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Rice field soil quality assessment through various environmental diversity sources in Ende District, East Nusa Tenggara, Indonesia

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Abstract. *Mutiara C, Bolly YY, Hutubessy JIB, Aggrey H, Dahiba S, Palelet EY, Romadhon MR, Irmawati V, Hasanah K. 2025. Rice field soil quality assessment through various environmental diversity sources in Ende District, East Nusa Tenggara, Indonesia. Asian J Agric 9: 264-275.* Ende District, located in East Nusa Tenggara, Indonesia, is an important agricultural area known for its diverse food commodities, particularly rice. Despite ongoing rice cultivation, local production satisfies less than 50% of the community's needs, necessitating substantial imports from outside the region. Wewaria Sub-district, with 1,526.4 hectares of rice fields, is the largest rice-producing area in the district and the sole source of premium-quality rice. However, rice productivity in Ende remains low due to constraints such as suboptimal seed quality, inadequate infrastructure, and poor agronomic management. This study highlights the crucial influence of soil quality on rice yields and investigates both the physical and chemical characteristics of soil in Wewaria. A descriptive exploratory survey was conducted, focusing on environmental variability in relation to drainage patterns, altitude, and slope gradients. Land mapping units were delineated using thematic maps, Geographic Information System (GIS) tools, and soil sampling to determine representative locations for analysis. Preliminary assessments revealed key limitations, including nutrient deficiencies, low soil pH, and limited availability of potassium and nitrogen—factors that significantly restrict productivity. The findings emphasize the necessity of targeted soil quality assessments to guide sustainable agricultural practices, improve rice yields, and address critical challenges faced by local farmers. This research seeks to provide a comprehensive analysis of soil conditions in Wewaria to inform the development of effective strategies for enhancing rice production and strengthening regional food security.

Keywords: Agricultural sustainability, food security, soil fertility, soil health, Wewaria Sub-district

INTRODUCTION

Ende District, located in East Nusa Tenggara, Indonesia, is known for its diversity of food commodities, with rice being one of the most widely consumed staples among the local population. Despite being a rice-producing area, local production in Ende satisfies less than 50% of the community's needs, with the remainder sourced from outside the region (Indonesian Central Agency of Statistics 2021). The district comprises a total of 4,264.4 hectares of rice fields, including 3,268 hectares of irrigated fields and 996.4 hectares of rainfed fields. Among these, Wewaria Sub-district accounts for 1,526.4 hectares—approximately 35.79% of the total area (Ende District Agricultural Service 2021). It not only has the most extensive rice field coverage in the district but also serves as the sole source of premium-quality rice. In view of this, the local government has proposed to designate Wewaria as a central food production zone.

From 2018 to 2020, rice productivity in Ende District ranged between 3 and 4 tons per hectare (Indonesian Central Agency of Statistics 2021). Interviews with agricultural extension workers and local farmers in Wewaria indicate that achieving yields close to 4 tons per hectare is difficult and generally considered suboptimal. According to productivity classifications, yields below 5 tons per hectare are categorized as low, 5-6 tons as medium, and above 6 tons as high (Indonesian Central Agency of Statistics 2007). Numerous factors affect both rice availability and field productivity. In response, the district government undertook a preliminary study in 2021 to assess the rice sector in Wewaria, identifying issues related to seed pricing, availability of quality seeds, inadequate infrastructure, and farmer group management (Fatima et al. 2022). However, soil conditions—an essential factor in rice productivity—remain insufficiently analyzed.

Soil characteristics significantly influence the quantity and quality of crop production (Mujiyo et al. 2022). Variations in the physical and chemical properties of soil can directly impact rice yield outcomes (Pratama et al. 2024). Moreover, soil attributes are intrinsically linked to agricultural performance (Herawati et al. 2024). In Wewaria, rice cultivation typically lacks organic inputs, with inorganic fertilizers applied at rates of 250-300 kg per hectare. Theoretically, such application rates should support yields exceeding 5 tons per hectare (Hasnain et al. 2020). However, persistent low productivity indicates underlying constraints associated with soil quality.

Assessing soil quality provides a pathway to enhance productivity by identifying critical limitations (Surendran et al. 2021). Dossou-Yovo et al. (2020) reported that potassium and total nitrogen availability are key constraints in rice cultivation. Similarly, Michael (2021) identified common issues such as nutrient deficiencies, low soil pH, and phosphorus fixation. Targeted soil quality research enables the formulation of site-specific strategies to address such constraints. For example, the combined application of nitrogen fertilizer and rice straw can improve both yield and soil health (Zhang et al. 2021). Moreover, conservation practices such as no-tillage and organic farming systems have demonstrated superior outcomes in rice productivity and soil quality compared to conventional methods (Denardin et al. 2020; Romadhon et al. 2024).

Despite these insights, no comprehensive studies have been conducted in Wewaria to evaluate the physical, chemical, and biological aspects of rice field soils. As a result, productivity improvement efforts remain fragmented and ineffective. Therefore, this study aims to assess the soil quality of rice fields in Wewaria Sub-district through a combination of field surveys, soil sampling, and laboratory analysis, thereby providing evidence-based strategies to improve rice productivity in the region.

MATERIALS AND METHODS

Research time and location

This study was conducted in Wewaria Sub-district, located within Ende District, East Nusa Tenggara Province, Indonesia (Figure 1). Geographically, Wewaria lies between 8°39′49.8″-8°28′18.3″ S and 121°47′46.7″-121°37′07.9″ E. As the most extensive rice-producing area in Ende, Wewaria holds considerable agricultural significance, particularly as a source of premium rice. The region encompasses approximately 1,526.4 hectares of rice fields, which are key to understanding local agricultural practices and production challenges. The research specifically focuses on evaluating soil and climatic conditions that influence rice productivity, with emphasis on pH levels, nutrient availability, and overall soil quality.

Research materials

Field activities were conducted in rice fields managed by Universitas Flores, which supports the local farming community in Wewaria. The primary environmental variables considered for analysis were drainage systems, altitude, and land slope. Two main types of rice field drainage systems—irrigated and rainfed—were identified (Figure 2). To delineate Land Mapping Units (LMUs), researchers overlaid the Rupa Bumi Indonesia base map with thematic maps representing environmental diversity across the study area. These included drainage type, elevation (Figure 3), and slope characteristics (Figure 4). The resulting land classifications (Table 1) informed the selection of sampling points, which were then georeferenced on the working map (Figure 5). Climatic data for the region were obtained from the Weather-Spark website (2024), which aggregates long-term climate data globally.

