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Research Article

Soil Fertility Index on Rainfed and Irrigated Paddy Fields in Babat District, Lamongan

Muhammad Rizal Romadhon[1*], Bambang Hermiyanto[1], Basuki[1]

[1]Departement of Soil Science, Faculty of Agriculture, Jember University, Kalimantan Street No. 37 Kampus Tegal Boto, Jember, East Java, Indonesia.

Corresponding author, email: rizal.romadhon@mail.unej.ac.id

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Abstract

Fluctuations in agricultural production, arising from the lack of available soil fertility information have led to unsuitable land management practices. This study aims to state the chemical properties of soil as fertility indicators in Babat District, Lamongan and to compare fertility status between irrigated and rainfed paddy fields. In addition, this study aims to identify the values, classes and status of the soil fertility index within the study area. The study was conducted from February to June 2025 using a soil survey approach with purposive sampling across eight land mapping units (LMUs) with three field replicates per LMU at a depth 0-30 cm. Soil chemical properties analyzed included: Soil pH, OC, CEC, Total N, P available, K, Ca and Mg. The soil fertility index was calculated using scoring and weighting methods used, while differences between water management systems were assessed using an independent-samples t-test. The results state that the chemical soil properties at the research sites ranged from low to high criteria. Soil fertility index values ranged between 220 and 240, corresponding moderate to moderately high classes. T-test revealed no statistically significant differences in soil fertility index between irrigated and rainfed fields ($p=0.55 > 0.05$). Mg was the only parameter showing a statistically significant response to land management system ($p=0.02 < 0.05$) Given the limited sample size, these findings should be interpreted with caution and warrant further confirmation. These results suggest a need for increased organic matter inputs to improve soil fertility status in the study area.

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1. Introduction

Soil physical, chemical, and biological properties are closely associated with soil fertility levels, which directly influence plant growth and development. Soil fertility is defined as the capacity of soil to support optimal crop production under managed soil environments (Arsyad, 2018). Lamongan Regency recorded the largest paddy harvested area in East Java Province in 2023, with Babat District standing out as one of the areas with the highest land extent and production levels (BPS Lamongan, 2024). This provides a strong rationale for selecting Babat District as a suitable study site. Moreover,

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Babat represents a typical lowland paddy agroecosystem characterized by both technical irrigation and rainfed systems, which exhibit distinct features such as water limitations during the dry season and variability in crop productivity. Babat District comprises several administratively defined villages, including Moropelang, Kebalandono, Keyongan, and Sambangan, which constitute the study area. Agricultural production in these villages is predominantly carried out on irrigated paddy fields and rainfed paddy fields. Variations in land use across the study area influence soil physical, chemical, and biological properties, thereby affecting overall soil fertility status (Nguyen et al., 2024).

The study area exhibits fluctuations in crop yield, highlighting the need for soil fertility information as a basis for implementing suitable land management practices. Increasing food demand has intensified pressure on soil and water resources, while the depletion of soil nutrients poses a major challenge to achieving optimal crop productivity (A. K. Srivastava et al., 2021). Flooding is a common characteristic of paddy field systems, where land management typically involves intensive fertilization and irrigation practices. Paddy cultivation under prolonged inundated conditions constitutes a distinctive feature of paddy agroecosystem (Asakawa et al., 2024). However, intensive land use can lead to a decline in soil fertility status if not properly managed. To mitigate land degradation, several management practices can be adopted, including the utilization of livestock feed residues, tree litter, and crop biomass residues, as well as the application of compost, organic and inorganic mulches, and green manure, all of which have been shown to significantly improve soil productivity (Mebrate et al., 2022).

Soil fertility indices have been widely used to assess soil conditions in various ecosystems. In paddy fields, such assessments help evaluate soil fertility and guide fertilizer recommendations (Anago et al., 2025; Malo & Saha, 2025; Romadhon & Hermiyanto, 2021; Zhao et al., 2023). However, limited studies have compared soil fertility between rainfed and irrigated paddy systems. Therefore, this study aims to evaluate differences in soil fertility under different paddy land-use systems.

Soil fertility is evaluated based on chemical properties that are averaged to determine overall soil fertility status (Chaudhry et al., 2024; Widijanto et al., 2025). These properties influence crop productivity and soil fertility under different management systems (P. J. Gao et al., 2024; T. Li et al., 2025). Suitable land management is essential to maximize the productivity of fertile soils (Javed et al., 2022). This study evaluates soil chemical properties of soil as indicators of fertility and determines the fertility index, classes and status of paddy soils in Babat District, Lamongan. Specifically, the study aims to characterize the chemical properties of paddy soils, quantify and classify soil fertility index and assess variations in soil fertility under different hydrological conditions. The findings are expected to provide a scientific contribution to a deeper understanding of soil fertility dynamics within paddy agroecosystems under varying hydrological conditions. From a practical perspective, the findings may serve as a valuable reference for farmers and land managers in developing more effective and sustainable soil management strategies.

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2. Material and Methods

2.1 Study Area and Period

Soil sampling was conducted in both irrigated and rainfed paddy fields across several villages in Babat District, Lamongan Regency, East Java, Indonesia. The study area is geographically located within the coordinates of 7o 4′ 27.99″ – 7o 8′ 31.36″ S and 112 o 13′ 37.34″ – 112o 15′ 45.40″ E. Laboratory analyses were performed at the Soil Physics Laboratory and the Soil Fertility Laboratory, Faculty of Agriculture, University of Jember. Field surveys and sampling were conducted in February, followed by laboratory analysis and data interpretation from March through June 2025.

2.2 Material and Instruments

The materials and instruments used in this study included:

1. air-dried soil samples
2. laboratory chemical reagents
3. An analytical balance
4. UV–Visible spectrophotometer
5. Atomic Absorption Spectrophotometer (AAS)

2.3 Experimental Design and Analytical Procedures

2.3.1 Site selection and instrument preparation

Field observations were conducted to identify suitable soil sampling locations and prepare the necessary equipment. Babat District was selected for its extensive, highly productive lowland paddy area, comprising both technically irrigated and rainfed paddy fields. Sampling sites were determined by purposive sampling based on land mapping unit (LMU) derived from overlaying administrative and land-use maps and subsequently verified through field checks to ensure consistency with actual land conditions. A total of 24 soil samplings were collected during the first growing season, comprising three field replicates from each of the eight identified LMUs, using a soil auger and shovel, the sample was stored in plastic containers for laboratory analysis.

2.3.2 Soil sampling

Soil sampling was based on field observations to determine representative sampling point reflecting soil variability within each observation unit, conducted over a two-week period across all designated land-use units according to the LMU map. At each sampling point, five subsamples were collected diagonally and composited into a single representative sample at a depth of 0-30 cm, corresponding to the root zone of food crops. Three field replicates were collected per LMU, yielding a total of 24 composite soil samples from the eight identified LMUs.

