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Integrating geographic system and soil fertility analysis for sustainable paddy land suitability assessment in South Sulawesi, Indonesia

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ABSTRACT

Evaluating land suitability is crucial for guiding sustainable agricultural land management in tropical agroecosystems. This research assessed the suitability of land for cultivating paddy rice (*Oryza sativa* L.) in South Sulawesi, Indonesia, by combining geographic information system (GIS) analysis with laboratory-based soil characterization. The FAO maximum-limitation framework was employed within GIS to evaluate land suitability, utilizing 12 characteristics obtained from field surveys and laboratory analyses. GIS land mapping units (LMUs) were categorized into S2na (moderately suitable) or S3na (marginally suitable) classes, with nutrient availability (na) being the limiting factor throughout the study area. All physical land parameters, such as drainage, texture, effective rooting depth (>50 cm), soil pH (5.78–6.82), slope gradient (<8%), erosion risk, and flood risk, achieved S1 (highly suitable) ratings across all mapping units. Meanwhile, cation exchange capacity (CEC = 18.82–26.00 cmol(+)/kg) reached S1 in most mapping units, although reduced nutrient-retention capacity (S2–S3) further limited three units. The main limiting factors were critically low available phosphorus (P2O5 = 9.82–14.92 mg/100 g) and low-to-very-low total nitrogen (N-total = 0.08–0.24%), exacerbated by insufficient soil organic carbon (C-Organic = 0.76–2.44%) in several units. The IAERI identified varying levels of agro-environmental risk among LMUs, highlighting nutrient limitations as the dominant constraint to paddy production. The integration of GIS, soil fertility diagnostics, and IAERI provides a spatial decision-support framework for sustainable paddy land management.

Keywords: land suitability evaluation, paddy rice, GIS, sustainable land management, soil fertility.

INTRODUCTION

Food security is intrinsically linked to the availability of high-quality agricultural land, especially in densely populated agrarian nations like Indonesia. Despite Indonesia's significant reserves of arable land, only a small fraction meets the necessary physical and chemical standards for consistently high-yield food crop production. The rest is limited by inadequate soil fertility, drainage issues, or challenging terrain (Mulyani et al., 2023). This issue is exacerbated by the ongoing conversion of prime irrigated farmland to non-agricultural purposes, which increasingly restricts the nation's rice production capacity to a diminishing area of suitable land, thereby increasing the risk of future food shortages (Faoziyah et al., 2024). Thus, ensuring food security involves not only maintaining the quantity of agricultural land but also protecting and improving its quality, making land suitability evaluation essential for identifying areas where productive capacity can be maintained or enhanced (Ariani et al., 2024).

Land suitability evaluation is fundamental to sustainable land use planning, particularly in tropical countries where rapid population growth and ecological vulnerability make land degradation a serious threat to long-term food security (Susanti et al., 2024). As agricultural intensification and climate change accelerate soil degradation, assessing land's capacity to support specific crops without harming ecosystem functions has gained increasing scientific and policy significance (Tiruneh et al., 2024). Indonesia, with the world's fourth-largest population and a shrinking agricultural land base, needs systematic spatial analysis of land constraints to develop evidence-based policies that promote both food security and environmental sustainability (Irwandhi et al., 2024).

South Sulawesi has historically been a key paddy rice production area in eastern Indonesia, playing a crucial role in regional food security (BPS, 2025). However, recent field surveys and production data reveal a trend of stagnant yields (Anago et al., 2025). Data from the Bone Regency Agricultural Office show that average paddy yields in Awangpone Subdistrict have remained around 4.5–5.0 t/ha in recent seasons, significantly below the potential 7–8 t/ha achievable with optimal management (BPS, 2025). This discrepancy may be due to spatial variations in soil fertility, particularly low nitrogen and phosphorus availability, rather than seed or irrigation issues alone (Arifin et al., 2024). Therefore, a comprehensive land suitability evaluation is necessary to identify the biophysical limitations contributing to this productivity gap (Huang et al., 2023).

The FAO (1976) land suitability evaluation framework offers a globally standardized and operationally effective system for aligning land qualities and characteristics with crop growth needs. The framework assigns land to four hierarchical suitability classes: S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable), applying the limiting factor principle derived from Leibig's Law of the Minimum, whereby the most restrictive land quality governs overall suitability classification (Nurkholis et al., 2020). In Indonesia, the FAO land evaluation framework has been institutionalized through the Regulation of the Minister of Agriculture of The Republic of Indonesia No. 79 of 2013 concerning Land Suitability Guidelines for Food Crops, which establishes standardized criteria for evaluating land suitability for food crop commodities, including paddy rice (Ministry of Agriculture of the Republic of Indonesia, 2013). Its application across tropical agroecosystems has consistently demonstrated the capacity to generate actionable spatial information for site-specific land management and conservation planning (Ngadisih et al., 2024).

Land suitability evaluation is not limited to agronomic assessment. Decreasing levels of C-organic and nutrient depletion might signal more extensive soil degradation, such as diminished carbon storage and compromised soil structure (Dhaliwal et al., 2023). Natural vegetation to intensively farmed agricultural land in tropical regions can lead to a reduction in soil carbon, nitrogen, and phosphorus stocks by 64%, 52%, and 71%, respectively, which has significant implications for ecosystem services (Huang et al., 2023). Investigations into C-organic dynamics in paddy systems further validate that extended cultivation without adequate organic matter replenishment gradually diminishes nutrient supply capacity and biological soil function (Zhang et al., 2025).

