, activating enzymes, and enhancing plant tolerance to environmental stresses (Marschner, 2012). Consequently, low potassium availability may limit plant growth and productivity, particularly under saline conditions.

Magnesium concentrations in Tambakroto, Perampelan, and Pilangsari ranged from 5.7 to 7.4 cmol(+) kg⁻¹ and were classified as S2 (moderately suitable). In comparison, Banjarsari and Sidorejo exhibited lower Mg concentrations, ranging from 3.5 to 4.1 cmol(+) kg⁻¹, resulting in an S3 classification. Magnesium is an essential component of chlorophyll molecules and plays a central

role in photosynthetic processes (Mengel & Kirkby, 1982). Therefore, insufficient Mg availability may reduce photosynthetic efficiency and limit crop performance.

A similar trend was observed for calcium. The Ca content in Tambakroto, Perampelan, and Pilangsari ranged from 6.4 to 6.9 cmol(+) kg⁻¹ and was classified as S2, whereas Banjarsari and Sidorejo contained lower concentrations of 3.9–4.1 cmol(+) kg⁻¹ and were categorized as S3. Calcium contributes to cell wall formation, root growth, and the maintenance of soil structural stability. The relatively low concentrations of Ca and Mg in several locations indicate the need for land improvement through the application of Ca- and Mg-based amendments or fertilizers to enhance soil fertility and support sustainable paddy rice production (Hardjowigeno & Widiatmaka, 2011).

