

Assessment of Soil Fertility Index on Various Soil Types in Rice Fields Using Principal Component Analysis in Tikung District, Indonesia

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Abstract

Background: Soil fertility is key determinant of sustainable and productive rice cultivation and may vary according to soil type and irrigation systems. This study aimed to assess the Soil Fertility Index (SFI) of paddy fields under different soil types and irrigation systems in Tikung District, Lamongan Regency, Indonesia. **Methodology:** A survey using purposive sampling was conducted at 32 observation points representing four soil types: Typic Endoaquerts, Haplustalfs, Haplustepts, and Haplusterts, under technical and semi-technical irrigation systems. Soil samples were collected from depths of 0–30 and 30–60 cm, resulting in 64 samples. Soil pH, Cation exchange capacity, Aase saturation, Available phosphorus, Exchangeable potassium, and Soil organic carbon were analyzed. Principal Component Analysis was used to determine the contribution of soil properties and derive weighting factors for SFI calculation. **Findings:** SFI values ranged 0.53 to 0.90, classified into moderate and high fertility categories. Typic Endoaquerts and Haplustalfs exhibited the highest fertility status, whereas Typic Haplustepts showed the lowest. Paddy fields under technical irrigation generally had higher SFI values than those under semi-technical irrigation. Spatial analysis showed that 861.48 ha (19.7%) had high fertility, while 3,507.52 ha (80.28%) was classified as moderate fertility. Soil organic carbon was identified as the primary limiting factor across most locations. **Contribution:** The findings demonstrate that soil type and irrigation systems are associated with variation in soil fertility status and provide field-based information for developing site-specific soil fertility management strategies and particularly highlight the importance of improving soil organic carbon management to support sustainable rice production.

Keywords: Irrigation Systems; Principal Component Analysis; Rice Fields; Soil Fertility Index; Soil Types



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INTRODUCTION

Soil is a natural resource that plays a vital role in supporting agricultural production, particularly in paddy field ecosystems. Rice productivity is strongly influenced by soil conditions, including its physical, chemical, and biological properties (Alam et al., 2020). Among these factors, soil fertility is one of the most important determinants of crop growth and yield because it reflects the soil's capacity to supply essential nutrients in sufficient amounts and balanced proportions for optimal plant development (Pa et al., 2023). Continuous cultivation, intensive fertilizer application, and improper soil management may gradually reduce soil fertility, resulting in lower nutrient-use efficiency and decreased crop productivity (Topa et al., 2025).

Rice fields are agricultural ecosystems that are intensively managed and continuously cultivated. Long-term use of inorganic fertilizers, repeated tillage practices, and differences in irrigation management can significantly affect soil chemical properties and nutrient availability (Putra et al., 2024). Furthermore, variations in soil type contribute to differences in nutrient retention, nutrient supply capacity, and overall soil fertility (Chen et al., 2018). Therefore, assessing soil fertility is essential for developing appropriate and sustainable soil management strategies to maintain agricultural productivity.

Tikung District, Lamongan Regency, East Java, is one of the major rice-producing areas in Indonesia. The region is characterized by extensive paddy fields supported by both technical and semi-technical irrigation systems. In addition, the district possesses diverse soil types, including Typic Endoaquerts, Typic Haplustalf, Typic Haplustepts, and Typic Haplusterts, which have developed from different parent materials and pedogenic processes. These differences are expected to influence soil chemical characteristics, nutrient dynamics, and fertility levels, thereby affecting rice production potential.

Tikung District requires particular attention because it is an important rice-producing area characterized by extensive paddy fields, diverse soil types, and differences in irrigation management. The coexistence of technical and semi-technical irrigation systems creates differences in water availability and field management, while the presence of Typic Endoaquerts, Typic Haplustalfs, Typic Haplustepts, and Typic Haplusterts indicates considerable variation in soil properties. These conditions may result in differences in nutrient availability, nutrient retention, and overall soil fertility among paddy fields. Therefore, Tikung District provides an appropriate area for evaluating the interaction between soil characteristics and irrigation management using an integrated Soil Fertility Index approach.