GIS facilitates the spatial integration and visualization of soil and land data across diverse paddy landscapes (Karapetsas et al., 2024). GIS-based land suitability mapping for paddy rice has proven effective in pinpointing priority management zones and providing site-specific input recommendations that enhance nutrient use efficiency and mitigate environmental impacts like nutrient leaching and runoff (Ngadisih et al., 2024). The integration of laboratory-derived soil data with GIS spatial analysis is now widely regarded as best practice in land evaluation for developing tropical agricultural systems (Baja, 2022). Recent studies have demonstrated the value of integrating GIS, remote sensing, digital terrain analysis, and spatial modeling for environmental risk assessment, land-use and land-cover change analysis, disaster management, and sustainable water and land resource management (Jain, 2024; Karapetsas et al., 2024; Sadaf, 2024; Tarate et al., 2024)

Although the FAO (1976) framework has been extensively used to classify tropical agricultural land, four interconnected gaps remain in the literature. Firstly, most GIS-based evaluations, including recent studies in Indonesia and Southeast Asia, are purely classificatory, assigning S1-S3 status without diagnosing the soil-chemical properties that cause the limitation (Nurkholis et al., 2020; Ngadisih et al., 2024; Tiruneh et al., 2024). Secondly, laboratory-derived fertility diagnostics are seldom integrated with GIS analysis, leaving the spatial connection between nutrient-retention capacity (CEC) and nutrient availability status unexplored (Oldfield et al., 2019). Thirdly, suitability maps rarely translate S1-S3 status into

LMU-specific management prescriptions, limiting their practical utility for explicit environmental risk (Saisana et al., 2023). Despite South Sulawesi being a strategic rice-producing province and documented yield stagnation in Bone Regency, few studies combine subdistrict-scale GIS mapping with laboratory-based fertility diagnostics to address these gaps. This study tackles them by integrating laboratory-derived nutrient constraints with site-specific, potential suitability-oriented, and environmentally sustainable paddy land management in Awangpone Subdistrict.

Despite the widespread application of GIS-based land suitability evaluation for paddy rice cultivation, limited attention has been given to integrating laboratory-based soil fertility diagnostics with spatial suitability assessment and environmental management prioritization. Furthermore, existing soil quality and environmental assessment indicators are commonly developed independently of spatial land suitability zoning (Nardo et al., 2008; Saisana et al., 2023). Therefore, this study integrates GIS-based land suitability evaluation with laboratory-derived soil fertility assessment and develops an Integrated Agro-Environmental Risk Index (IAERI) within a unified assessment framework. The proposed approach not only identifies the spatial distribution of land suitability constraints but also evaluates the relative environmental risk and management priority of each land mapping unit (LMU) based on nutrient-correction intensity, nutrient-retention vulnerability, and soil-carbon depletion status. The novelty of this study is threefold: (i) integrating GIS-based FAO land suitability evaluation with laboratory-derived soil fertility diagnostics at LMU level, (ii) translating suitability constraints into LMU-specific management prescriptions, and (iii) developing the IAERI to prioritize environmental management interventions beyond conventional suitability classification.

MATERIALS AND METHODS

Conceptual framework of the study

Figure 1 illustrates the conceptual framework guiding this study, tracing the logical sequence from land productivity constraints in Awangpone Subdistrict, through GIS-based FAO (1976) land suitability evaluation, to the derivation of integrated nutrient management recommendations.

Study area

The study was conducted in Awangpone Subdistrict, Bone Regency, South Sulawesi Province, Indonesia (Figure 2). The study area occupies an approximate geographical extent of 4°24'–4°32' South Latitude and 120°13'–120°25' East Longitude, encompassing a total paddy field area of approximately 7.200 ha. The area is characterized by a tropical monsoon climate, with mean annual rainfall of approximately 2.610 mm distributed bimodally and a mean annual temperature of 25.8 °C, conditions broadly favorable to irrigated rice cultivation. The landscape consists predominantly of low-lying alluvial terrain with slopes not exceeding 8%, traversed by an established irrigation network that has historically sustained intensive paddy cultivation. Analyses were performed at the Laboratory of Soil Chemistry and Fertility, Faculty of Agriculture, Hasanuddin University, Makassar.

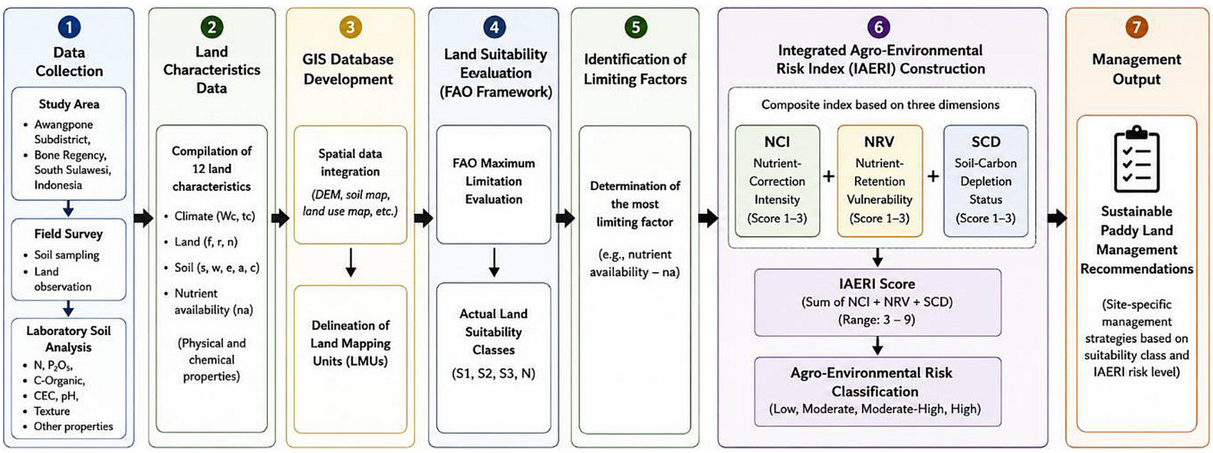

Figure 1. Conceptual framework of the study, from land productivity constraints through GIS-based FAO (1976)

Land mapping unit delineation

Land mapping units (LMUs) were delineated by digitizing village administrative boundaries and field polygons in ArcGIS 10.8, integrating field boundary data, cadastral information, and satellite imagery to produce a working map at 1:50.000 scale. Eighteen observation points were established based on polygon distribution, field accessibility, and spatial representativeness (Burrough and McDonnell, 2015), and georeferenced by GPS to sub-metre accuracy. Composite samples at each point were formed from subsamples within homogeneous management zones, representing the dominant soil condition of each LMU.

The 18 LMUs correspond to village administrative polygons, each a spatially discrete production unit with homogeneous land management history. One composite per LMU was considered adequate given the area's uniform alluvial geology, narrow slope range (<8%), and consistent irrigation infrastructure, consistent with subdistrict-scale and evaluation practice in Indonesia (Ngadisih et al., 2024). This approach follows semi-detail mapping standards at 1:50.000 scale under Ministry of Agriculture Regulations No. 79/2013, supported by a minimum of five cross-transect subsamples per LMU. A single composite sample per LMU may not fully capture within unit macro scale variability a limitation future studies could address through denser sampling grids or geostatistical interpolation.