Sampling locations were considered representative of spatial variability within the study area, supported by prior overlay analysis of slope gradient maps ensuring that observed differences primarily reflect variations in land-use rather than topography. The resulting study area map delineates the distribution of rainfed and irrigated paddy fields, the focus of this research with LMUs indicating the designated sampling locations (Table 1).

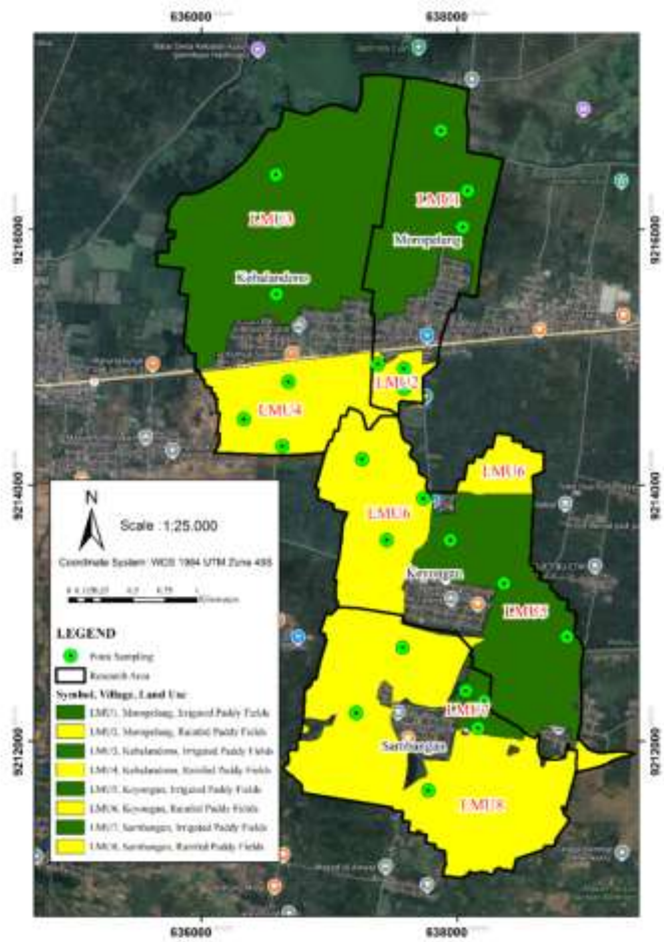

Figure 1. Spatial map of research area.

Table 1. Description of sample code, site location and land use.

Code	Village	Land Use	Areas (Ha)
LMU 1	Moropelang	Irrigated Paddy Fields	121.3
LMU 2	Moropelang	Rainfed Paddy Fields	17.0
LMU 3	Kebalandono	Irrigated Paddy Fields	239.4
LMU 4	Kebalandono	Rainfed Paddy Fields	82.0
LMU 5	Keyongan	Irrigated Paddy Fields	134.6
LMU 6	Keyongan	Rainfed Paddy Fields	126.8
LMU 7	Sambangan	Irrigated Paddy Fields	16.0
LMU 8	Sambangan	Rainfed Paddy Fields	238.5

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Sampling locations were determined based on the study area maps (Figure 1), which spatially delineates differences in water supply systems, making it suitable for comparing soil chemical properties and fertility status. Sampling points within each land mapping unit (LMU) were selected to proportionally and spatially represent irrigated and rainfed paddy fields in each research village. As the sites were located in proximity climate and topography were relatively similar (Figure 2), allowing observed differences to be primarily attributed to land-use and water supply system.

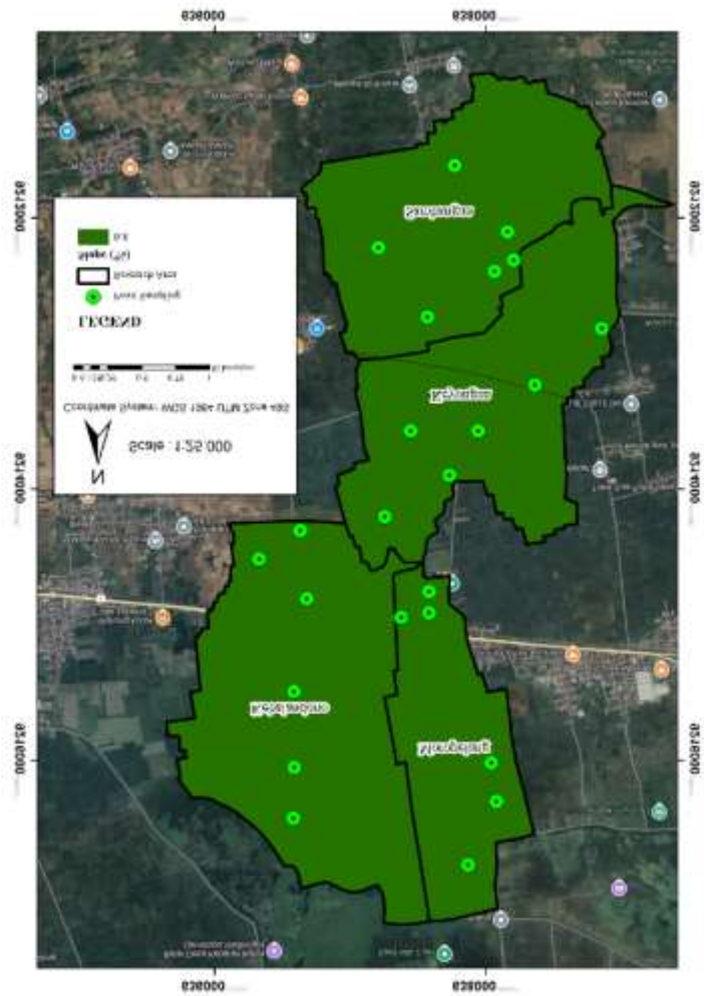

Figure 2. Slope (%) of research area.

2.3.3 Soil analysis

Laboratory soil analyses were conducted to precisely characterize soil chemical properties. The chemical characteristics and fertility status of soils in the study area were subsequently scored to determine the soil fertility index. Soil chemical properties are dynamic and may vary depending on land management practices applied to the analyzed sites. The chemical soil properties evaluated in this study included key fertility-related parameters used to assess soil quality and fertility status.

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2.4 Observation Variables And Data Analysis

Air-dried soil samples were gently disaggregated and sieved through 2 mm and 0.05 mm mesh sieves prior to laboratory analysis. As part of the quality control procedure, one duplicate sample was analyzed for every ten soil samples for each parameter examined. This procedure was implemented to ensure consistency, reliability and analytical accuracy of the laboratory result. The variables used in the analysis were selected to represent the main chemical properties affecting soil fertility status. These variables were analyzed using standard laboratory methods to ensure the accuracy of the research results. Parameters used in this analysis were chosen based on their ability to describe nutrient availability in the soil, soil capacity, and soil chemical conditions in soil fertility evaluation activities. The analytical methods used for each parameter are presented in Table 2.