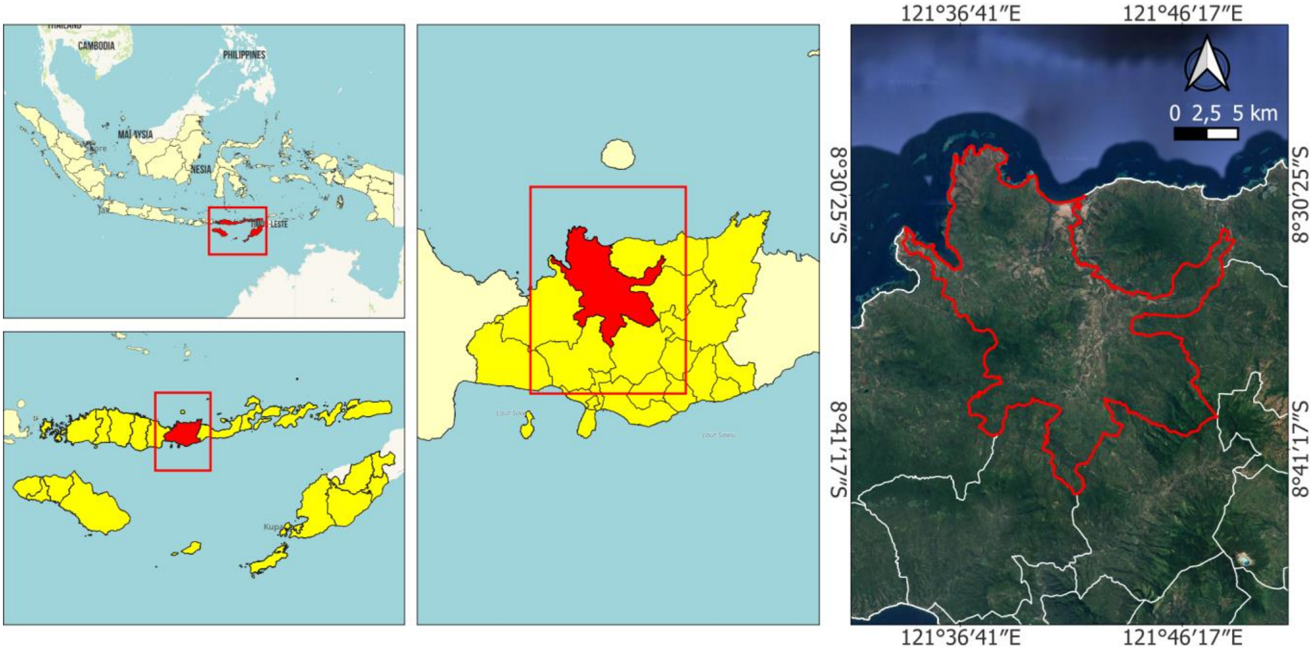

Figure 1. Map of the study site in Wewaria Sub-district, Ende District, East Nusa Tenggara Province, Indonesia

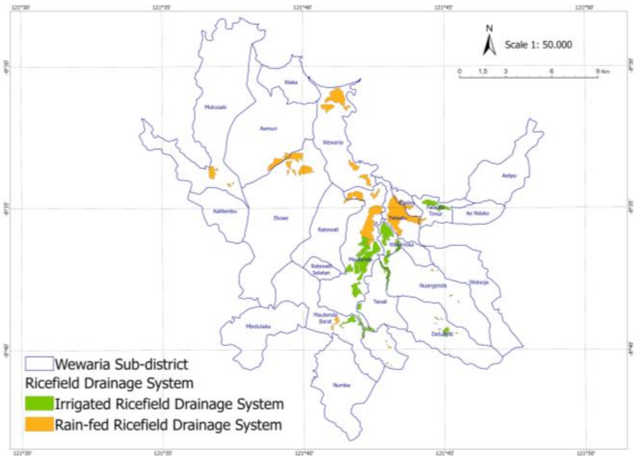

Figure 2. Map showing irrigated (green) and rain-fed (orange) ricefield drainage systems in Wewaria Sub-district, Lio, Indonesia

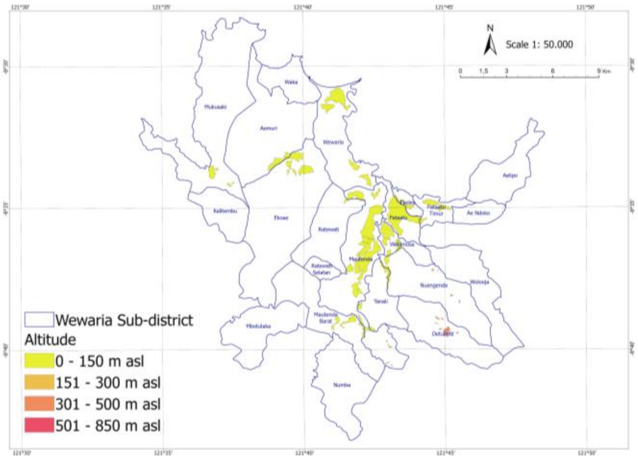

Figure 3. Map illustrating altitudinal variation (masl) across landscape in Wewaria Sub-district, Lio, Indonesia

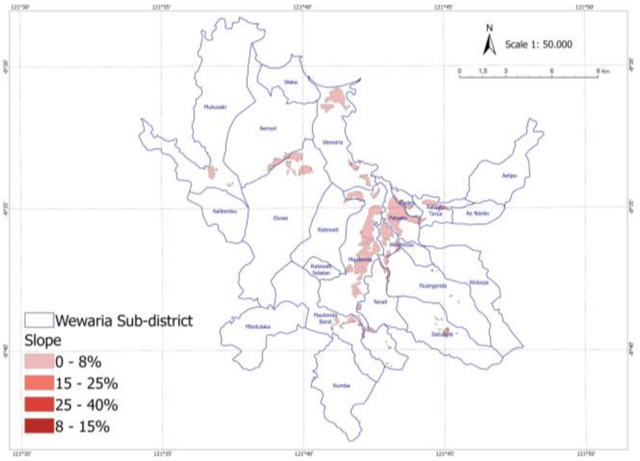

Figure 4. Map showing slope gradients across the landscape in Wewaria Sub-district, Lio, Indonesia