Soil sampling and laboratory analysis

Composite soil samples were collected from all 18 unit LMUs to a depth corresponding to the effective root zone (0–50 cm). At each observation point, a minimum of five subsamples were collated using a soil auger along a cross-transect pattern and composited to a single representative sample per LMU. Samples were air-dried at ambient temperature (25 °C), ground, and sieved through a 2 mm mesh prior to analysis. Analytical parameters and corresponding laboratory methods are presented in Table 1.

Sampling point coordinates

The geographic coordinates of the soil sampling locations representing each LMU in study area are presented in Table 2.

Remote sensing and digital elevation data

Google Earth imagery (2024) and DEMNAS (Digital Elevation Model Nasional; 8 m spatial resolution, Geospatial Information Agency of Indonesia were used to verify terrain

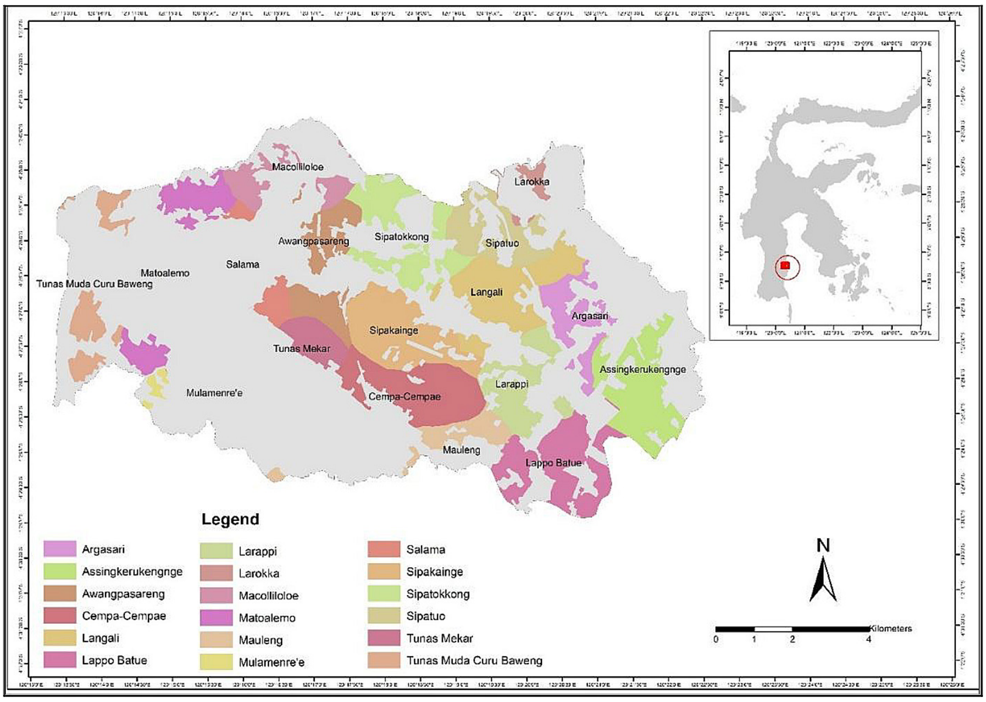

Figure 2. Study area map of Awangpone Subdistrict, Bone Regency, South Sulawesi Province

Table 1. Soil analysis parameters and methods employed in this study

No.	Parameter	Analytical method
1	Soil texture	Hydrometer method (Bouyoucos)
2	C-Organic (%)	Walkley and Black wet oxidation method
3	CEC (cmol(+)/kg)	NH□OAc saturation extraction, pH 7
4	Soil pH (H_2O)	Electrometric method (pH meter, 1:2.5 soil:water suspension)
5	Total nitrogen (%)	Kjeldahl digestion and distillation method
6	Available K_2O (cmol(+)/kg)	HCl 25% extraction (modified Egner-Riehm)
7	Available P_2O_5 (mg/100g)	Olsen extraction (pH ≥5.5); Bray-1 (pH <5.5)

Table 2. Geographic coordinates of soil sampling points for each land mapping unit (LMU)

No.	Land mapping unit (LMU)	Latitude	Longitude
1	Lappo Batue	120°20’32.79” E	4°28’56.77” S
2	Assingkerukengnge	120°21’47.48” E	4°28’20.52” S
3	Argasari	120°20’27.86” E	4°26’50.08” S
4	Larappi	120°19’51.24” E	4°28’26.52” S
5	Sipatuo	120°19’54.76” E	4°26’08.03” S
6	Langali	120°19’33.59” E	4°26’42.35” S
7	Sipakainge	120°17’54.75” E	4°27’15.97” S
8	Mauleng	120°19’21.23” E	4°28’46.20” S
9	Cempa-Cempae	120°18’51.40” E	4°28’15.28” S
10	Awangpasareng	120°16’45.16” E	4°26’03.13” S
11	Sipatokkong	120°18’01.13” E	4°25’40.05” S
12	Macolliloloe	120°16’03.16” E	4°25’12.83” S
13	Tunas Mekar	120°17’00.86” E	4°27’33.70” S
14	Mulamenre’e	120°14’46.48” E	4°28’05.63” S
15	Matoalemo	120°14’31.86” E	4°28’45.83” S
16	Salama	120°16’25.65” E	4°26’58.51” S
17	Tunas Muda C.B.	120°13’40.93” E	4°27’10.34” S
18	Larokka	120°20’10.51” E	4°25’13.81” S

characteristics and support LMU delineation. These datasets were also used to delineate slope classes and confirm the <8% slope category. Software Versions. Spatial data processing, LMU delineation, and thematic map production were conducted using ArcGIS 10.8. Descriptive analyses and IAERI calculations were performed using Microsoft Excel.