Table 2. Soil analysis variables and analytical methods.

No	Variable	Method
1	Soil pH H_2O	pH meter
2	Organic Carbon	Walkley and Black method
3	Total N	Kjeldahl method
4	Available P	Olsen method
5	Cation exchange capacity (CEC)	NH_4OAc extraction (pH 7)
6	Exchangeable K	NH_4OAc extraction (pH 7)
7	Exchangeable Ca	NH_4OAc extraction (pH 7)
8	Exchangeable Mg	NH_4OAc extraction (pH 7)

2.4.1 Soil Fertility Status Assessment and Data Analysis

Soil chemical properties that influence soil fertility status were subsequently classified by comparing laboratory analysis results with standard criteria established by the Soil Research Center, 2023. The weighting of each parameter was determined based on its relative contribution to soil fertility (Table 3). However, it should be noted that the upper boundary value of the soil test result is classified into the lower class.

Table 3. Criteria, rating, scores, and weighting factors for soil analysis parameters.

No	Parameter	Weight	Nutrient Criteria		
			Low: 1	Medium: 2	High: 3
1	Soil pH	15	<5.5 or >7.5	5.5 – 6.5	6.5 – 7.5
2	Organic Carbon (%)	25	<1.25	1.25 – 2.5	>2.5
3	Total soil N (%)	10	<0.125	0.125 – 0.5	>0.5
4	Available P (mg/kg)	10	<10	10 – 15	>15
5	CEC (cmol(+)/kg)	20	<16	16 - 24	>24
6	Exchangeable K (cmol(+)/kg)	10	<0.3	0.3 – 0.5	>0.5
7	Exchangeable Ca (cmol(+)/kg)	5	<5	5 - 10	>10
8	Exchangeable Mg (cmol(+)/kg)	5	<1	1 - 2	>2

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The Soil Fertility Index (SFI) was calculated to evaluate the overall fertility status of the study area using the following formula:

$$SFI = (R'_H \times W_H) + (R'_C \times W_C) + (R'_N \times W_N) + (R'_P \times W_P) + \left(R'_{\{CEC\}} \times W_{\{CEC\}}\right) + (R'_K \times W_K) + \left(R'_{\{Ca\}} \times W_{\{Ca\}}\right) + \left(R'_{\{Mg\}} \times W_{\{Mg\}}\right)$$

Where: W_i= Weighting Factor; R'_i= Rating Score; H= Soil pH; C= Organic Carbon (%); N= Total Soil Nitrogen (%); P= Available Phosphorus (mg/kg); CEC= Cation Exchange Capacity (cmol(+)/kg); K= Exchangeable Potassium (cmol(+)/kg); Ca= Exchangeable Calcium (cmol(+)/kg); Mg= Exchangeable Magnesium (cmol(+)/kg).

The rating scores for each soil nutrient parameter were assigned according to established soil fertility criteria reported by (Soil Research Center, 2023). Weighting factors for each parameter were determined using the Analytic Hierarchy Process (AHP) developed by (Saaty, 1987). The eight selected soil fertility indicators were considered highly influential on crop productivity (Kumar et al., 2025). The weight of each indicator was determined through a pairwise comparation matrix using Saaty's 1-9 scale, in which a value of 1 indicates equal importance between two indicators, while a value of 9 indicates that one indicator is absolutely more important than the other. A reciprocal square matrix A = [a_{jk}] was subsequently generated, with all values assigned based on the pairwise comparisons. Each entry a_{jk} of matrix A represents the relative importance of the *j*th soil indicator compared to the *k*th soil indicators. The entries of matrix A must satisfy the following conditions:

$$a_{jk} \cdot a_{kj} = 1$$

$$For\ j\ and\ k = 1, 2,\ \dots\ n$$

Where *n* denotes the number of soil indicators evaluated.

The pairwise comparisons were assessed based on a synthesis of the relevant literature and subsequently aggregated using the geometric mean. The weight of each indicator was obtained by normalizing the comparison matrix, i.e., by dividing each element of the matrix by the sum of its respective column and then averaging the values across each row. To ensure an unbiased assessment throughout the pairwise comparison process, the consistency ratio (CR) of the resulting matrix A was calculated as follows:

$$CR = \frac{CI}{RI}$$

Where *CI* is the consistency index and *RI* is a random inconsistency index, as established by (Saaty, 1987). The consistency index (*CI*) was calculated according to the following equation:

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

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Where λ_{max} is the principal (largest) eigenvalue of the A matrix, n is the number of indicators evaluated. The comparison matrix was considered consistent when CR ≤ 0.10; if CR.> 0.10, the the pairwise judgement were revised until an acceptable level of consistency was achieved. Weight calculations were performed using Microsoft Excel.

2.4.2 Soil Fertility Index Classification

The Soil Fertility Index (SFI) was classified into five categories namely high; moderately high; moderate; moderately low and low fertility classes. Class intervals were determined using the equal interval method proposed by (Kraak & Ormeling, 2011), the class interval was calculated using the following equation:

$$Class\ interval = \frac{Maximum\ value - Minimum\ value}{Number\ of\ classes}$$

Based on this method, soil fertility levels were categorized according to their respective index values, resulting in the classification of soil fertility status into distinct levels, classes, and index ranges (Table 4).

Table 4. Soil fertility levels, classes, and index ranges.

Fertility Level	Fertility Class	Soil Fertility Index
I	High	261–300
II	Moderately high	221–260
III	Moderate	181–220
IV	Moderately low	141–180
V	Low	100–140

The calculated values were used to determine the soil fertility index, which was subsequently presented in tabular form and analyzed descriptively based on the associated soil parameters. In addition, laboratory-derived data were subjected to descriptive statistical analysis to characterize soil chemical properties and fertility status across the study area. Prior to comparing group means, normality of each soil chemical parameter was assessed using the Shapiro-Wilk test at the 5% significance level. When data did not meet the normality assumption ($p<0.05$), a log10 ($n+1$) transformation was applied to stabilize variance and approximate a normal distribution. Homogeneity of variance between groups (irrigated and rainfed fields) was evaluated using Levene's test. For, normally distributed data, difference between group means were tested using independent-samples t-test. The t-test was applied to assess differences in chemical properties (pH, OC, CEC, N, P, K, Ca, Mg and SFI) between irrigated paddy fields and rainfed paddy fields. If the variance values are equal or significant (>0.05), the Equal variance assumed method will be used, if the variance values are not significant (<0.05) the unequal variance assumed method will be applied.