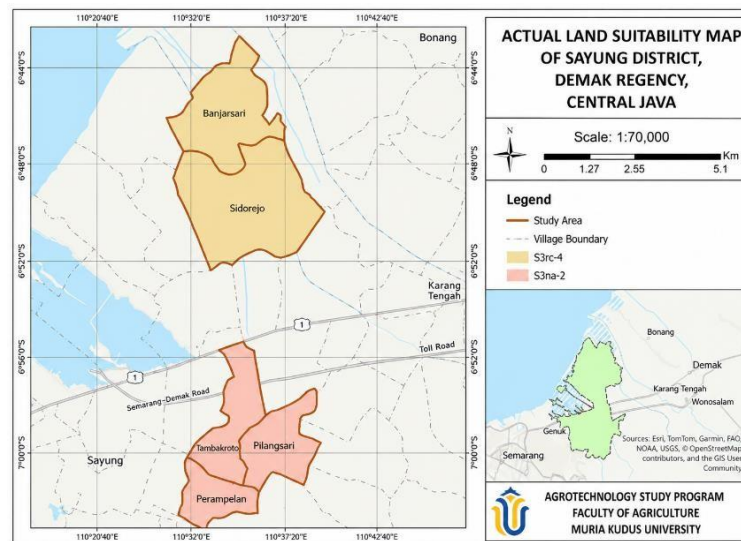


Figure 2. Map of Kudus Regency Actual land suitability

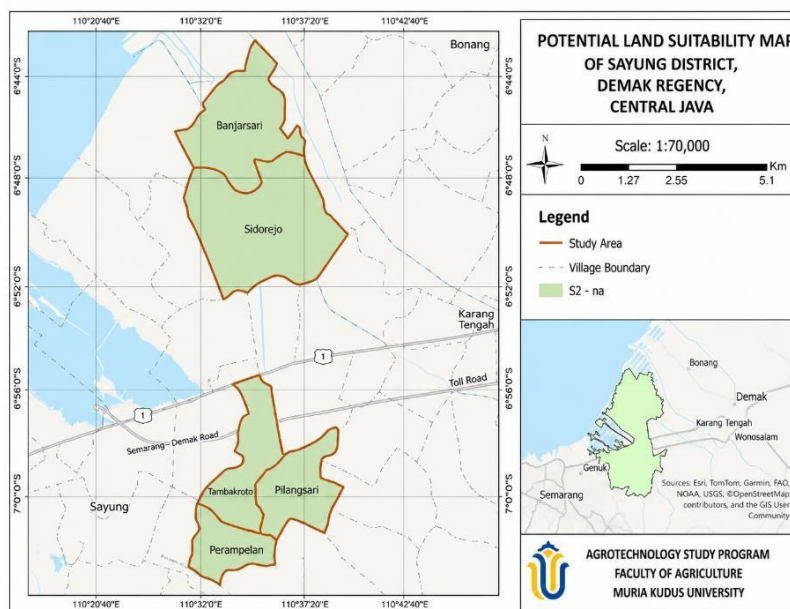


Figure 3. Map of Kudus Regency's potential land suitability

Land Characteristic	Tambakroto		Perampela		Pilangsari		Banjarsari		Sidorejo	
	Value	Class	Value	Class	Value	Class	Value	Class	Value	Class
Temperature (t)										
Mean Temperature (C)	28,32	S1	28,32	S1	28,32	S1	28,32	S1	28,32	S1
Water Availability (wa)										
Rainfall (mm/year)	2.482	S2	2.482	S2	2.482	S2	2.482	S2	2.482	S2
Humidity (%)	79,1	S1	79,1	S1	79,1	S1	79,1	S1	79,1	S1
Oxygen Availability (oa)										
Drainage	Agak	S1	Sedang	S1	Agak terhambat	S1	Agak terhambat	S1	Agak terhambat	S1
Root Compartement (rc)										
Soil texture	Agak halus	S1	Agak halus	S1	Agak halus	S1	Agak halus	S1	Agak halus	S1
Rough material (%)	1	S1	1	S1	0	S1	1	S1	0	S1
Soil depth (cm)	40	S1	43	S1	40	S1	40	S1	40	S1
Nutrient Retention (nr)										
CEC (cmol/kg)	41.44	S1	41.30	S1	40.85	S1	51.55	S1	51.55	
pH H2O	6,83	S1	6,99	S1	6,03	S1	5,70	S1	5,66	S1
C organic (%)	2.65	S1	2.45	S1	1.25	S1	2.06	S1	2.06	
Nutrient availability (na)										
N Total (%)	Sedang	S1	Sedang	S1	Sedang	S1	Sedang	S1	Sedang	S1
P2O5 Olsen (ppm)	Sangat rendah	S3	Sangat rendah	S3	Sangat rendah	S3	Tinggi	S1	Tinggi	S1
K2O (ppm)	Sangat rendah	S3	Sangat rendah	S3	Rendah	S2	Sedang	S1	Sedang	S1
Mg (cmol+)/kg)	Sedang	S2	Sedang	S2	Sedang	S2	Rendah	S3	Rendah	S3
Ca (cmol+)/kg)	Sedang	S2	Sedang	S2	Sedang	S2	Rendah	S3	Rendah	S3
Toxinity (xc)										
Salinity (Ds/m)	2,7	S2	2,6	S2	3,7	S2	4,1	S3	6,8	N
Erosion Hazard (eh)										
Slope (%)	<3	S1	<3	S1	<3	S1	<3	S1	<3	S1
Erosion Hazard	Low	S1	Low	S1	Low	S1	Low	S1	Low	S1

Land Characteristic	Tambakroto		Perampela		Pilangsari		Banjarsari		Sidorejo	
	Value	Class	Value	Class	Value	Class	Value	Class	Value	Class
Flooding hazard (f)										
Genangan	None	S1	None	S1	None	S1	None	S1	None	S1
Land preparation (l)										
Rock surface (%)	0	S1	0	S1	0	S1	0	S1	0	S1
Outcrop rock (%)	0	S1	0	S1	0	S1	0	S1	0	S1
Subclass	S3-na		S3-na		S3-na		S3-na, xc		S3-na, xc	
Unit	S3na-2, na-3,		S3na-2, na- 3,		S3na-2		S3-na4, xc1		S3-na5, xc1	
Limiting factor	Fosfor dan Kalium		Fosfor dan Kalium		Fosfor		Kalsium dan Magnisium		Kalsium dan Magnisium	