Land suitability evaluation

Land suitability for rice was evaluated using the FAO (1976) maximum limitation method as operationalized through Ministerial Regulation No. 79 of 2013 (Ministry of Agriculture, 2013). Seven land qualities were assessed, including temperature (tc), water availability (wa), rooting condition (rc), nutrient retention (nr), nutrient availability (na), erosion hazard (eh), and flood hazard (fh). Nutrient retention was represented by soil pH, cation exchange capacity (CEC), and organic carbon, while nutrient availability was evaluated using total nitrogen, available phosphorus (P_2O_5), and available potassium (K_2O). Each land characteristic was matched against standard suitability criteria to determine suitability subclasses. Following the maximum limitation principle, the most limiting factor determined the final actual land suitability class for each Land Mapping Unit (LMU). Potential land suitability was then estimated by assuming an increase in the limiting factor that could be managed through appropriate land management interventions (Table 3).

Table 3. Land suitability criteria for paddy rice (*Oryza sativa* L.) based on Ministry of Agriculture of the Republic of Indonesia, 2013

Land characteristic	S1	S2	S3	N
Temperature (°C)	24–29	22–24 / 29–32	18–22 / 32–35	<18 / >35
Drainage	Somewhat impeded, moderate	Impeded, good	Very impeded	Rapid
Texture	Fine, somewhat fine	Medium	Somewhat coarse	Coarse
Effective depth (cm)	>50	40–50	25–40	<25
CEC (cmol(+)/kg)	>16	5–16	<5	–
pH H_2O	5.5–7.0	4.5–5.5 / 7.0–8.0	<4.5 / >8.0	–
C-Organic (%)	>1.2	0.8–1.2	<0.8	–
Total N	Medium	Low	Very low	–
P_2O_5	High	Medium	Low–Very low	–
K_2O	Medium	Low	Very low	–
Slope (%)	<3	3–8	8–30	>30
Flood height (cm)	<25	25–50	50–75	>75

Note: S1 – Highly Suitable; S2 – Moderately Suitable; S3 – Marginally Suitable; N – Not Suitable; (–) – criterion not applicable.

GIS-based spatial mapping

Spatial distribution maps of actual and potential land suitability classes were produced using ArcGIS 10.8 suitability class attributes were joined to the LMU polygon layer and thematic maps were rendered using a standardized color scheme: green for S2na (moderately suitable with nutrient availability limitation) and orange for S3na (marginally suitable with critical nutrient limitation). Standard cartographic elements including north arrow, scale bar, legend, coordinate grid, and inset reference maps were incorporated following established map composition protocols (Longley et al., 2015). Potential suitability maps were derived by simulating the removal of technically remediable limiting factors through prescribed management interventions.

Integrated agro-environmental risk index construction

The index was constructed following the composite indicator approach of Nardo et al. (2008), using three dimensions derived from the land suitability evaluation and laboratory soil analyses, where 1 indices low vulnerability, 2 moderate vulnerability, and 3 high vulnerability. The IAERI was calculated as;

$$[IAERI = NCI + NRV + SCD] \qquad (1)$$

where: (*NCI*) is the nutrient-correction intensity score, (*NRV*) is the nutrient-retention vulnerability score (Table 4 and Table 5), and (*SCD*) is the soil-carbon depletion status score. Equal weighting was applied because no empirical basis was available to justify differential weighting among the three dimensions (Nardo et al., 2008). This approach is widely used in spatial analysis and environmental assessment for classifying heterogeneous datasets.

RESULTS AND DISCUSSION

Laboratory soil characteristics of land mapping units

The findings suggest that variations in land suitability across the 18 LMUs are largely linked to soil fertility rather than the physical characteristics of the land (Figure 3). All LMUs were found to have favorable conditions for rice cultivation, such as appropriate temperatures, sufficient rainfall, deep rooting depth, minimal erosion risk, and no flood hazards. Consequently, the spatial differences in land suitability were mainly influenced by variations in soil properties related to nutrients. The study identified low levels of soil organic carbon, total nitrogen, and available phosphorus as the main limiting factors in the area. Some LMUs had less than 2% soil organic carbon, indicating limited organic matter reserves and reduced nutrient availability. Recent research on paddy ecosystems has shown that increasing soil organic carbon

Table 4. Scoring criteria used for IAERI construction

Component	Criteria	Score
Nutrient-Correction Intensity (NCI)	Low nutrient correction requirement (dominantly S1 nutrient status)	1
	Moderate nutrient correction requirement (S2 nutrient limitations present)	2
	High nutrient correction requirement (one or more S3 nutrient limitations present)	3
Nutrient-Retention Vulnerability (NRV)	CEC Class S1	1
	CEC Class S2	2
	CEC Class S3	3
Soil-Carbon Depletion Status (SCD)	Adequate (>1.2% C-Organic)	1
	Near-Critical (0.8–1.2% C-Organic)	2
	Critical (<0.8% C-Organic)	3

Table 5. IAERI risk classification and interpretation

IAERI score	Risk category	Interpretation
3–4	Low	Low agro-environmental vulnerability
5–6	Moderate	Moderate agro-environmental vulnerability
7	Moderate-high	Elevated agro-environmental vulnerability requiring management attention
8–9	High	Very high agro-environmental vulnerability and priority for intervention

significantly enhances soil fertility by improving nitrogen availability, nutrient cycling, and overall soil quality (Meng et al., 2025). The observed close spatial relationship between soil organic carbon and total nitrogen in this study aligns with these findings. Most LMUs exhibited a generally high cation exchange capacity (CEC), indicating a strong ability to retain nutrients.

CEC was generally high across most LMUs, indicating a strong capacity for nutrient retention. The coexistence of high CEC and low nutrient availability suggests that soil fertility constraints in Awangpone are mainly related to insufficient nutrient replenishment rather than poor nutrient holding capacity. Similar results were reported by (Huang et al., 2023), who found that improvements in soil fertility were strongly associated with enhanced nutrient inputs and soil organic matter management. Therefore, increasing organic matter inputs and optimizing nitrogen and phosphorus fertilization should be prioritized to improve rice productivity and sustain soil fertility in Awangpone.

Land suitability classification results

The results of the land suitability evaluation for all 18 LMUs are presented systematically in Table 6. The evaluation unequivocally classified all 18 LMUs as either S2na (moderately suitable with nutrient availability as the limiting factor) or S3na (marginally suitable with critical nutrient availability limitation). No LMU attained S1 status, and none was relegated to the N (not suitable) category. The nutrient availability subclass (na) was the sole and universal determinant of actual land suitability across all mapping units, confirming that the primary constraint to paddy rice production in Awangpone lies in chemical fertility depletion rather than irreversible physical land conditions. Comparable findings, in which nutrient limitation constitutes the governing factor in paddy land suitability evaluations, have been reported across multiple tropical settings in Indonesia and Southeast Asia (Arifin et al., 2024).