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3. Results and Discussion

3.1 Soil pH

The soil test results (Table 5) indicate that the average pH levels of both irrigated and rainfed paddy fields are equally favorable (7.1 and 6.9). The pH range of this agricultural land is between 6.4 and 7.3, classified as slightly acidic to slightly alkaline. Soil pH is the most dynamic fertility parameter and the most sensitive to water regimes; this is related to redox electrochemical reactions under waterlogged conditions and alternating wet-dry conditions (Z. Zhang & Furman, 2021). Changes in the pH of paddy field soil following flooding and drainage indicate that irrigated paddy fields tend to be more stable and closer to neutral during the flooded period than during dry conditions (Ding et al., 2019; Mmbaga & Materu, 2025).

Table 5. Soil pH values**.**

LMU	Soil pH	Rating×15	Score
1	7.1 ± 0.47	3	45
2	7.3 ± 0.25	3	45
3	7.0 ± 0.07	3	45
4	6.4 ± 0.12	2	30
5	7.1 ± 0.03	3	45
6	6.5 ± 0.33	2	30
7	7.2 ± 0.73	3	45
8	7.2 ± 0.53	3	45

Rainfed paddy fields tend to be more acidic than irrigated paddy fields, though they are also close to neutral. Irregular wet-dry cycles cause greater fluctuations in soil pH. During the dry phase, the soil oxidizes and the pH tends to become acidic due to the formation of organic acids, while during the brief waterlogged phase, the pH temporarily rises to near neutral before dropping again as the soil dries out (Saputra et al., 2023). Soil fertility including pH in rainfed and irrigated paddy fields is influenced by the interaction of farming practices, rainfall levels, and landforms (Xing, Xie, et al., 2025).

3.2 Organic carbon (OC)

The results of soil analysis (Table 6) indicate that the average organic carbon (SOC) content in rainfed paddy fields (0.91%) was higher than that in irrigated paddy fields (0.57%). This difference is attributed to more intensive land management practices commonly applied in irrigated paddy systems, which can accelerate organic matter decomposition. Tillage intensity significantly influences soil properties, root development, and water use; therefore, minimum tillage practices play an important role in conserving soil organic matter (L. Li et al., 2022). Soil organic matter serves as a primary nutrient source for plants, as its mineralization releases plant-available ions such as NH_4^+,

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NO_3^-, HPO_4^{2-}, K^+, Ca^{2+}, and other essential elements. Measurements of SOC at the study sites ranged from 0.23% to 2.50%. These values fall within the low to high fertility criteria.

Soil organic carbon levels are dynamic and may increase through the incorporation of organic amendments such as compost and crop biomass residues, while simultaneously decreasing due to organic matter decomposition processes (Munawar, 2011).

Table 6. Organic carbon values (%).

LMU	Avg. OC (%)	Rating×25	Score
1	0.50 ± 0.23	1	25
2	0.59 ± 0.38	1	25
3	0.39 ± 0.13	1	25
4	2.50 ± 0.72	2	50
5	1.04 ± 0.61	1	25
6	0.30 ± 0.18	1	25
7	0.35 ± 0.13	1	25
8	0.23 ± 0.26	1	25

The lower percentage of organic carbon in irrigated paddy fields is due to continuous flooding, which accelerates water percolation through the soil profile, leading to the leaching of water-soluble organic matter and, consequently, the loss of carbon from the topsoil (Hou et al., 2025). Soil organic carbon content is influenced not only by land use type (irrigated and rainfed paddy fields) but also by the consistency of organic matters in addition to agricultural land. The wet-dry cycle that occurs in rainfed paddy fields increases microbial activity and accelerates carbon mineralization; however, when balanced by regular inputs of organic matter, the rate of carbon accumulation can exceed the rate of decomposition, resulting in an increase in soil organic matter (Peng et al., 2025; N. Zhang et al., 2025).

3.3 Cation Exchange Capacity (CEC)

The soil analysis results (Table 7) indicate that cation exchange capacity (CEC) in rainfed paddy fields (46.2 cmol(+)/kg) was higher than that in irrigated paddy fields (42.2 cmol(+)/kg). Measurements of CEC across the study area ranged from 36.8 to 64.4 cmol(+)/kg, which is included in the high fertility categories. Clay is strongly influenced by the presence of soil colloids carrying negative or positive electrical charges. Negatively charged colloidal surfaces have the capacity to absorb and retain soil cations (Hanafiah, 2014).

Table 7. Cation exchange capacity values (cmol(+)/kg).

LMU	Avg. Soil CEC	Rating×20	Score
1	43.3 ± 3.23	3	60
2	44.7 ± 2.46	3	60
3	41.0 ± 7.35	3	60

LMU	Avg. Soil CEC	Rating×20	Score
4	38.5 ± 7.50	3	60
5	36.8 ± 4.00	3	60
6	37.3 ± 0.50	3	60
7	47.6 ± 15.0	3	60
8	64.4 ± 5.40	3	60

Soil colloids consist of inorganic colloids (clay minerals) and organic colloids (humus). The proportion and type of clay minerals significantly affect soil CEC; clay minerals are secondary minerals formed through the weathering of primary minerals. The relatively high clay content indicates a well-developed soil, which contributes to elevated CEC values (Hardjowigeno, 2016). CEC is also influenced by the organic carbon content, which directly increases the negative charge of soil colloids. The higher organic matter content in rainfed paddy fields is directly proportional to a higher cation exchange capacity compared to irrigated paddy fields (Bi et al., 2023). The CEC values for both land-use types remain in the high range, indicating that organic matter and soil texture are similar across the study area's land-use types, given that CEC is consistently determined by a combination of organic matter and soil particle size composition (CIRIC et al., 2023; Mishra et al., 2022).

3.4 Total Nitrogen (N-total)

Nitrogen is classified as a primary macronutrient, meaning it is required by plants in relatively large quantities. It is frequently the most limiting nutrient affecting crop yields in tropical regions (Sanchez, 1992). Plants primarily absorb nitrogen in the form of nitrate (NO_3^-) and ammonium (NH_4^+). Soil analysis (Table 8) revealed comparable nitrogen contents in rainfed and irrigated paddy fields, with average values of 0.42% and 0.39%, respectively. Nitrogen concentrations measured across the study sites ranged from 0.28% to 0.58%, which corresponds to a moderate to high fertility category. The similarity in nitrogen levels between irrigated and rainfed paddy systems indicates relatively balanced nitrogen availability across land use types. Soil nitrogen content is influenced by several processes, including leaching, volatilization, and plant uptake (Verma et al., 2023).

Table 8. Total nitrogen values (%).