4. DISCUSSION

Land evaluation for paddy rice cultivation in Sayung District, Demak Regency, during 2021–2025 showed an average annual temperature of 28°C, which was classified as S1 (highly suitable) because it falls within the optimum temperature range for rice growth (22–29°C). Temperature is an important environmental factor affecting plant growth and development. Lower temperatures may reduce respiration activity, whereas appropriate humidity conditions can enhance photosynthesis (Widiastuti et al., 2004). Optimal temperatures also play a crucial role in physiological processes, particularly during the vegetative and grain-filling stages, by enhancing enzyme activity, photosynthesis, and nutrient uptake (Yoshida, 1981). Conversely, excessively low or high temperatures may inhibit growth and reduce rice yield (Dobermann & Fairhurst, 2000). According to Fahad et al. (2021) and Abbas et al. (2022), temperatures exceeding the optimum range can decrease photosynthetic efficiency, accelerate respiration, and impair grain formation and filling.

Annual rainfall in Demak Regency ranged from 1,500 to 2,500 mm, with an average of approximately 2,482 mm year⁻¹, placing it in the S1 (highly suitable) category for paddy rice cultivation. Water availability is essential for rice growth because it functions as a solvent and transport medium for nutrients within the plant (Kemas, 2013). Adequate and well-distributed rainfall supports both vegetative and reproductive growth stages and contributes to higher crop productivity (Fagi & Las, 1988; Bouman et al., 2007). Recent studies have also demonstrated that optimal water availability enhances photosynthesis, nutrient uptake, tiller formation, and grain yield (Singh et al., 2021; Abbas et al., 2022). The average relative humidity in Demak Regency during 2020–2025 was approximately 75%, which was also classified as S1 because it supports optimal rice growth. Relative humidity influences evapotranspiration, water uptake, and physiological activities. Excessively high humidity may increase disease incidence, whereas low humidity can induce water stress in plants (Andhika, 2008). According to Yoshida (1981) and Gardner et al. (1991), suitable humidity levels improve photosynthetic efficiency, metabolic activity, and rice productivity.

Drainage conditions in the study area were generally favorable and capable of providing adequate soil aeration for root development. Good drainage promotes a balanced water–air relationship within the soil, improves nutrient uptake, and prevents excessive waterlogging (Djaenuddin et al., 2011; Hanafiah, 2014). Drainage characteristics are influenced by soil macroporosity and parent material; limestone-derived soils tend to facilitate water movement, whereas fine-textured volcanic materials may restrict water flow (Siswanto, 2006). Recent studies have shown that proper drainage enhances soil aeration, microbial activity, and rice productivity (Rahman et al., 2021; Zhang et al., 2022). The soils in the study area were characterized by sandy clay loam texture and an effective soil depth exceeding 100 cm, resulting in an S1 classification. Deep soils support root development and improve the capacity for water and nutrient uptake (Hardjowigeno & Widiatmaka, 2011; Arsyad, 2010). Furthermore, soil texture influences water availability, aeration, permeability, and erosion susceptibility (Ritung et al., 2011; Brady & Weil, 2008). Zhang et al. (2021) and Liu et al. (2022) reported that favorable soil texture and rooting depth can improve water storage capacity and rice productivity.

Organic carbon content ranged from 1.25% to 2.65%, exceeding the minimum threshold of 1.2% and therefore classified as S1. Soil organic matter plays a critical role in improving soil fertility, enhancing soil structure, increasing water-holding capacity, stimulating microbial activity, and improving nutrient availability (Widiastuti et al., 2016; Muzaiyanah & Subandi, 2016). Recent studies have further demonstrated that organic matter contributes to higher rice productivity through improvements in soil physical, chemical, and biological properties (Zhang et al., 2021; Liu

et al., 2022). Cation exchange capacity (CEC) values ranged from 40.85 to 51.55 cmol(+) kg⁻¹ and were classified as S1. CEC reflects the soil's capacity to retain and supply nutrients to plants (Damanik et al., 2011). Higher CEC values indicate a greater ability to retain nutrients and sustain soil fertility (Suryani, 2014; Hardjowigeno, 2010). High CEC has also been associated with enhanced nutrient storage, microbial activity, and rice productivity (Zhang et al., 2021; Liu et al., 2022).