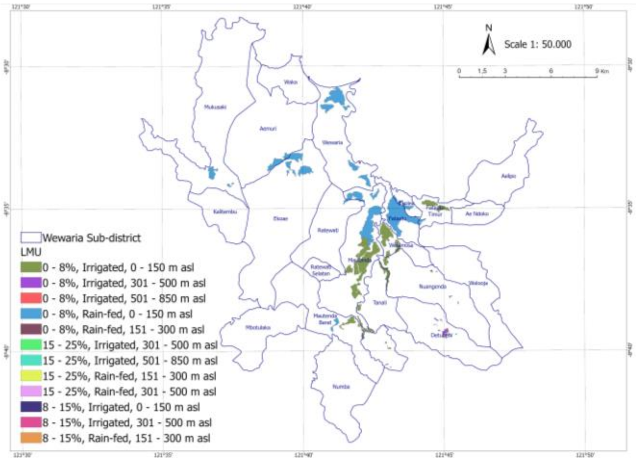

Figure 5. Map showing Land Mapping Unit (LMU) locations classified by slope, altitude, and ricefield drainage systems in Wewaria Sub-district, Lio, East Nusa Tenggara, Indonesia

Table 1. The Land Mapping Units (LMU) based on environmental diversity

LMU	Ricefield Drainage System	Altitude (masl)	Slope (%)
1	Irrigated	0-150	0-8
2	Irrigated	301-500	0-8
3	Irrigated	501-850	0-8
4	Rain-fed	0-150	0-8
5	Rain-fed	151-300	0-8
6	Irrigated	301-500	15-25
7	Irrigated	501-850	15-25
8	Rain-fed	151-300	15-25
9	Rain-fed	301-500	15-25
10	Irrigated	0-150	8-15
11	Irrigated	301-500	8-15
12	Rain-fed	151-300	8-15

Note: A total of 12 LMU types were each sampled three times (n=3), resulting in 36 soil samples for soil quality index observation

Research methods

A descriptive and exploratory research design was adopted to evaluate soil quality across various landscape units. The methodology involved both field-based observations and systematic soil sampling. Soil quality assessment was conducted using a scoring approach that integrated environmental parameters, morphological data, and laboratory analysis results (Table 2). A total of 12 LMUs were identified, with three replicate samples collected from each, resulting in 36 sampling points for Soil Quality Index (SQI) evaluation.

Research analysis on Soil Quality Index (SQI)

The Soil Quality Index (SQI) was determined using a combination of Principal Component Analysis (PCA) and the Minimum Data Set (MDS) approach, following the classification framework proposed by Cantú et al. (2007). PCA was utilized to statistically evaluate the laboratory-derived soil parameters (Table 2), allowing for dimensionality reduction by identifying the most influential variables—a method supported by prior studies (Nehrani et al. 2020; Zhan et al. 2020). Based on the PCA results, the MDS approach was then employed to select key indicators from each Principal Component (PC), ensuring minimal redundancy while preserving the dataset's integrity. The primary objective of this analysis was to uncover correlations among soil quality indicators that significantly contribute to SQI estimation. The distribution of the accumulated results of the SQI weighting that has been calculated is then classified based on the distribution of the total weight as an SQI class criteria presented in Table 3. Correlation analyses were conducted to assess the relationships between individual soil quality parameters and the resulting SQI values, as shown in Figure 13.

$$\mathrm{SQI} = \sum_{i=1}^{n} 1 = Wi \times Si^{n}$$

Where: SQI = Soil quality index; Wi = Weighting index; Si = Score index; n = Number of soil quality indicators.

Data analysis

The soil quality parameters obtained from different cultivation systems were subjected to Analysis of Variance (ANOVA) to assess the impact of varying paddy field cultivation practices on the Soil Quality Index (SQI). When significant differences were detected, a Duncan's Multiple Range Test (DMRT) was conducted to determine pairwise differences in SQI values across cultivation systems. Furthermore, Pearson correlation analysis was employed to evaluate the relationships between SQI and various environmental factors, thereby enabling a clearer understanding of the associations between individual parameters and the overall index. This statistical analysis provided a foundation for identifying key interrelationships and determining the principal factors influencing soil quality under different agricultural management practices.

RESULTS AND DISCUSSION

Analysis of SQI

The results of the Principal Component Analysis (PCA) are presented, showing the contribution of eight principal components (PC1 to PC8) to the total variance (Table 4). The first principal component (PC1) accounted for 15.3% of the total variance and is most strongly associated with Base Saturation (BS), active pH (pH-act), and Bulk Density (BD). The second Principal Component (PC2) explained 14.8% of the variance and included aluminum (Al), iron (Fe), and potassium (K). The third component (PC3) contributed 11.7% to the total variance, incorporating phosphorus (P), electrical conductivity (EC), and water content (WC). The fourth component (PC4) explained 9.5% of the variance and was most strongly associated with penetration resistance (PRdx). The fifth component (PC5) accounted for 8.1% of the variance and comprised manganese (Mn) and Particle Density (PD). The sixth component (PC6), contributing 7.7% of the variance, included the carbon-to-nitrogen ratio (C/N) and Cation Exchange Capacity (CEC). The seventh principal component (PC7) accounted for 7.1% of the variance and consisted of carbon biomass (CMB). The eighth principal component (PC8) explained 5.3% of the variance and included Psty, potentiometric pH (pH-pot), nitrogen (N), and carbon (C).

Table 3. SQI class criteria

Value	Class criteria
0.80 - 1.00	Very high
0.60 - 0.79	High
0.40 - 0.59	Medium
0.20 - 0.39	Low
0.00 - 0.19	Very low

Source: Cantú et al. (2007)

Table 2. Soil Quality Index (SQI) scoring criteria: Limiting factors and corresponding relative scores (1-5) for physical, chemical, and biological soil indicators used to assess land suitability

Indicators		Limiting factors and relative scores				
		1	2	3	4	5
Physical	Particle density (g/cm^3)	>1.6	1.5-1.6	1.4-1.5	1.3-1.4	<1.3
	Bulk density (g/cm^3)	>1.5	1.4-1.5	1.3-1.4	1.2-1.3	<1.2
	Porosity (%)	>20	18-20	15-18	10-15	<10
	Water content (%)	>30	<2	2-8	9-20	20-30
	Electrical conductivity (dS/m)	<3	3-5	5-7	7-10	>10
Chemical	pH level	<5; >8.2	5.0-5.4; 7.8-8.2	5.4-5.8; 7.4-7.8	5.8-6.0; 7.0-7.4	6.0-7.0
	Total-N (%)	<0.1	0.1-0.2	0.21-0.5	0.51-0.75	>0.75
	Available-P (ppm)	<10	10-15	16-25	16-35	>35
	Available-K (mg/100g)	<0.1	0.1-0.2	0.3-0.5	0.6-1	>1
	Organic-C (%)	<0.5	0.5-1	1-3	3-5	5-10
	C/N ratio	<5	>25	16-25	5-10	11-15
	Cation Exchange Capacity (me/100g)	<5	5-16	17-24	25-40	>40
	Base saturation (%)	<20	21-30	31-50	51-70	>70
	Potential redox (mV)	0-100	101-200	201-300	301-400	>400; <(-100)
	Al (ppm)	>50	40-50	35-40	20-35	<20
	Fe (ppm)	>53	53-19	19-5	5-3	<3
	Mn (ppm)	>20	15-20	10-15	5-10	<5
Biological	C-Microbes Biomass (µg/g)	>25	20-25	10-20	5-10	<5