LMU	Avg. N (%)	Rating×10	Score
1	0.36 ± 0.16	2	20
2	0.38 ± 0.15	2	20
3	0.33 ± 0.10	2	20
4	0.31 ± 0.46	2	20
5	0.28 ± 0.25	2	20
6	0.54 ± 0.05	3	30
7	0.58 ± 0.62	3	30
8	0.43 ± 0.55	2	20

Soil nitrogen content in irrigated and rainfed paddy fields is controlled by losses due to leaching and runoff, as well as N supply from the mineralization of organic matter. Water management plays a crucial role in soil nitrogen efficiency, as N concentrations in surface water are more prone to loss through runoff and percolation during rainfall in flooded periods (S. Zhang et al., 2026). The nitrogen status in the study area requires improvement to ensure adequate nutrient availability for cultivated crops. The application of organic and inorganic fertilizers represents an effective strategy to enhance soil nitrogen availability and sustain crop productivity (K. Zhang et al., 2025).

3.5 Phosphorus (Available P)

Primary and secondary phosphorus minerals undergo weathering and dissolution processes that supply $H_2PO_4^-$ and HPO_4^{2-} ions into the soil solution. Inorganic phosphorus adsorbed onto mineral surfaces in the form of orthophosphate can be released back into the soil solution, thereby contributing to plant-available phosphorus pools (Nurhidayati, 2017). The results (Table 9) show that irrigated paddy fields exhibited a higher average available phosphorus content (45.82 mg/kg) compared to rainfed paddy fields (33.56 mg/kg). Available phosphorus concentrations ranged from 20.47 to 65.85 mg/kg, indicating high fertility levels.

Table 9. Available phosphorus values (mg/kg).

LMU	Avg. P (mg/kg)	Rating × 10	Score
1	25.29 ± 4.31	3	30
2	25.06 ± 2.47	3	30
3	44.56 ± 9.22	3	30
4	58.87 ± 16.7	3	30
5	65.85 ± 13.2	3	30
6	29.83 ± 5.77	3	30
7	47.57 ± 1.96	3	30
8	20.47 ± 10.1	3	30

The relatively high availability of phosphorus in the study area is associated with intensive agricultural inputs. The availability of phosphorus in irrigated paddy fields is related to the redox chemistry of iron. Under flooded conditions, the low redox potential causes Fe^{3+} to be reduced to Fe^{2+}, which dissolves iron-phosphorus compounds, thereby making phosphorus more available to plants (Ando et al., 2022). The water-logging regime in irrigated paddy fields maintains reductive conditions that support the consistent release of P from Fe minerals throughout the growing season. In contrast, in rainfed paddy fields, irregular wet-dry cycles cause the soil to be in an oxidative state, leading to the conversion of Fe^{2+} to Fe^{3+} and the re-binding of P (P fixation), which ultimately reduces the efficiency of P uptake by plants (Wang et al., 2024).

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3.6 Potassium (K)

Potassium is an essential macronutrient that plays a critical role in plant physiological and metabolic processes, and no other element can substitute its function. Plants absorb potassium primarily in the form of K^+ ions. Although total potassium concentrations in soils are often high, only a small fraction is readily available for plant uptake (Munawar, 2011). The results (Table 10) indicate that rainfed paddy fields had a higher average exchangeable potassium content (0.67 cmol(+)/kg) compared to irrigated paddy fields (0.53 cmol(+)/kg). Exchangeable potassium values ranged from 0.41 to 0.85 cmol(+)/kg, which is included in the medium to high fertility category.

Table 10. Exchangeable potassium values (cmol(+)/kg).

LMU	Avg. K (cmol(+)/kg)	Score × 10	Result
1	0.76 ± 0.15	3	30
2	0.85 ± 0.10	3	30
3	0.51 ± 0.02	3	30
4	0.63 ± 0.29	3	30
5	0.45 ± 0.18	2	20
6	0.64 ± 0.18	3	30
7	0.41 ±0.04	2	20
8	0.58 ± 0.24	3	30

Irrigated paddy fields with continuous waterlogging cause continuous water percolation, which leads to the leaching of base cations—including K+—from the topsoil layer (Wu et al., 2026). Potassium management is crucial for plants because this element is a macronutrient. Crop yield responses generally increase with higher fertilization levels until optimal nutrient supply is achieved (J. Liu et al., 2024). The low frequency of irrigation in rainfed paddy fields can help retain potassium for a longer period, but the exchangeable potassium status is determined by agronomic management (type and frequency of fertilizer application, drainage levels) rather than solely by the water regime (Z. Gao et al., 2025; McCarthy et al., 2025).

3.7 Secondary Macronutrients

Primary and secondary macronutrients are distinguished mainly by the quantity required by plants for optimal growth rather than by their functional importance. Secondary macronutrients consist of magnesium (Mg), calcium (Ca), and sulfur (S), all of which are essential for plant nutrition. Deficiency of these nutrients can significantly constrain plant growth, like deficiencies of primary macronutrients (Munawar, 2011). Calcium is absorbed by plants predominantly in the form of Ca^{2+} ions, whereas magnesium is taken up as Mg^{2+} ions.

Laboratory analyses (Table 11) indicate that exchangeable calcium (Ca-exch) concentrations range from 4.01 to 4.92 cmol(+)/kg, while exchangeable magnesium (Mg-exch) values range from 4.29 to 4.78 cmol(+)/kg. Ca and Mg are bases whose availability dynamics are controlled by water through

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different mechanisms of leaching and accumulation. Both irrigated and rainfed paddy fields have similar Ca and Mg contents. These two elements are more stable than other elements under varying water regimes compared to highly sensitive nutrients (Fe, P, or N). The availability of these two elements in the soil is influenced more by CEC and soil pH than by the water regime itself (Z. Liu et al., 2021). This equilibrium also reflects the balance between these two factors, emphasizing that the availability of Ca and Mg is influenced by the interaction between soil texture and soil organic matter. This indicates that the water regime is not the sole determinant of soil fertility parameters (Ndegwa et al., 2023; H. Sun et al., 2025; Xing, Xie, et al., 2025)

Table 11. Exchangeable calsium and magnesium values (cmol(+)/kg).

LMU	Avg. Ca (cmol(+))/kg)	Score×5	Result	Avg. Mg (cmol(+)/kg)	Score×5	Result
1	4.71 ± 0.65	1	5	4.62 ± 0.09	3	15
2	4.59 ± 0.32	1	5	4.58 ± 0.03	3	15
3	4.93 ± 0.06	1	5	4.75 ± 0.13	3	15
4	4.49 ± 0.21	1	5	4.64 ± 0.09	3	15
5	4.01 ± 0.04	1	5	4.78 ± 0.13	3	15
6	4.21 ± 0.56	1	5	4.29 ± 0.30	3	15
7	4.77 ± 0.60	1	5	4.50 ± 0.03	3	15
8	4.57 ± 0.86	1	5	4.34 ± 0.18	3	15

3.8 Statistical Analysis of Soil Properties

Normality tests were conducted to determine the distribution of data for each soil parameter in the irrigation and rainfed paddy field land-use systems. Normality tests were performed using the Shapiro-Wilk test with a significance level of 5% (p = 0.05); the test results are presented in table 12.