Soil pH values ranged from 5.6 to 6.9 and were classified as S1. Soil pH reflects the degree of soil acidity and the concentration of H⁺ ions in the soil solution. A pH range of 6–7 is considered neutral and optimal for nutrient availability (Hakim et al., 1986; Brady & Weil, 2008). Soil pH influences the availability of essential nutrients such as phosphorus (P) and potassium (K), as well as the solubility of potentially toxic elements (Hardjowigeno & Widiatmaka, 2011). Low pH levels may increase the availability of toxic elements and affect microbial activity and nutrient uptake (Gunawan et al., 2019; Hanafiah, 2014). According to Tan (2011), soil pH is an important indicator of soil fertility. Recent studies have shown that near-neutral pH conditions improve microbial activity, nutrient-use efficiency, root development, and rice productivity (Zhang et al., 2021; Liu et al., 2022).

Total nitrogen (N) content ranged from 0.17% to 0.29%, corresponding to the S2 (moderately suitable) category. Nitrogen is an essential nutrient involved in the synthesis of proteins, enzymes, nucleic acids, and chlorophyll, all of which support photosynthesis and vegetative growth (Napitupulu et al., 2010; Gardner et al., 1991; Anwar et al., 2022). Nitrogen deficiency may result in stunted growth, leaf chlorosis, and reduced yield (Havlin et al., 2014). Adequate nitrogen availability has been shown to enhance photosynthesis, tillering, leaf area development, water-use efficiency, and rice productivity (Zhang et al., 2021; Liu et al., 2022; Rahman et al., 2023).

Available phosphorus (P) in Tambakroto, Perampelan, and Pilangsari villages was classified as S3 (very low), with concentrations ranging from 5.3 to 7.2 ppm. In contrast, Banjarsari and Sidorejo exhibited high phosphorus availability (26.3–32.2 ppm) and were classified as S1. Phosphorus is an essential macronutrient absorbed by plants primarily as H₂PO₄⁻ and HPO₄²⁻ and plays a fundamental role in plant growth, development, and crop quality (Handayanto, 2017; Nursyamsi & Setyorini, 2009). It is involved in energy transfer (ATP), root development, flowering, and seed formation (Brady & Weil, 2008). Phosphorus deficiency can inhibit root growth and cause dark green to purplish leaf discoloration (Hanafiah, 2014). Recent studies have demonstrated that phosphorus promotes root development, metabolic efficiency, nutrient-use efficiency, stress tolerance, and rice productivity (Zhang et al., 2021; Liu et al., 2022; Wang et al., 2023).

Potassium (K) availability was classified as S3 (very low) in Tambakroto and Perampelan, with concentrations ranging from 6.4 to 8.6 ppm. Pilangsari was classified as S2 (moderately suitable) with a K concentration of 23.5 ppm, while Banjarsari and Sidorejo were categorized as S1 (high) with concentrations ranging from 45.0 to 49.4 ppm. Potassium plays a vital role in plant productivity by regulating osmotic balance and supporting various metabolic processes (Yusdian et al., 2021; Utomo et al., 2022). According to Marschner (2012), potassium is involved in enzyme activation, stomatal regulation, and plant resistance to environmental stress. Tisdale et al. (1993) further emphasized its importance for crop quality and water-use efficiency.