Source: Indonesian Center for Research and Development of Agricultural Land Resources (2024)

Table 4. Principal Component Analysis (PCA) results for each Soil Quality Indicator (SQI). The table presents eigenvalues, proportions of explained variance, cumulative variance, and the loadings of each SQI variable on the first eight principal components (PC1-PC8). Values marked with an asterisk (*) indicate the highest loading for each variable, contributing to the Minimum Data Set (MDS) selection

Eigenvalue	2,9109	2,8137	2,2222	1,7975	1,5347	1,4554	1,3401	1,0005
Proportion	0,153	0,148	0,117	0,095	0,081	0,077	0,071	0,053
Cumulative	0,153	0,301	0,418	0,513	0,594	0,670	0,741	0,793
Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
PD	0,199	0,076	0,243	0,095	***0,461**	0,112	0,004	-0,414
BD	***0,244**	0,124	-0,179	-0,110	-0,223	-0,380	-0,211	-0,029
Psty	0,009	0,173	-0,380	0,158	-0,239	0,200	-0,035	***0,454**
WC	-0,105	-0,146	***0,301**	-0,286	-0,412	-0,036	0,178	-0,077
EC	0,274	-0,093	***0,355**	-0,017	-0,161	0,348	0,045	0,180
pH-act	***0,409**	-0,048	-0,021	0,053	0,084	0,274	-0,280	0,034
pH-pot	0,280	-0,160	-0,016	0,238	-0,037	0,232	-0,019	***0,302**
N	-0,145	0,215	0,389	-0,060	0,164	-0,293	-0,187	***0,459**
P	0,089	-0,187	***0,447**	-0,212	-0,131	0,192	0,076	0,093
K	0,073	***0,466**	0,092	-0,173	0,176	0,037	0,217	-0,052
C	-0,254	0,091	-0,046	-0,491	0,282	0,128	-0,115	***0,334**
C/N	-0,087	-0,115	-0,381	-0,393	0,080	***0,420**	0,055	-0,196
CEC	-0,395	0,051	0,098	0,186	-0,266	***0,298**	-0,096	-0,133
BS	***0,468**	-0,102	-0,083	-0,092	0,032	-0,246	0,197	0,070
PRdx	-0,198	-0,067	0,129	***0,416**	0,188	0,059	-0,363	-0,019
Al	0,082	***0,494**	0,050	-0,024	-0,118	0,128	-0,148	-0,117
Fe	0,152	***0,495**	0,040	0,009	-0,046	0,241	0,072	0,035
Mn	-0,084	-0,164	-0,058	0,105	***0,424**	0,079	0,397	0,284
CMB	-0,105	0,194	0,011	0,331	-0,113	-0,032	***0,610**	0,009

Note: PD: Particle Density; BD: Bulk Density; Psty: Porosity; WC: Water Content; EC: Electrical Conductivity; pH-act: Actual pH; pH-pot: Potential pH; N: Total Nitrogen; P: Available Phosphorus; K: Available Potassium; C: Organic Carbon; C/N: Carbon/Nitrogen Ratio; CEC: Cation Exchange Capacity; BS: Base Saturation; PRdx: Potential Redox; Al, Fe, Mn: Aluminum, Iron, and Manganese concentrations, respectively; CMB: Carbon Microbial Biomass

The influence of these parameters on the SQI is illustrated in Figure 6. These indicators displayed considerable weights and positive intercorrelations, indicating their mutual relevance to soil quality. Despite these correlations, the selection of a single indicator from each principal component ensures that the indicators used in MDS are independent within the PCA grouping framework. Consequently, all 19 indicators were retained for MDS construction. Each MDS indicator was assigned a weight index (Wi), calculated by dividing the variance explained by its respective principal component by the cumulative variance of all selected components. The SQI was subsequently derived by multiplying each indicator's Wi value by its normalized MDS score. The final computed SQI values are depicted in Figure 6.

The spatial analysis of the Soil Quality Index (SQI) revealed two distinct soil quality classes—low and medium—across the Land Mapping Units (LMUs) of the study area. The low SQI class dominates LMUs 1-19 and 23-25, particularly concentrated in the northern and eastern regions of the Wewaria Sub-district. In contrast, medium SQI values are primarily observed in LMUs 20-22 and 26-36, which are situated in the northern sector of the region (Figure 7). Overall, the findings suggest that soil quality across the study area is predominantly low, with limited zones of moderate quality. This uneven distribution highlights a critical need for targeted interventions to improve soil health, especially in low-SQI regions.

The primary objective of the study was to determine the underlying factors influencing the variability in SQI across different LMUs. Utilizing statistical techniques, particularly Analysis of Variance (ANOVA), the study identified several significant contributors to the observed differences in soil quality. Among these, the type and efficiency of rice field drainage systems emerged as a critical determinant. Inadequate drainage can lead to excess soil moisture, reduced aeration, salt accumulation, and degradation of soil structure—conditions that severely impair root function and nutrient uptake (Adelana et al. 2022). Additionally, topographic slope was found to significantly influence SQI variation. Steeper slopes accelerate runoff and erosion, increasing the risk of nutrient loss and further reducing soil productivity (Rosskopf et al. 2020).

The interplay between natural factors (such as slope and rainfall) and anthropogenic influences (notably land management practices) plays a defining role in shaping soil quality. The differentiation between low and medium SQI classes reflects this interaction, emphasizing the importance of site-specific soil conservation strategies (Tian et al. 2022). The robustness of the ANOVA framework enabled the validation of these relationships (Table 5), supporting the conclusion that integrated soil management approaches—including improved drainage infrastructure and erosion control—are essential to elevate soil quality in vulnerable regions (Martín-Sanz et al. 2022).