Table 12. Normality test.

Parameter	Shapiro-Wilk	
	Sig.Rainfed	Sig. Irrigated
pH	0.854	0.149
OC	0.641	0.225
CEC	0.132	0.053
Nitrogen	0.750	0.150
Phosphorus	0.063	0.856
K	0.097	0.875
Ca	0.889	0.078
Mg	0.076	0.521
SFI	0.163	0.065

Note: n = 12, number of samples analyzed; each group (irrigated and rainfed) consisted of 12 samples

Based on the Shapiro-Wilks (Table 12) normality test, the majority of the data on the parameters of rainfed and irrigated paddy fields had significance values > 0.05. Most of these data can be considered

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normally distributed, only organic carbon needs data transformation using log10 (n+1). The results of the normality test determine the subsequent analysis for comparing soil characteristics between rainfed and irrigated paddy fields. Further testing will be conducted to assess the homogeneity of variances using Levene's test (Table 13), variance of soil organic carbon carbon differed significantly (p=0.01<0.05). This parameter was subsequently analyzed using an independent-samples t-test under the equal variance not assumed condition, all other soil chemical parameters exhibited homogeneous variances (p> 0.05), followed by an independent samples t-test.

Table 13. Homogenity test.

Parameter	Levene's Test (F)	Sig.	Note
pH	2. 442	0.132	Homogeneous
OC	7.831	0.010	Non-homogeneous
CEC	1.604	0.219	Homogeneous
N	1.616	0.217	Homogeneous
P	0.018	0.896	Homogeneous
K	1.255	0.275	Homogeneous
Ca	0.807	0.379	Homogeneous
Mg	2.627	0.119	Homogeneous
SFI	1.456	0.240	Homogeneous

Note: *n* = 12, number of samples analyzed; each group (irrigated and rainfed) consisted of 12 samples

To further evaluate differences in soil chemical properties between irrigated and rainfed paddy fields, an Independent-samples t-test was conducted for all observed parameters. Independent-samples t-test indicated non statistically significant differences (Table 14) in most soil chemical properties between irrigated (n=12) and rainfed (n=12) at the 5% significance level (p>0.05). Soil pH tended to be higher in irrigated paddy fields (7.08± 0.38) than in rainfed paddy fields (6.85± 0.51), though the difference was not significant (p=0.235). Soil total N was likewise comparable between irrigated (0.38± 0.15) and rainfed paddy fields (0.41± 0.12; p=0.658).

Table 14. Result of t-test statistical analysis of soil properties.

Parameter	Group	Mean ± Sd	t	df	p-value	Std. Error Mean	Mean Difference	95% Cl of the Mean Difference
pH	Irrigated	7.08± 0.38	1.220	22	0.235	0.18242	0.22250	-0.15582 – 0.60082
	Rainfed	6.85± 0.25						
OC	Irrigated	0.57± 0.41	-0.149	16.4	0.883	0.15525	-0.02311	-0.35152 – 0.30531
	Rainfed	0.90± 0.48						
CEC	Irrigated	42.18± 8.52		22	0.357		-4.01667	

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Parameter	Group	Mean ± Sd	t	df	p-value	Std. Error Mean	Mean Difference	95% Cl of the Mean Difference
	Rainfed	46.20± 12.07	-0.942			4.26511		-12.86197 – 4.82864
N	Irrigated	0.38± 0.15	–0.448	22	0.658	0.05392	-0.02417	-0.13599 – 0.08765
	Rainfed	0.41± 0.12						
P	Irrigated	45.81± 16.65	1.735	22	0.097	7.06212	12.25417	-2.39593 – 26.90426
	Rainfed	33.55± 17.94						
K	Irrigated	0.54± 0.18	-1.714	22	0.101	0.07925	-0.13583	-0.30019 – 0.02852
	Rainfed	0.67± 0.20						
Ca	Irrigated	4.60± 0.53	0.659	22	0.517	0.20868	0.13750	-0.29527 – 0.57027
	Rainfed	4.46± 0.49						
Mg	Irrigated	4.66± 0.15	2.594	22	0.017	0.07709	0.20000	0.04013 – 0.35987
	Rainfed	4.46± 0.22						

Note: n = 12, number of samples analyzed; each group (irrigated and rainfed) consisted of 12 samples.

Organic carbon and CEC tended to be higher in rainfed land, consistent with the role of organic matter in providing negative charges that enhance cation retention, although neither difference reached significance. Available P tended to be higher in irrigated land, while exchangeable K tended to be higher in rainfed land; these non-significant variations may reflect differences in fertilizer application, plant uptake, leaching, and water dynamics between the two management systems. The most pronounced difference was observed for soil Mg, which was significantly higher in irrigated land ($t = 2.594$, $p = 0.017$; mean difference = 0.200, 95% CI: 0.040–0.359). This finding suggests that differences in water dynamics and management practices between irrigation systems may influence the retention and mobility of Mg cations in soil. Soil Ca did not differ significantly between the two systems ($p = 0.517$).

Overall, Mg was the only parameter showing a statistically significant response to land management system, while pH, OC, CEC, N, P, K, and Ca did not. Given the relatively small sample size ($n = 12$ per group), the statistical power to detect smaller effects for these parameters may have been limited; thus, the absence of significant differences should not be interpreted as conclusive evidence of equivalence between the two management systems.

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3.9 Soil Fertility Index

The Soil Fertility Index (SFI) was determined based on a weighted evaluation of selected soil chemical properties to assess the overall fertility status of the study area (Table 15). Each analytical parameter was assigned a specific score and weight, allowing for an integrated assessment that reflects actual soil fertility conditions. The calculated SFI values for each land mapping unit provide a comprehensive representation of soil fertility variability across the research location and are presented in the following table. The soil fertility index in this study is essentially determined by pH, organic carbon, nitrogen, and available potassium compared to other parameter data due to differences in soil analysis results between land units. These four parameters reflect the general pattern that parameters with a significant coefficient of variation evidently determine the differentiation of fertility classes, whereas parameters with uniform variation tend to disappear statistically regardless of the nominal weight assigned to them (Bostani et al., 2025).

Soil fertility reflects the availability of essential nutrients in the soil and serves as a fundamental basis for determining suitable land management strategies to support optimal crop growth. According to Winarso, 2005 soil fertility is defined as the capacity of soil to supply nutrients in sufficient, adequate, and balanced amounts to plants in readily available forms. Based on the data analysis, the study area located in Babat District (Moropelang, Kebalandono, Keyongan, and Sambangan villages) exhibits soil fertility index values ranging from moderate to moderately high. Variations in land use and land management practices across study sites are key factors influencing soil fertility status. These findings provide an important reference for developing land management practices that are aligned with land capability and suitability to enhance crop productivity (AbdelRahman et al., 2025; Ewunetu et al., 2025).