Magnesium (Mg) concentrations in Tambakroto, Perampelan, and Pilangsari ranged from 5.7 to 7.4 cmol(+) kg⁻¹ and were classified as S2 (moderately suitable), whereas Banjarsari and Sidorejo exhibited lower values (3.5–4.1 cmol(+) kg⁻¹) and were classified as S3 (marginally suitable). Magnesium is essential for chlorophyll synthesis and photosynthetic enzyme activation (Marschner,

2012; Mengel & Kirkby, 2001). Insufficient Mg availability may reduce photosynthetic efficiency, while adequate levels contribute to improved rice productivity (Zhang et al., 2021; Liu et al., 2022).

Similarly, calcium (Ca) levels in Tambakroto, Perampelan, and Pilangsari ranged from 6.5 to 6.9 cmol(+) kg⁻¹ and were categorized as S2, whereas Banjarsari and Sidorejo exhibited lower concentrations (3.9–4.1 cmol(+) kg⁻¹) and were classified as S3. Calcium plays a key role in cell wall formation, root development, and tissue strengthening (Taiz et al., 2015). Calcium deficiency may inhibit plant growth, whereas adequate Ca availability enhances crop resilience and productivity (Wang et al., 2023; Liu et al., 2022).

Salinity values in Tambakroto, Perampelan, and Pilangsari ranged from 2.7 to 3.7 dS m⁻¹ and were classified as S2, while Banjarsari and Sidorejo exhibited higher salinity levels of 4.1–6.8 dS m⁻¹ and were classified as S3. Increased salinity reduces soil water potential, thereby restricting water and nutrient uptake by plants. According to Munns and Tester (2008), salinity induces osmotic and ionic stress, disrupting photosynthesis, growth, and nutrient balance. Maas and Hoffman (1977) also reported that elevated salinity can significantly reduce crop yields, including rice. Recent studies have confirmed that excessive salinity impairs growth, water-use efficiency, and rice productivity through physiological disturbances and excessive ion accumulation within plant tissues (Hasanuzzaman et al., 2020; Li et al., 2021).

The slope gradient across the study area ranged from 0% to 3%, corresponding to the S1 category because the land is classified as flat to nearly flat (<8%). Slope is an important land characteristic affecting land quality and suitability for rice cultivation (Senawi, 1999). Such topographic conditions are highly favorable for paddy rice production because they facilitate irrigation management, maintain stable water ponding, and minimize erosion and nutrient losses. Pramono et al. (2017) reported that flat land strongly supports irrigated rice systems due to more uniform water distribution and efficient land management. Furthermore, Arsyad (2010) emphasized that slope gradient is a major factor influencing erosion, with gentler slopes resulting in lower runoff and soil degradation risks. Ritung et al. (2017) also noted that flat topography enhances land suitability for food crops, particularly rice, which requires flooded conditions. Recent studies indicate that low-slope landscapes improve water-use efficiency and support stable rice production systems. According to Zhang et al. (2021), flat topography promotes more uniform water distribution and higher rice yields, while Liu et al. (2022) highlighted its contribution to irrigation efficiency and sustainable crop productivity.

5. CONCLUSION

Sayung District exhibits a high level of land suitability (S1–S2) for paddy rice cultivation based on climatic conditions and most soil characteristics. The main limiting factors identified were low nitrogen (N), phosphorus (P), and potassium (K) availability, as well as soil salinity and insufficient calcium (Ca) and magnesium (Mg) levels in certain areas. Improvement measures involving the application of P₂O₅ and K₂O fertilizers and Ca–Mg amendments were effective in alleviating these constraints, resulting in an increase in land suitability classes from S3 (marginally suitable) to S2 (moderately suitable). These findings highlight the importance of appropriate nutrient management and soil amelioration practices in enhancing the productivity and sustainability of paddy rice cultivation in saline-affected coastal areas.

5.1 Declaration of competing interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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5.3 AI Usage Statement

Generative AI tools (such as ChatGPT by OpenAI) were used solely to enhance the clarity and readability of the manuscript through language editing. No AI tool was involved in developing the research concept, analyzing data, or drawing scientific conclusions. All AI-assisted suggestions were carefully reviewed, verified, and refined by the authors, who retain full responsibility for the integrity and accuracy of the final manuscript.

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