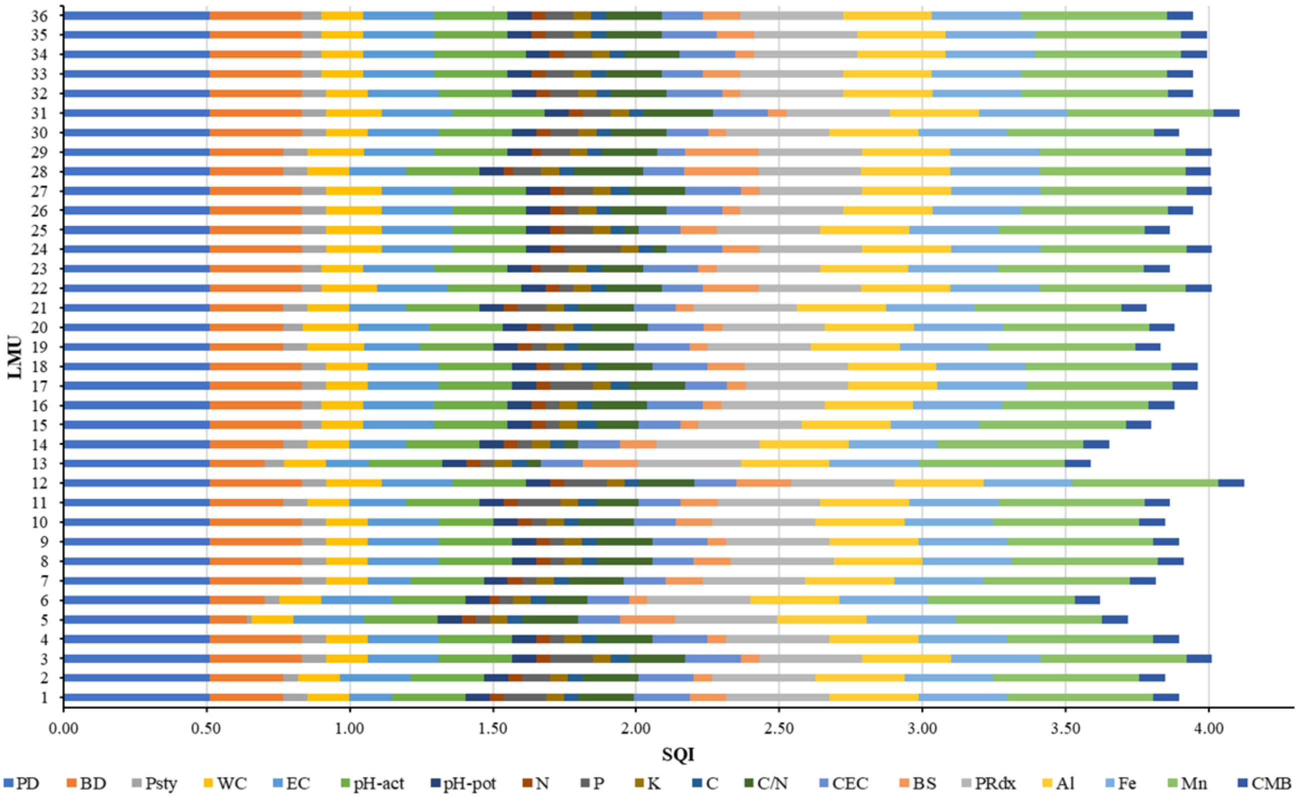

Figure 6. Stacked bar chart of Soil Quality Index (SQI) across Land Mapping Units (LMUs), showing contributions of individual indicators

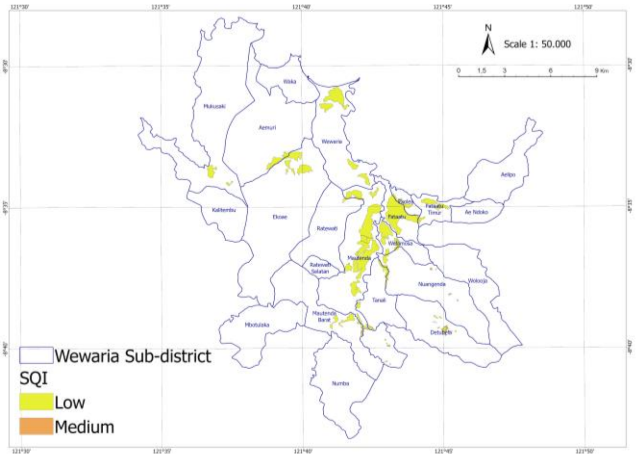

Figure 7. Spatial distribution of Soil Quality Index (SQI) classes (low and medium) across Wewaria Sub-district

Table 5. The ANOVA result of environmental diversity on SQI

Environmental diversity	Ricefield drainage systems	Altitude	Slope
SQI	0.000**	0.472ns	0.007**

Note: ns: non significant; *: significant; **: very significant (ns>0.05; *<0.05; **<0.01)

Furthermore, the study highlights the contrasting challenges faced by drainage-based and rainfed rice cultivation systems. In drainage-based systems, persistent waterlogging and salinization constrain oxygen availability and limit nutrient uptake, leading to poor plant performance. As reported by Devkota et al. (2022), ineffective drainage infrastructure intensifies salinity stress, ultimately reducing soil fertility and rice yields. On the other hand, rainfed rice systems are highly susceptible to intermittent moisture stress, which promotes soil erosion and nutrient depletion. According to Majumdar et al. (2023), fluctuations in soil moisture negatively impact soil microbial dynamics and structure, further diminishing its capacity to support crop growth.

These findings reinforce the necessity for tailored soil management strategies for both cultivation systems. Addressing the site-specific drivers of degradation is crucial to maintaining long-term soil functionality and agricultural sustainability in rice-based agroecosystems. The slope of a paddy field exerts a critical influence on soil fertility and overall quality. Steeper slopes are typically associated with increased erosion, reduced water retention, nutrient leaching, and compaction—factors that collectively impair soil fertility (Parvez et al. 2024). In contrast, flatter terrains offer more favorable conditions for rice cultivation, including improved moisture retention, enhanced nutrient stability, and higher accumulation of organic matter. To address the adverse effects of slope gradients, site-specific management interventions such as erosion control, water regulation, and the application of soil amendments are essential for maintaining long-term soil health and productivity (Dewi et al. 2022).