Spatial distribution of actual land suitability

The spatial distribution of the actual land suitability classes illustrated in Figure 4 reveals a mosaic arrangement of S2na and S3na zones across Awangpone Subdistrict. S2na (moderately suitable) areas are predominantly concentrated in central and southern landscape positions, whereas S3 (marginally suitable) units are clustered within the northern, eastern, and peripheral zones. The nine S2na units may be associated with spatial variability in nutrient status and landscape position, and S3na units may also be associated with

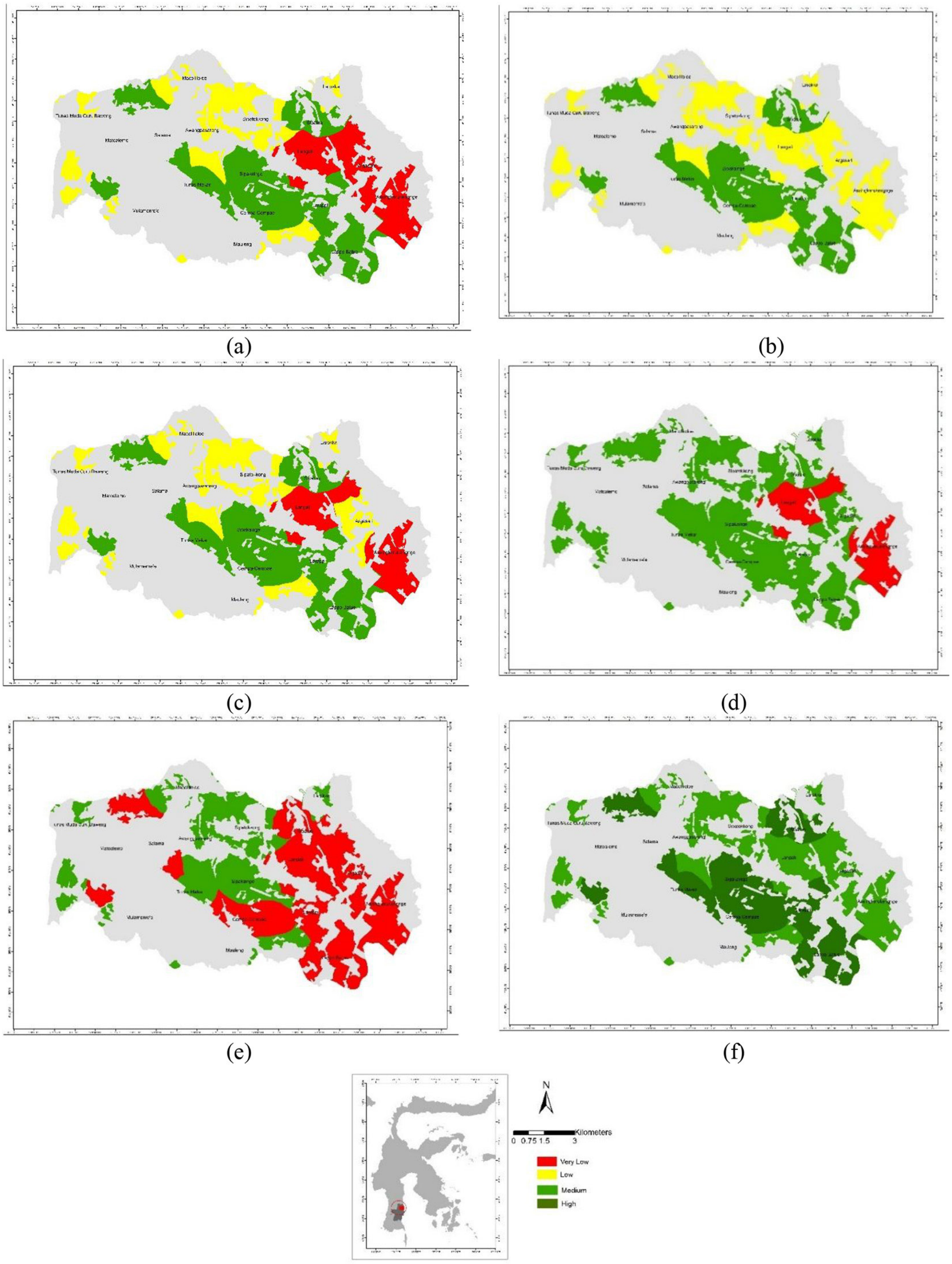

Figure 3. Spatial distribution of nutrient (a) C-Organic; (b) pH; (c) N; (d) P_2O_5; (e) K_2O; (f) CEC

spatial differences in soil nutrient status and organic matter conditions, although these relationships were not directly assessed. Spatially differentiated nutrient limited suitability class patterns of kind have been consistently documented in GIS-based evaluations of lowland paddy systems across Indonesia (Nurkholis et al., 2020)

The practical consequences of this spatial arrangement are crucial for strategies focused on site-specific nutrient management. In intensively irrigated rice systems, current fertilizer management practices often fail to account for the significant variations in nutrient supply and crop demand across different fields. To enhance nutrient-use efficiency and economic outcomes, a site-specific nutrient management approach is essential (Girsang et al., 2025). The GIS-based land suitability map developed in this study offers the

Table 6. Land quality ratings and actual land suitability classification per land mapping unit in Awangpone Subdistrict