The analysis showed that rainfed paddy fields had higher organic matter content (0.91%) than irrigated paddy fields (0.57%). This condition is presumably associated with the more intensive soil management practices commonly applied in irrigated fields compared with rainfed systems. Intensive tillage can disrupt soil aggregates and expose previously protected organic matter to microbial activity (R. K. Srivastava, 2025). Consequently, the decomposition rate of organic matter increases, leading to lower soil organic carbon (SOC) content in irrigated paddy fields. The decline in SOC content also reduces the abundance of functional groups, particularly carboxyl and phenolic groups, which serve as important sources of negative charges in soil (Q. Li et al., 2023). A reduction in these negative charges decreases the soil's capacity to adsorb and exchange cations. Consequently, the retention of base saturations becomes less effective, resulting in lower cation exchange capacity (CEC) values in irrigated paddy fields (42.2 cmol(+)/kg) compared with rainfed paddy fields (46.2 cmol(+)/kg). In addition to organic matter, the clay fraction also plays a significant role in determining soil CEC (Yang et al., 2024).

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Table 15. Soil fertility index (SFI).

LMU	*R′*×*W* pH	*R′*×*W* OC	*R′*× W N	*R′*x*W* P	*R′*× *W* K	*R′* × *W* CEC	*R′* × *W* Ca	*R′*×*W* Mg	SFI Value	SFI Class
1	45	25	20	30	30	60	5	15	230 ± 13.22	Moderately High
2	45	25	20	30	30	60	5	15	230 ± 20.81	Moderately High
3	45	25	20	30	30	60	5	15	230 ± 7.64	Moderately High
4	30	50	20	30	30	60	5	15	240 ± 26.45	Moderately High
5	45	25	20	30	20	60	5	15	220 ± 7.64	Moderate
6	30	25	30	30	30	60	5	15	225 ± 10.41	Moderately High
7	45	25	30	30	20	60	5	15	230 ± 12.58	Moderately High
8	45	25	20	30	30	60	5	15	230 ± 30.41	Moderately High

Notes: *R′* = Rating, *W* = Weight; LMU = Land Mapping Unit.

The nitrogen content of rainfed fields is higher than that of irrigated paddy fields. However, nitrogen losses range from 24.90% to 76.29%, depending on irrigation conditions, fields that are continuously flooded are prone to losses due to high leaching rates (Uddin et al., 2021). High nitrogen loss in irrigated paddy fields is influenced by denitrification under flooded conditions. Inorganic N contained in chemical fertilizers breaks down quickly and is easily lost, whereas N contained in organic fertilizers breaks down more slowly and is more easily retained in the soil (Ma et al., 2023).

Increasing nitrogen fertilizer application rates can lead to high nitrate accumulation, resulting in nitrogen loss through leaching, which can reduce fertilizer efficiency and soil fertility (Kuśmierz et al., 2023). Organic nitrogen, which is more stable in the soil and capable of enhancing soil fertility sustainably in both irrigated and rainfed paddy fields. Land management combining organic fertilizers with proper irrigation practices can help maintain and enhance soil fertility sustainably (A. Ahmad et al., 2025). Exchangeable base cations in both irrigated and rainfed paddy soils exhibited relatively high concentrations of K and Mg, whereas Ca was classified as low. The application of organic fertilizer coupled with suitable land management is expected to enhance the exchangeable cation content and mitigate the risk of nutrient deficiency resulting from runoff-leaching losses and intensive cultivation systems (Sarkar et al., 2025; Yang et al., 2024).

The study area comprises two major land-use types, namely rainfed paddy fields and irrigated paddy fields. Figure 3 shows that irrigated paddy fields were predominantly classified as having a moderate (LMU 5) to moderately high (LMU 1, 3, 7) soil fertility index. Irrigated paddy fields represent the most intensively utilized agricultural land by farmers, with paddy as the dominant crop.

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Consequently, intensive soil cultivation practices are unavoidable in these systems (Bwire et al., 2024; Wei et al., 2022). A moderately high level of soil fertility is generally sufficient to sustain relatively high crop productivity; however, land management must prioritize sustainability to prevent soil degradation that could lead to declining fertility. The soil fertility class of irrigated paddy fields makes it possible to grow crops year-round with high crop productivity. The availability of nutrients and soil buffering capacity can adequately meet the plants' nutritional needs while maintaining soil fertility through balanced agricultural inputs (N. M. Ahmad et al., 2026; Xing, Wang, et al., 2025).

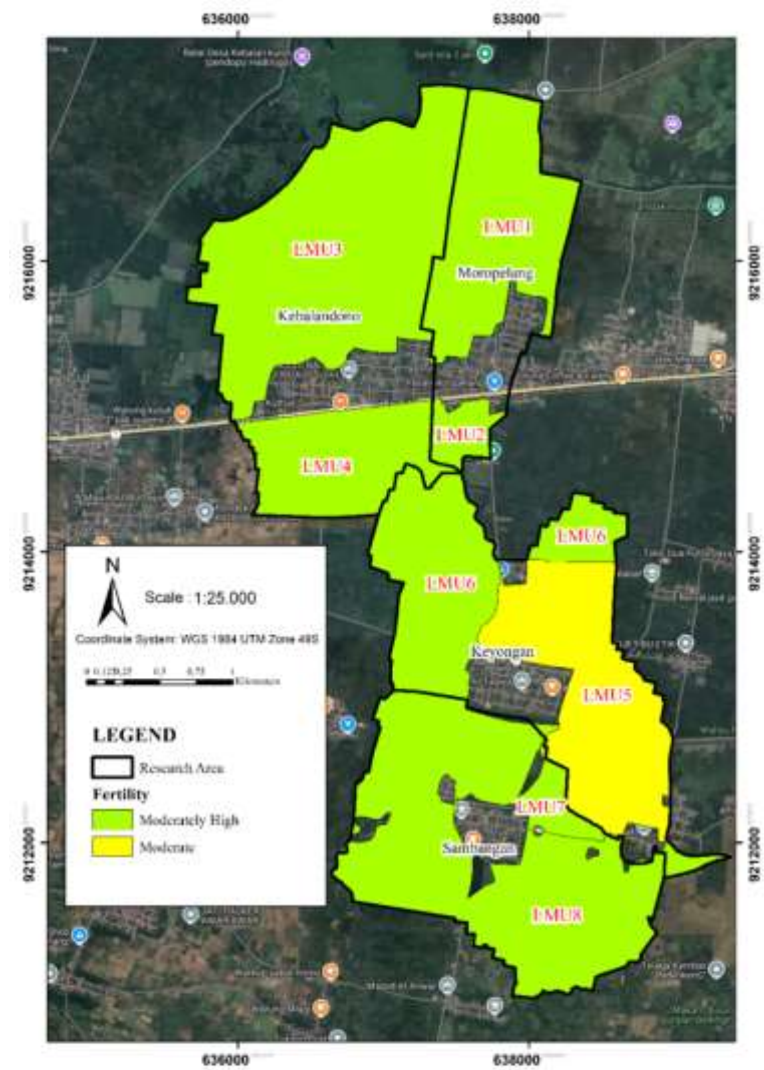

Figure 3. Spatial distribution map of soil fertility index.