Results from the Duncan's Multiple Range Test (DMRT) comparing irrigation systems in relation to Soil Quality Index (SQI) reveal that rainfed rice fields exhibit significantly higher SQI values than other systems (Figure 8). The lowest SQI values were recorded in irrigated rice fields, particularly those utilizing the Irrigation Cultivation Technique (IKT). Across all cultivation methods, statistically significant differences in SQI were observed, with the rainfed system outperforming the irrigation-based system by 2.63%. Al Viandari et al. (2022) reported that rainfed rice fields maintain sufficient water availability to support optimal nutrient cycling, a condition further enhanced by the sustained application of appropriate agro-technologies. Furthermore, Ray and Chakraborty (2021) observed a markedly higher diversity of soil organisms in rainfed fields compared to irrigated systems, suggesting enhanced biological activity under natural rainfall regimes.

Rainfed rice cultivation supports greater microbial diversity than irrigated systems, largely due to ecologically dynamic soil environments (Liu et al. 2022). Natural rainfall induces periodic fluctuations in soil moisture, which foster microbial richness by supporting diverse physiological groups (Jiang et al. 2021). Additionally, rainfall introduces external organic inputs, enriching substrates available to soil microorganisms. Temperature and aeration conditions in rainfed systems also vary more frequently, creating favorable conditions for aerobic microbial communities. In contrast, the prolonged waterlogged conditions typical of irrigated rice fields often create anaerobic environments, thereby suppressing microbial diversity (Majumdar et al. 2021). Moreover, the intensive use of chemical inputs in irrigated systems can diminish soil microbial populations, further limiting community complexity. Therefore, differences in water management practices, moisture variability, and organic matter dynamics play a key role in shaping microbial community structures across rice cultivation systems (Muhammad et al. 2022).

Slope-related processes also significantly impact soil fertility and quality, as illustrated in Figure 9. Steep slopes experience more severe soil erosion, leading to the loss of topsoil and associated nutrients and organic matter, which directly reduces soil fertility (Arunrat et al. 2022). Rapid surface runoff on such slopes also limits water infiltration, compromising moisture availability for crop uptake. In contrast, gentler slopes facilitate higher infiltration rates, promoting soil moisture retention and the accumulation of surface organic matter, both of which enhance soil fertility. Additionally, better drainage on flatter terrains improves aeration, thereby stimulating microbial activity crucial for organic matter decomposition and nutrient cycling (Ahmad et al. 2020). Soils on steep slopes are often more degraded, coarser in texture, and less capable of retaining water and nutrients. Consequently, steeper landscapes pose greater challenges for maintaining soil fertility, whereas flatter areas offer more favorable conditions for sustainable soil and crop management (Derakhshan-Babaei 2021).

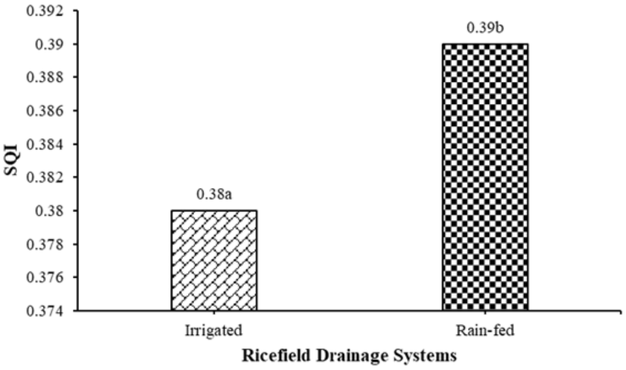

Figure 8. Effect of ricefield drainage systems on SQI based on DMRT. Different letters indicate significant differences ($p < 0.05$)

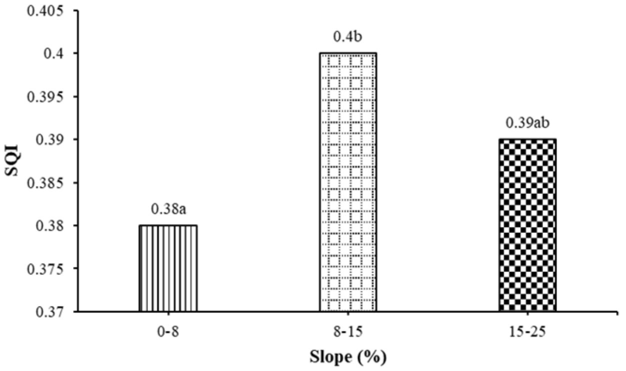

Figure 9. Effect of slope (%) on SQI based on DMRT. Different letters denote significant differences ($p < 0.05$)

Examination of climate conditions and their connection to SQI

Ende, located in East Nusa Tenggara, is characterized by a tropical savanna climate (Aw) based on the Köppen climate classification (Figure 10). This region displays distinct seasonal patterns, with a marked wet season extending from November to April and a dry season from May to October. Temperatures remain relatively stable throughout the year, with daily averages ranging from 23 to 33°C. Rainfall is moderate, peaking between December and March. These climatic conditions are shaped by the region's geographic and topographic characteristics, which contribute to microclimatic variations that may influence Soil Quality Index (SQI) dynamics.

Rainfall in Ende District, East Nusa Tenggara, exhibits marked seasonal and interannual variability. Over the past five years (2020-2024) (Figure 11), the rainy season typically spans approximately five months, beginning around November 16 and extending to about April 17, during which the probability of rainfall exceeds 29%. February is generally the wettest month, with an average of 15 rainy days. The district receives an average annual rainfall of 1,129 mm, with the majority occurring between November and April. Notably, historical data indicate significant fluctuations in annual precipitation, with a high of 1,439 mm recorded in 2017 and a low of 568.51 mm in 2022.

Temperature variation in the region is minimal throughout the year. The diurnal temperature amplitude is approximately 6.0°C, with maximum daytime temperatures reaching 33°C and nighttime lows averaging 23°C. However, rainfall distribution across Ende District may vary locally due to geographic and topographic heterogeneity, which can influence microclimatic conditions and, in turn, affect soil moisture and quality.

Monthly air humidity data for Ende District over the past five years (2020-2024) reveal considerable temporal variability. Minimum, maximum, and average humidity levels for Ende City have been consistently recorded and are accessible through official sources such as the Indonesian Central Agency of Statistics (2022) and Weather-Spark (2024). These humidity patterns are influenced by a range of geographic, topographic, and seasonal factors, which contribute to localized microclimatic conditions. Given the complexity and variability of these factors, researchers are encouraged to reference the most recent datasets and perform detailed analyses to gain an accurate and comprehensive understanding of the region's climatic profile (Figure 12).