Soil fertility can be evaluated through various soil chemical properties, such as soil pH, cation exchange capacity (CEC), base saturation (BS), available phosphorus, exchangeable potassium and soil organic carbon (Nguemezi et al., 2020). However, evaluating each parameter separately often makes it difficult to describe overall soil fertility conditions. To overcome this limitation, the Soil Fertility Index (SFI) has been widely used as an integrated approach that combines multiple soil fertility indicators into a single quantitative value. The SFI provides a comprehensive assessment of soil quality by incorporating weighted contributions of individual soil properties and has

been recognized as an effective tool for comparing soil fertility across different land management systems and soil types.

The application of the Soil Fertility Index is particularly important in areas with heterogeneous soil characteristics, where conventional fertility evaluation methods may not fully capture spatial variations in soil quality. By integrating several key soil fertility indicators into a single index, SFI enables a more comprehensive understanding of soil fertility status and facilitates the identification of factors limiting agricultural productivity. Such information is valuable for supporting site-specific soil management and improving the sustainability of rice cultivation systems.

Previous studies have demonstrated that soil fertility assessment can be improved by integrating several soil chemical properties into a composite index. The Soil Fertility Index (SFI), particularly when combined with Principal Component Analysis (PCA), has been applied to identify key soil fertility indicators and evaluate variations in soil fertility across different soil types and land management systems (Bagherzadeh et al., 2018; Suntoro et al., 2023). However, soil fertility conditions may vary considerably within the same agricultural region due to differences in soil characteristics, irrigation systems, and field management practices. Therefore, the application of SFI at a local scale is important to identify spatial differences in soil fertility and the dominant limiting factors.

Despite the increasing application of SFI for soil fertility assessment, information integrating soil type, irrigation system, and spatial distribution of soil fertility in paddy fields of Tikung District remains limited. In particular, comparative information on soil fertility conditions between technical and semi-technical irrigation systems across different soil types is still insufficient. This knowledge gap limits the availability of site-specific information for identifying fertility constraints and developing appropriate soil management strategies in the study area. Therefore, an integrated assessment using SFI and spatial analysis is needed to provide a more comprehensive understanding of soil fertility variability in Tikung District. Therefore, this study aimed to assess the Soil Fertility Index (SFI) of paddy fields across several soil types in Tikung District, Lamongan Regency. The results are expected to provide information on the relative fertility status of different soil types and irrigation systems, as well as to serve as a scientific basis for developing sustainable soil fertility management strategies to enhance rice production in the region.

METHOD

Study Area

This study was conducted in paddy fields located in Tikung District, Lamongan Regency, East Java, Indonesia. Geographically, the study area is located between 7°10'37" S and 112°26'24" E, covering approximately 4,336.16 Ha of paddy-field area. The study area consisted of four soil types, namely Typic Endoaquerts (TEV), Typic Haplustalfs (THA), Typic Haplustepts (THI), and Typic Haplusterts (THV), distributed under both technical and semi-technical irrigation systems. Soil sampling was carried out at two depths, namely 0–30 cm and 30–60 cm.

The paddy field polygon used in this study was obtained from the Dinas Ketahanan Pangan dan Pertanian (DKPP) of Lamongan Regency as the official source

of agricultural spatial data. The polygon was used as the spatial reference for delineating rice-field areas within Tikung District and for supporting the spatial analysis of soil fertility status. The spatial data were subsequently processed and overlaid with the soil fertility index (SFI) results using Geographic Information System (GIS) to estimate the spatial distribution and area of each soil fertility class.