Land characteristic		Soil CEC (cmol/kg)	Soil pH	Organic carbon (%)	Total N (%)	P_2O_5	K_2O
Lappo Batue	Value	25.42	6.75	2.29	0.21	12.03	0.19
	Class	S1	S1	S1	S2	S2	S2
Assingkerukengnge	Value	21.27	5.85	0.89	0.08	9.82	0.16
	Class	S1	S1	S2	S3	S3	S2
Argasari	Value	23.12	5.78	0.76	0.1	10.16	0.17
	Class	S1	S1	S3	S3	S3	S2
Larappi	Value	25.42	6.57	2.3	0.23	12.05	0.2
	Class	S1	S1	S1	S1	S2	S2
Sipatuo	Value	25.31	6.58	2.27	0.25	12.07	0.18
	Class	S1	S1	S1	S1	S2	S2
Langali	Value	21.29	5.82	0.79	0.05	9.83	0.15
	Class	S1	S1	S2	S3	S3	S2
Sipakainge	Value	26	6.82	2.44	0.24	14.92	0.32
	Class	S1	S1	S1	S1	S2	S2
Mauleng	Value	22.57	6.18	1.59	0.16	10.01	0.24
	Class	S1	S1	S1	S2	S3	S2
Cempa-Cemapae	Value	25.42	6.75	2.33	0.21	12.03	0.19
	Class	S1	S1	S1	S1	S2	S2
Awangpasareng	Value	21.58	6.15	1.63	0.18	10.03	0.26
	Class	S1	S1	S1	S2	S3	S2
Sipatokkong	Value	21.47	6.16	1.55	0.16	10.08	0.23
	Class	S1	S1	S1	S2	S3	S2
Macolliloloe	Value	21.51	6.18	1.59	0.15	10.02	0.25
	Class	S1	S1	S1	S2	S3	S2
Tunas Mekar	Value	23.56	6.82	2.41	0.24	14.92	0.35
	Class	S1	S1	S1	S1	S2	S2
Mulamenre’e	Value	24.95	6.25	1.22	0.13	11.27	0.25
	Class	S1	S1	S1	S2	S2	S2
Matoalemo	Value	25.62	6.73	2.25	0.21	12.03	0.22
	Class	S1	S1	S1	S1	S2	S2
Salama	Value	25.32	6.71	2.32	0.21	12.01	0.19
	Class	S1	S1	S1	S1	S2	S2
Tunas Muda Curu Baweng	Value	21.57	6.18	1.57	0.16	10.07	0.28
	Class	S1	S1	S1	S2	S3	S2
Larokka	Value	18.82	6.11	1.17	0.12	10.8	0.21
	Class	S1	S1	S2	S2	S3	S2

Note: S1 – Highly Suitable; S2 – Moderately Suitable; S3 – Marginally Suitable. The actual class reflects the most restrictive subclass rating per FAO (1976) and Ministry of Agriculture of the Republic of Indonesia (2013).

spatial foundation necessary for creating nutrient management zones. This allows for the calibration of fertilizer formulas based on specific nitrogen and phosphorus deficits in each LMU, rather than applying them uniformly across sub-districts. Management priorities and intervention needs to achieve higher suitability are determined by land suitability classes (Arifin et al., 2024). The S3na unit in the northern and eastern zones of Awangpone should be prioritized for integrated organic and inorganic soil fertility enhancement, particularly through the combined use of compost, balanced urea SP-36 fertilization, and straw incorporation to address C-organic and N-P co-limitation

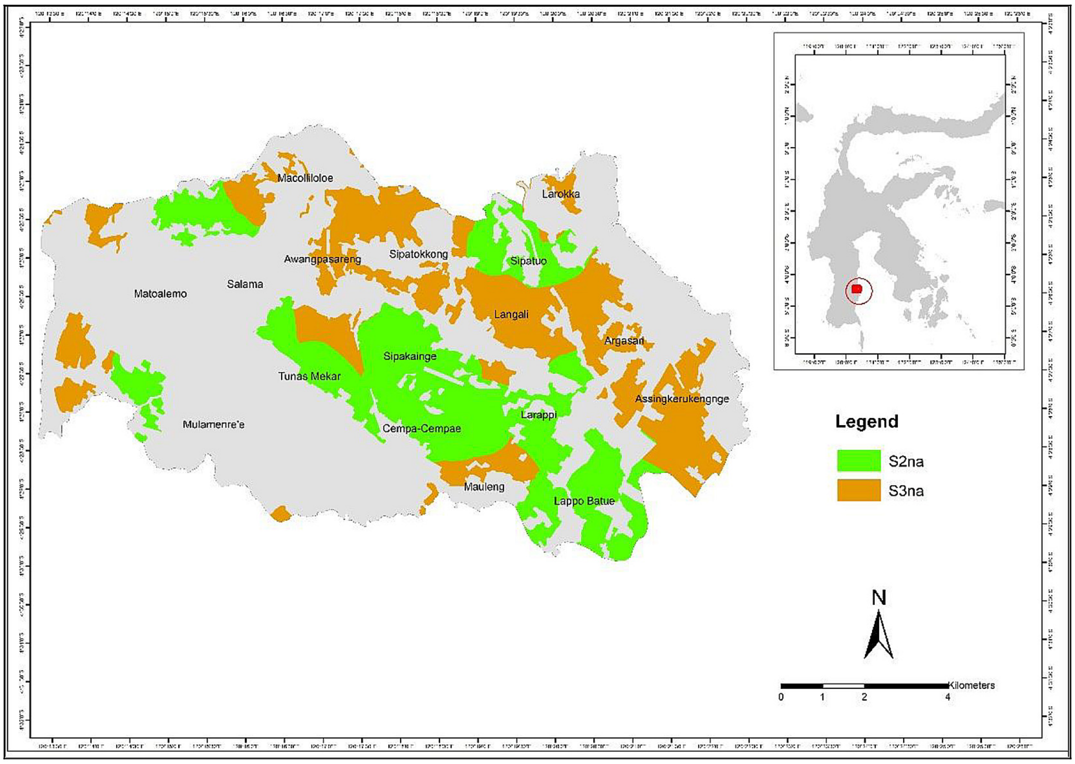

Figure 4. Spatial distribution of actual land suitability for paddy rice (*Oryza sativa* L.) in Awangpone Subdistrict, Bone Regency, South Sulawesi

simultaneously (Huang et al., 2023). Incorporating organic inputs like Azolla and rice straw with customized synthetic fertilizers enhances organic carbon levels and offers a more suitable and comprehensive approach to soil health. Total soil nitrogen is strongly positively correlated with organic carbon, phosphorus uptake, and phosphatase enzyme activity (Tiruneh et al., 2024).