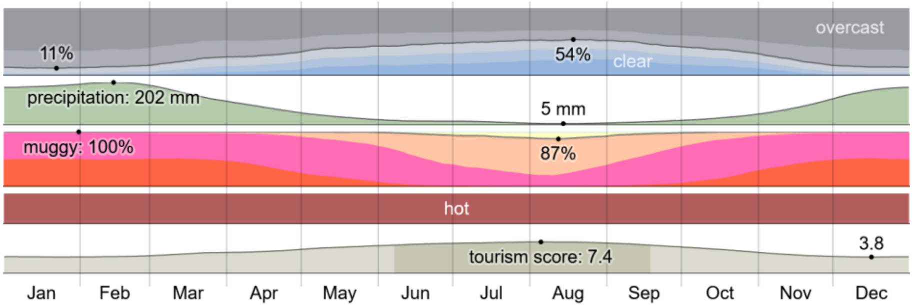

Figure 10. Monthly climate trends in Ende from 2020 to 2024, showing variation in cloud cover, precipitation, humidity, temperature, and tourism score

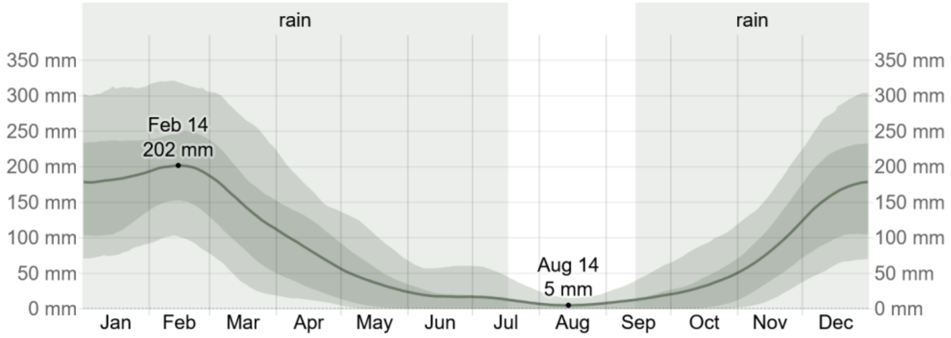

Figure 11. Average monthly rainfall in Ende in the past 5 years (2020-2024)

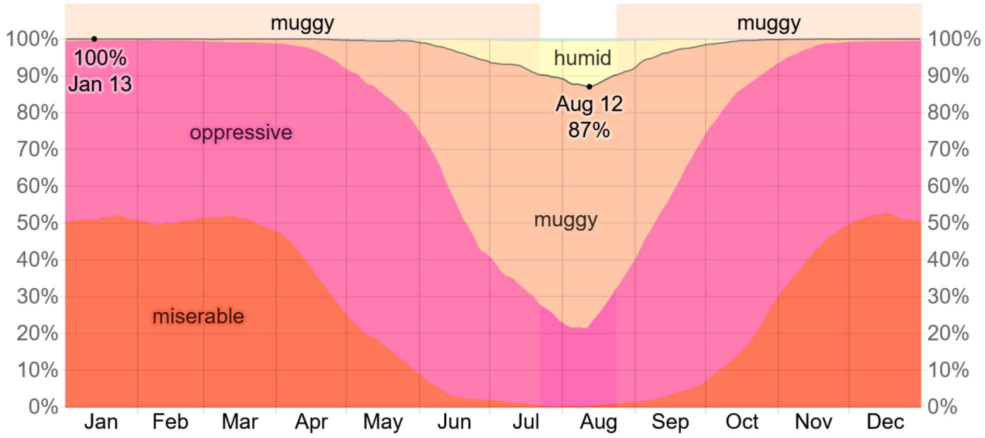

Figure 12. Average monthly humidity comfort levels in Ende in the past 5 years (2020-2024)

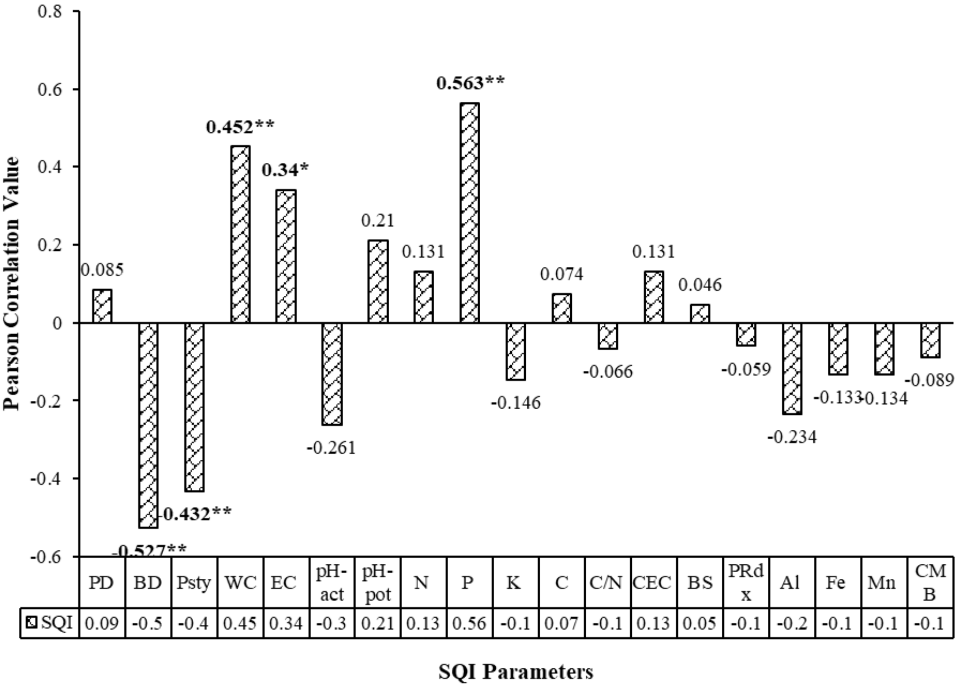

Figure 13. Pearson correlation analysis of various soil parameters with the Soil Quality Index (SQI). Note: PD: Particle Density; BD: Bulk Density; Psty: Porosity; WC: Water Content; EC: Electrical Conductivity; pH-act: actual pH level; pH pot: potential pH level; N: Total-N; P: Available-P; K: Available-K; C: Organic-C; C/N: C/N ratio; CEC: Cation Exchange Capacity; BS: Base Saturation; PRdx: Potential Redox; CMB: C-Microbes Biomass; *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed)

The SQI determining factors analysis

A correlation analysis was conducted to determine the relationships between various soil physicochemical parameters and the Soil Quality Index (SQI), a key indicator for evaluating overall soil health (Figure 13). The analysis identified five key parameters that significantly influence SQI: bulk density, porosity, water content, Electrical Conductivity (EC), and available phosphorus (available-P).