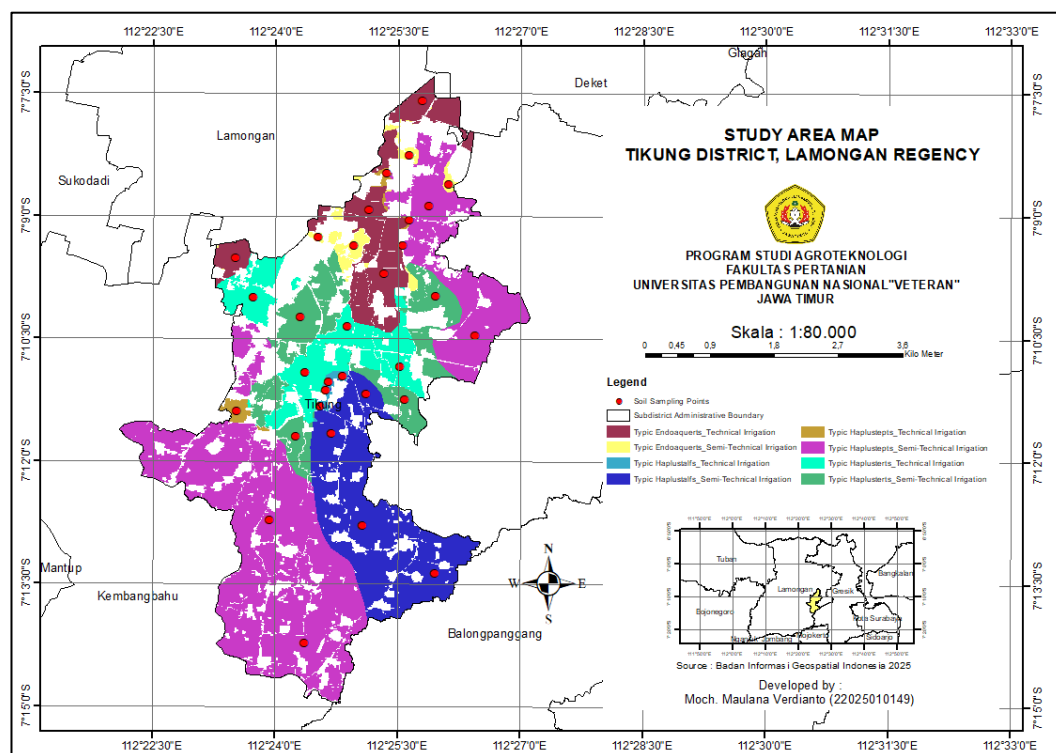


Figure 1. Study Area Map of tikung District, Lamongan Regency

Soil Sampling

This study employed a survey method with purposive sampling based on soil type and irrigation system. A total of 32 observation points were selected, consisting of four observation points for each combination of soil type and irrigation system. At each observation point, soil samples were collected from two depths, namely 0–30 cm and 30–60 cm, resulting in a total of 64 soil samples.

Soil sampling was conducted using a soil auger through the boring method. At each predetermined sampling point, soil was collected at two depth intervals, namely 0–30 cm and 30–60 cm. The soil auger was inserted vertically into the soil to obtain soil material from the specified depth. Soil samples collected from each sampling point and depth were placed in labeled sampling bags according to the soil type, irrigation system, sampling location, and soil depth. The collected samples were then transported to the laboratory for further preparation and analysis. Prior to laboratory analysis, the soil samples were air-dried, gently crushed, and passed through a 2-mm sieve to obtain soil samples for analysis.

Laboratory Analysis

Laboratory analyses were conducted to determine selected soil chemical properties associated with soil fertility. The analyzed parameters included soil pH (H₂O), cation exchange capacity (CEC), base saturation (BS), available phosphorus (P), exchangeable potassium (K), and soil organic carbon (SOC). Soil pH was measured using a pH meter in a soil-water suspension. Cation exchange capacity (CEC) and exchangeable potassium (K) were determined using NH₄OAc extraction at pH 7. Available phosphorus was analyzed using the Olsen method, while soil organic carbon was determined using the *Walkley and Black* method. Base saturation was calculated from the proportion of exchangeable base cations to the total cation exchange capacity.

Tabel 1. Laboratory Analysis Methods

No.	Parameters	Method analysis
1.	pH	pH H ₂ O
2.	CEC (cmol/kg)	Extract NH ₄ OAc 1N pH7
3.	Base Saturation (%)	Extract NH ₄ OAc 1N pH7
4.	Available-P (ppm)	Olsen
5.	Exchangable K (cmol/kg)	Extract NH ₄ OAc 1N pH7
6.	Organic Carbon (%)	Walkley and Black

Soil Fertility Index Assessment

The Soil Fertility Index (SFI) was developed using a Principal Component Analysis (PCA)-based weighting approach. Six soil fertility indicators, namely soil pH, CEC, base saturation, available phosphorus, exchangeable potassium, and soil organic carbon, were used in the analysis. The Soil Fertility Index (SFI) for each sampling location was calculated using a weighted scoring approach. Each soil fertility indicator was assigned a score ranging from 1 to 5 based on the established soil fertility criteria. The SFI calculation followed the soil fertility index approach described by [Bagherzadeh et al., \(2018\)](#). The weighted score of each indicator was calculated as:

$$C_i = W_i \times S_i \dots\dots\dots (1)$$

The SFI was subsequently calculated as:

$$SFI = \frac{\sum_{i=1}^m C_i}{S_{max}} \dots\dots\dots (2)$$

Where: C_i is the weighted score of the i -th soil fertility indicator, W_i is the weighting factor derived from Principal Component Analysis (PCA), S_i is the scoring value assigned to the corresponding soil fertility indicator, m is the number of soil fertility indicators ($m = 6$), and S_{max} is the maximum scoring value ($S_{max} = 5$).