Land units classified as S2na show moderate limitations in chemical nutrient availability, primarily reflected in medium total nitrogen and medium available P_2O_5 levels, while C-Organic content generally meets or exceeds the S1 threshold of >1.2%. In these units, fine-textured clays with CEC values of 18.82–26.00 cmol(+)/kg, near-neutral pH of 6.25–6.82, and impeded drainage collectively establish a favorable physical environment that supports adequate paddy rice nutrient use efficiency when chemical fertility is properly maintained. According to (Food and Agriculture Organization (FAO), 1976) that S2 class land can sustain commercially acceptable paddy yields with modest, targeted fertility inputs. The nine S2na LMUs in Awangpone thus represent priority zones for precision nutrient management aimed at upgrading toward S1. Agroecological nutrient management strategies integrating soil test based fertilization with organic amendments have been shown to progressively restore soil fertility in tropical paddy systems across Indonesia (Widiatmaka et al., 2016).

Nine LMUs classified as S3na present more critical agronomic and environmental conditions. The primary and most severe limiting factor across these units is critically deficient available P (P_2O_5: 9.82–10.82 mg/100 g). In tropical soils, phosphorus deficiency is not solely attributable to intrinsically low total P content; it is substantially amplified by strong anion sorption mechanisms involving iron and aluminum hydroxide minerals characteristic of tropical clay mineralogy, which suppress plant-available P concentrations well below total soil P stocks (Brady and Weil, 2016). Only 10–25% of applied phosphorus fertilizer is typically recovered by crops within a single growing season in tropical paddy soils, with the remainder immobilized through sorption on metal oxyhydroxides (Lal, 2024). Co-limitation by the very low to low total N (0.08–0.16%) in S3na units further intensifies the yield-depressing effect, as nitrogen and phosphorus deficiencies interact synergistically to impair crop physiological processes from germination through grain fill (Wei et al., 2024).

Table 7. Recommendation matrix of limiting factors and FAO-based land improvement measures per land mapping unit in Awangpone Subdistrict

No	Land mapping unit (LMU)	Actual suitability class	Principal limiting factor(s)	FAO-Based recommended improvement measures	Potential suitability class
1	Lappo Batue	S2na	Moderate N, P_2O_5 and K_2O availability (S2); C-Organic near S1/S2 threshold	Balanced N-P-K fertilization calibrated to soil-test values, combined with organic matter enrichment (compost or green manure) to sustain long-term nutrient supply. Low FAO input level.	S1
2	Assingkerukengnge	S3na	Co-critical total N and available P_2O_5 (S3); K_2O moderate (S2); C-Organic near-critical (0.89%)	Combined soil-test-calibrated urea and SP-36/rock-phosphate application integrated with rice-straw compost and Sesbania rostrata green manure to rebuild C-Organic and enhance N-P mineralization. Medium-to-high FAO input level.	S1*
3	Argasari	S3na	Co-critical total N and available P_2O_5 (S3); reduced nutrient-retention capacity; C-Organic critically low (0.76%)	Intensive integrated correction: soil-test-calibrated urea and SP-36/rock-phosphate application with priority organic matter rebuilding (compost, green manure, and straw incorporation) to restore C-Organic above 1.2%. High FAO input level; priority intervention unit.	S1*
4	Larappi	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
5	Sipatuo	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
6	Langali	S3na	Co-critical total N and available P_2O_5 (S3); K_2O moderate (S2); C-Organic near-critical (0.89%)	Combined soil-test-calibrated urea and SP-36/rock-phosphate application integrated with rice-straw compost and Sesbania rostrata green manure to rebuild C-Organic and enhance N-P mineralization. Medium-to-high FAO input level.	S1*
7	Sipakainge	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
8	Mauleng	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2)	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter incorporation to reduce Fe/Al-oxide P-fixation; maintenance N and K fertilization. Medium FAO input level.	S1*
9	Cempa-Cempae	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
10	Awangpasareng	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2)	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter incorporation to reduce Fe/Al-oxide P-fixation; maintenance N and K fertilization. Medium FAO input level.	S1*
11	Sipatokkong	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2)	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter incorporation to reduce Fe/Al-oxide P-fixation; maintenance N and K fertilization. Medium FAO input level.	S1*

12	Macolliloloe	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2)	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter incorporation to reduce Fe/Al-oxide P-fixation and maintenance N and K fertilization. Medium FAO input level.	S1*
13	Tunas Mekar	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
14	Mulamenre'e	S2na	Moderate N, P_2O_5 and K_2O availability (S2); C-Organic near S1/S2 threshold	Balanced N-P-K fertilization calibrated to soil-test values, combined with organic matter enrichment (compost or green manure) to sustain long-term nutrient supply. Low FAO input level.	S1
15	Matoalemo	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
16	Salama	S2na	Moderate available P_2O_5 and K_2O (S2); N adequate (S1)	Soil-test-based maintenance fertilization with SP-36/TSP and KCl at moderate rates; periodic organic matter incorporation to sustain nutrient cycling. Low FAO input level.	S1
17	Tunas Muda C.B.	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2)	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter incorporation to reduce Fe/Al-oxide P-fixation and maintenance N and K fertilization. Medium FAO input level.	S1*
18	Larokka	S3na	Critically low available P_2O_5 (S3); total N and K_2O moderate (S2); C-Organic marginal	Priority phosphorus correction via soil-test-calibrated SP-36/rock-phosphate application combined with organic matter and C-Organic-building amendments, and maintenance N and K fertilization. Medium FAO input level.	S1*

Note: S1 – Highly Suitable; S2 – Moderately Suitable; S3 – Marginally Suitable. According to the FAO (1976) guidelines for land enhancement, management strategies that are both technically and economically viable are aligned with the intensity of the identified limiting factor to assess potential land suitability. (*) The potential class can be achieved through ongoing management over multiple seasons, as the restoration of C-Organic and co-limited nutrient conditions in these areas demands a prolonged recovery period.

Potential land suitability and management recommendations

The finding that all identified limiting factors are chemical nutritional rather than attributable to immutable physical constraints confirms that potential land suitability upgrades are technically attainable across all 18 LMUs. The integrated management strategy recommended for Awangpone encompasses three interdependent components. Table 7 presents a land unit-specific recommendation matrix summarizing the principal limiting factors and corresponding FAO-based improvement measures for each of the 18 LMUs, ahead of a detailed discussion of the three interdependent management components below.

Integrated agro environmental risk index

Applying the IAERI to the 18 LMUs yielded ten Low-risk, six Moderate-risk, one Moderate-High-risk, and one High-risk unit (Table 8).