Among these, water content ($r = 0.452$, $p<0.01$), electrical conductivity ($r = 0.340$, $p<0.05$), and available-P ($r = 0.563$, $p<0.01$) exhibited significant positive correlations with SQI. Adequate water content enhances microbial activity and nutrient mobility, while moderate EC levels reflect a favorable ionic balance that supports nutrient availability and plant health (Alkharabsheh et al. 2021). Available phosphorus, an essential macronutrient, directly contributes to plant growth and soil biological function, and its higher concentration was associated with better soil quality (Singh et al. 2020).

In contrast, bulk density ($r = -0.527$, $p < 0.01$) and porosity ($r = -0.432$, $p<0.01$) showed significant negative correlations with SQI. High bulk density typically indicates soil compaction, which restricts air and water movement, root penetration, and microbial activity—key elements of soil health (Hu et al. 2021; Samaei et al. 2022). Similarly, low soil porosity is associated with poor soil structure and reduced capacity for water and nutrient retention (Hafeez et al. 2022; Mondal and Chakraborty 2022).

These findings emphasize the importance of maintaining balanced soil physical and chemical properties for sustainable soil management. Ensuring optimal moisture levels, salinity, nutrient availability, and soil structure can improve SQI and enhance agricultural productivity. The identification of these five key determinants—bulk density, porosity, water content, EC, and available-P—offers valuable insights for targeted interventions to maintain or restore soil health in tropical savanna agroecosystems (Maharjan et al. 2020; Selim 2020).

Discussion

Improving soil health is a multifaceted challenge that requires addressing both direct soil quality indicators and broader agronomic constraints that can adversely affect crop productivity. This study identifies low phosphorus (P) availability as a significant limiting factor in the paddy fields of Wewaria Sub-district, where phosphorus levels range from low to deficient. Given phosphorus's essential role in plant development, its deficiency can significantly hinder rice growth unless corrected through targeted fertilization strategies (Kurniawan et al. 2023).

To address phosphorus limitations, integrating organic fertilization methods is recommended. Organic matter enhances P availability by competing for adsorption sites and facilitating the mineralization of organic phosphorus into plant-accessible forms. Rice husk biochar, in particular, has shown promise in augmenting soil P levels and improving the availability of other macronutrients like potassium (Pogorzelski et al. 2020). The synergistic use of biochar and organic fertilizers is thus considered a best management practice for optimizing nutrient availability.

Additionally, natural rock phosphate can serve as a long-term phosphorus source through gradual weathering and mineralization. In cases of acute phosphorus deficiency, the application of inorganic phosphorus fertilizers may be warranted, though care must be taken to apply them within agronomic recommendations to prevent nutrient imbalances (Amar et al. 2022).

Combining organic and inorganic fertilizers has been shown to yield superior outcomes in both productivity and soil health. Roba (2018) and Qaswar et al. (2020) found that balanced fertilization regimes significantly improve soil fertility and crop yields. Similar findings by Mahmood et al. (2017) and Mi et al. (2018) indicated that the co-application of NPK and compost not only enhances rice yields but also improves key soil parameters such as pH and phosphorus content. A study by Murnita and Taher (2021) recommends an optimal ratio of 25% NPK and 75% organic fertilizer, which yielded 8.05 tons/ha of rice and improved soil chemical properties, including available phosphorus (86.56 ppm), organic carbon (3.33%), and total nitrogen (0.21%).

In addition to soil amendments, incorporating biological agents is a promising approach. Organic inputs fuel microbial activity by supplying carbon, thereby enhancing soil biological processes (Cahyani et al. 2023). In particular, Arbuscular Mycorrhizal Fungi (AMF) significantly improve phosphorus uptake by extending root access to otherwise unavailable nutrient pools and releasing organic acids that mobilize P (Raymond et al. 2021). AMF also improve soil aggregation and water retention by producing glomalin, a glycoprotein that stabilizes soil structure (Holátko et al. 2021).

The organic farming system emerged as the most effective cultivation practice for improving soil health in this study. Compared to conventional and semi-organic systems, organic agriculture enhances soil aggregation, boosts microbial activity, and elevates soil organic carbon levels—contributing to better nutrient cycling and overall soil fertility (Yang et al. 2020; Yadav et al. 2021). These improvements create a more favorable environment for plant growth, ultimately supporting higher yields and long-term agricultural sustainability.

Climate also plays a critical role in rice farming systems in Ende, which is characterized by a tropical savanna climate (Aw). The distinct wet (November-April) and dry (May-October) seasons influence both irrigated and rain-fed rice cultivation practices. Adequate rainfall during the wet season supports rice growth, while the dry season necessitates efficient water management, especially in irrigated systems (Bose et al. 2024). In rain-fed systems, the timing and reliability of rainfall are crucial for crop success, underscoring the importance of climate-adaptive planning (Bell et al. 2022).

Irrigated rice systems benefit from consistent water availability during the wet season, with stable temperatures (23 to 33°C) and high humidity fostering optimal growth. However, evapotranspiration increases during the dry season, requiring effective irrigation strategies to mitigate water loss (Pizarro et al. 2022). Rain-fed systems, in contrast, rely heavily on seasonal rainfall patterns, with an average annual precipitation of 1,129 mm—peaking between December and March. Strategic planting schedules aligned with these patterns are vital for ensuring adequate water availability and avoiding crop failure (Mugi-Ngenga et al. 2023; Yan et al. 2023).

In conclusion, this study reveals that soil nutrient deficiencies, particularly phosphorus, potassium, and nitrogen, along with low soil pH, are major constraints to rice productivity in Wewaria Sub-district. Soil quality assessment based on the Soil Quality Index (SQI) classified the region into low and medium SQI categories, with variations attributed to slope and drainage conditions. Five critical SQI parameters were identified, highlighting the need for a comprehensive soil management strategy. To address these challenges, a holistic and integrated approach is required, which includes, combining organic and inorganic fertilization for balanced nutrient supply, leveraging biochar and rock phosphate for long-term soil fertility, incorporating biological agents like mycorrhizal fungi to enhance nutrient uptake, transitioning towards organic farming systems for sustainable soil and crop productivity, and aligning agronomic practices with climatic conditions to optimize water use and planting cycles.

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