The area of irrigated paddy fields with moderately high soil fertility covers 376.8 hectares, while the area with moderate soil fertility covers 134.6 hectares. These differences in soil fertility are most likely influenced by varying management histories among plots, even though they share the same

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irrigation type (Bostani et al., 2025). Farmer-level decision-making regarding variations in fertilization practices among farmers also differs, even within the same irrigation system and under the same regional recommendations. The use of organic or semi-organic fertilizers is more intensive than other methods. The application of fertilizers such as urea, Phonska, and ZA contributes to maintaining soil fertility and supports crop growth (N. M. Ahmad et al., 2026; Verma et al., 2023) Soil plays a central role in sustaining future livelihoods, and its relationship with life is closely linked to conservation efforts, nutrient cycling, and the long-term sustainability of agricultural systems that underpin the biosphere (Lybrand, 2023).

Soil fertility index value for rainfed paddy fields in the study area (Figure 3) was classified as having moderately high fertility (LMU 2, 4, 6, 8). A major constraint in rainfed paddy systems is water availability during the dry season. Nutrients associated with organic matter stimulate microbial activity, which subsequently enhances mineralization and decomposition processes, ultimately improving soil fertility in rainfed paddy fields (Hu et al., 2023). Rainfed paddy fields are generally cultivated during the rainy season, while land preparation and cropping activities are suspended during the dry season due to water scarcity. Nevertheless, rainfed paddy fields can be utilized during the dry season when sufficient supplemental water supply is available (Erythrina et al., 2021; Malo & Saha, 2025).

The area of rainfed paddy fields with moderately high fertility is 464.3 ha. The relatively flat slope variability (small elevation differences) causes the nutrient translocation mechanism between land positions to be weak, so no soil fertility gradient is formed (J. Sun et al., 2025). Paddy field management through puddling is a universal practice in paddy cultivation that can significantly alter soil properties, so the soil becomes anthropogenically modified compared to its original condition. This process mechanically mixes and levels the topsoil every planting season, which can effectively "standardize" the chemical properties of the soil surface (Asenso et al., 2022).

The management patterns carried out by farmers, such as mudding and flooding during the rainy season, become more dominant controlling factors compared to climate/landscape factors. All farmers in the study area apply relatively the same fertilizer doses, varieties, and planting patterns, so this uniform external nutrient input can compensate for the natural fertility variations of the land (Ando et al., 2026; Garnaik et al., 2022). Nutrient requirements in agricultural cropping systems are generally higher than those in other land uses, such as dryland farming or plantations, due to shorter crop rotation cycles. Soil fertility alone does not necessarily indicate land productivity; productive land is defined as land that effectively supports crop production to achieve maximum agricultural output (Winarso, 2005).

The study area is characterized by soil fertility levels that are suitable for crop cultivation, as the available nutrients are sufficient to meet crop demands. Both synthetic and organic fertilizers may be applied to maintain or enhance soil fertility in the study area (Ren et al., 2025). Balanced fertilizer

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management is essential to preventing nutrient imbalances in the soil solution, balanced fertilization rates play a critical role in maintaining soil fertility and ensuring an adequate supply nutrient to support optimal plant growth and (Samijan et al., 2024; Walia et al., 2024). The application of synthetic chemical fertilizers can enhance nutrient uptake by crops due to their rapid ability to replenish nutrients removed through plant absorption (Chang et al., 2024). However, the use of synthetic fertilizers should be integrated with organic amendments, such as animal manure and paddy straw soil organic matter improves soil fertility by modifying physical properties, including reducing soil compaction and enhancing the formation and stability of soil aggregates.

More intensive land management practices in irrigated paddy fields compared to rainfed systems can accelerate the decline in soil fertility by increasing the risk of soil degradation by approximately 67% and increasing the risk of erosion (Hassan et al., 2022). Therefore, soil conservation measures are essential to mitigate these risks. Agricultural soil must be maintained in adequate quantity and quality to sustainably produce food, fiber, and energy without causing adverse impacts on nutrient balance, environmental health, and ecosystem functions. Soil conservation practices and the application of soil amendments represent effective strategies for improving and sustaining soil fertility (Krasilnikov et al., 2022).

Table 16. Result of t-test statistical analysis of soil fertility index.

Parameter	Group	Mean ± Sd	t	df	p-value	Std. Error Mean	Mean Difference	95% Cl of the Mean Difference
SFI	Irrigated	225± 10.33	-0.607	22	0.550	7.54511	-4.58333	-30.23093 – 11.06426
	Rainfed	229± 24.01						

Note: n = 12 per group; low statistical power limits the ability to detected true differences

Based on the T-test statistical analysis (Table 16) Soil Fertility Index (SFI) values for rainfed paddy fields tended to be higher than those for irrigated paddy fields. However, the results of the t-test indicated no significant difference ($p= 0.55 > 0.05$) in SFI values between the two land-use system groups. These results indicate that the SFI values observed descriptively between the two land-use systems have not yielded a statistically significant difference; this is due to the limited data (n = 12) used in the analysis of the Soil Fertility Index (SFI) values at the study site. The absence of a significant difference does not necessarily mean that the land-use system has no effect on SFI values; rather, it may indicate the limitations of statistical tests in detecting significant differences in SFI between irrigated and rainfed paddy fields.

4. Conclusion

The Soil Fertility Index, calculated from soil chemical parameters (pH, organic carbon, total nitrogen, available phosphorus, cation exchange capacity [CEC], potassium [K], calcium [Ca], and magnesium [Mg], indicate moderate to moderately high fertility in Babat district. The values for available phosphorus, exchangeable magnesium, and CEC were relatively high across the study plots, while exchangeable calcium was the lowest. The t-test results state that only magnesium element showed a statistically significant response to land management system between irrigated and rainfed paddy fields ($p=0.02 < 0.05$). However, given the limited sample size, these findings require further confirmation. Differences in irrigation systems between technically managed and rainfed paddy fields are suspected to contribute to variations in nutrient status. The low nutrient content (organic carbon and Exch Ca) indicates the need to increase organic matter input on fields classified as low. Further research with a larger sample size is recommended to increase the statistical power of the test and the generalizability of the results.

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6. AI Writing Statement

During the preparation of this manuscript, the authors used “Claude (Anthropic)” to improve sentence structure and paraphrase content originally written in Indonesian by the authors, in order to enhance clarity and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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