Nutrient-retention capacity, represented by cation exchange capacity (CEC), played a key role in differentiating vulnerability levels among LMUs. Soils with lower CEC have a reduced ability to retain and supply nutrients, thereby increasing the risk of nutrient losses and reducing fertilizer-use efficiency (Brady and Weil, 2016). Similarly, soil organic carbon contributed substantially to IAERI variation because organic matter is closely associated with nutrient cycling, soil structural stability, and nutrient availability in agricultural systems (Dhaliwal

Table 8. Integrated agro-environmental risk index (IAERI) classification per land mapping unit in Awangpone Subdistrict

No	Land mapping unit (LMU)	NCI score	NRV/CEC score	SCD score	IAERI score	Risk category
1	Lappo Batue	1	1	1	3	Low
2	Assingkerukengnge	3	1	2	6	Moderate
3	Argasari	3	2	3	8	High
4	Larappi	1	1	1	3	Low
5	Sipatuo	1	1	1	3	Low
6	Langali	3	1	2	6	Moderate
7	Sipakainge	1	1	1	3	Low
8	Mauleng	2	1	1	4	Low
9	Cempa-Cempae	2	1	1	4	Low
10	Awangpasareng	3	1	1	5	Moderate
11	Sipatokkong	3	1	1	5	Moderate
12	Macolliloloe	3	1	1	5	Moderate
13	Tunas Mekar	1	1	1	3	Low
14	Mulamenre'e	1	2	1	4	Low
15	Matoalemo	1	1	1	3	Low
16	Salama	1	1	1	3	Low
17	Tunas Muda C.B	3	1	1	5	Moderate
18	Larokka	3	2	2	7	Moderate-high

et al., 2023; Oldfield et al., 2019). The higher IAERI scores observed in several LMUs were therefore primarily driven by the combined occurrence of phosphorus deficiency, low nitrogen status, and depleted soil organic carbon. Previous studies have demonstrated that nitrogen and phosphorus deficiencies often interact synergistically, limiting crop productivity and reducing nutrient-use efficiency under tropical conditions (Wei et al., 2024).

These findings demonstrate that the IAERI complements conventional land suitability assessment by providing an additional layer of information for prioritizing management interventions. While land suitability classes identify the dominant limiting factors, IAERI enables the ranking of LMUs according to the severity of agro-environmental vulnerability, thereby supporting more targeted and efficient site-specific nutrient management strategies.

Positioned against existing approaches to land and soil assessment, IAERI shares methodological common ground with established practice while offering a distinguishing combination of features. Conventional FAO (1976) land suitability classification, as applied in this and most prior studies (Nurkholis et al., 2020; Ngadisih et al., 2024; Tiruneh et al., 2024), assigns each land mapping unit to a categorical class (S1-S3-N) based on its single most limiting factor; this maximum-limitation principle, however, cannot differentiate the relative severity of risk among units sharing the same class, as illustrated by the nine S3na units in the present study, whose IAERI scores ranged from 4 to 8 despite an identical categorical status. Soil-fertility index approaches, such as that developed for paddy land in Benin (Anago et al., 2025), similarly aggregate multiple fertility parameters into a single numerical score and offer finer discrimination than categorical classification alone, but such indices are generally constructed independently of spatial suitability zoning and do not explicitly link fertility status to the management intensity required at each site. IAERI draws on the general composite-indicator methodology of Nardo et al. (2008) and Saisana et al. (2023) equal-weighted aggregation of standardized sub-indicators, but adapts this generic framework specifically to paddy land management by combining suitability-derived nutrient-correction intensity, nutrient-retention vulnerability, and soil-carbon depletion status within the same land-mapping-unit structure used for suitability mapping. In this sense, IAERI is intended to complement rather than replace FAO-based classification: suitability class indicates the type of limitation, while IAERI indicates its relative severity and management urgency. As with most composite indicators (Nardo et al., 2008), a principal limitation of this approach is that equal weighting assumes broadly comparable contribution from each dimension, an assumption that has not yet been empirically tested against yield or environmental performance data for this study area.

STUDY LIMITATIONS

This study has several limitations. First, each mapping unit (LMU) was represented by a single composite soil sample derived from multiple subsamples, preventing the quantification of within-unit spatial variability and associated statistical uncertainty. Consequently, the suitability and IAERI classifications should be interpreted as representative estimates rather than statistically validated means. Second, no formal inferential statistical tests were performed because FAO (1976land evaluation framework is primarily descriptive and classification-based rather than inferential in nature. It should be emphasized that this represents a deliberate methodological decision, consistent with semi-detailed (1:50,000-scale) land evaluation practice under Ministerial Regulation No. 79/2013 and comparable subdistrict-level FAO-based studies in Indonesia (Ngadisih et al., 2024), rather than an oversight in data collection or statistical treatment; a replicate-based sampling design capable of supporting formal inferential statistics would require a substantially denser observation grid that lies beyond the intended semi-detailed scope of the present assessment, and is instead proposed below as a direction for future research at finer spatial resolution. Third, although IAERI was developed following an established composite-indicator methodology (Nardo et al., 2008), it has not yet been validated against independent yield, nutrient-use efficiency, or environmental performance data. Therefore, IAERI should be regarded as a relative vulnerability ranking tool rather than a predictive model. Future studies should employ denser sampling designs and validate IAERI using agronomic and environmental indicators to improve its robustness and broader applicability.

CONCLUSIONS

This study integrated GIS-based FAO land suitability evaluation, laboratory-derived soil fertility diagnostics, and the integrated IAERI to assess paddy land suitability in Awangpone Subdistrict, South Sulawesi. The results classified nine LMUs as S2na and nine as S3na, indicating that nutrient availability, particularly phosphorus deficiency, low nitrogen content, and insufficient soil organic carbon, constitutes the primary constraint to rice production. In contrast, most physical land characteristics were highly suitability and did not significantly limit cultivation.

The findings demonstrate that the identified limitations are largely manageable through site-specific nutrient management and organic matter improvement, enabling potential upgrading of land suitability. Furthermore, IAERI revealed spatial differences in agro-environmental vulnerability that were not fully captured by conventional suitability classes, thereby providing additional information for prioritizing management interventions.

The novelty of this study lies in integrating FAO-based land suitability evaluation, laboratory soil fertility diagnostics, and IAERI within a spatially explicit decision-support framework, offering a practical approach for sustainable paddy land management in tropical agroecosystems.

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