The weighting factor for each variable was determined by dividing the proportion of its eigenvalue obtained from Principal Component Analysis (PCA) by the cumulative eigenvalue proportion of all selected variables. The dataset was

analyzed using Principal Component Analysis (PCA) in IBM SPSS Statistics. PCA was used to identify the key soil fertility variables explaining the variability of soil fertility characteristics and to determine the Minimum Soil Fertility Indicators (MSFI). The scoring process was performed by assigning scores to laboratory analysis results according to the classification criteria presented in Table 2.

Table 2. Nutrient Scoring Criteria

No.	Parameter	Score				
		1	2	3	4	5
1.	Available-P (ppm)	< 5	5 – 10	11-15	16-20	> 20
2.	Exchangeable-K (cmol/kg)	< 0.1	0.1 – 0.3	0.4 – 0.5	0.6 – 1.0	> 1.0
3.	Organic Carbon (%)	< 1	1 – 2	2 – 3	3 – 5	> 5
4.	Base Saturation (%)	< 20	20 – 40	41 – 60	61 – 80	> 80
5.	CEC (cmol/kg)	< 5	5 – 16	17 – 24	25 – 40	> 40
6.	pH	< 5	5 – 5.4	5.5 – 5.8	5.9 – 6.6	> 6.7

Source : [Suntoro et al., \(2023\)](#)

Table 3. Classification of Soil Fertility Index

Soil Fertility Index	Class
0.00 – 0.25	Very Low
0.25 – 0.50	Low
0.50 – 0.75	Moderate
0.75 – 0.90	High
0.90 – 1.00	Very High

Source : [Bagherzadeh et al., \(2018\)](#)

The calculated Soil Fertility Index (SFI) values ranged from 0 to 1, with higher values indicating better soil fertility conditions. The SFI values were classified into five categories: very high, high, moderate, low, and very low. The classification criteria used in this study are presented in Table 3.

RESULT AND DISCUSSION

Laboratory data were subjected to Principal Component Analysis (PCA) to identify the Minimum Soil Fertility Indicators (MSFI) and determine the relative contribution of the selected soil properties to overall soil fertility. Six soil fertility variables, namely soil pH, cation exchange capacity (CEC), base saturation (BS), available phosphorus (P-available), exchangeable potassium (K), and soil organic carbon (SOC), were included in the PCA. The PCA was performed using SPSS software. Two principal components (PC1 and PC2) had eigenvalues greater than 1 and were retained for further analysis.

Table 4. Laboratory Analysis Results

Sample Code	pH H ₂ O	CEC (cmol/kg)	BS (%)	P-Available (ppm)	K-dd (cmol/kg)	C-Org (%)
TEV IR1	6.13 (SA)	48.75 (VH)	84.83 (VH)	64.728 (VH)	1.76 (VH)	1.211 (L)
TEV IR2	5.86 (SA)	46.71 (VH)	68.54 (H)	25.223 (VH)	1.15 (VH)	0.939 (VL)
TEV IR3	6.08 (SA)	46.59 (VH)	68.90 (H)	13.044 (M)	0.73 (H)	0.801 (VL)
TEV IR4	8.31 (SLA)	54.45 (VH)	74.38 (H)	6.721 (L)	0.68 (H)	0.749 (VL)
TEV N1	7.74 (SLA)	42.22 (VH)	84.47 (VH)	77.661 (VH)	2.75 (VH)	1.000 (VL)
TEV N2	7.06 (N)	44.60 (VH)	59.86 (M)	2.352 (VL)	0.32 (M)	0.398 (CL)
TEV N3	6.72 (N)	46.49 (VH)	77.13 (H)	54.477 (VH)	1.34 (VH)	1.268 (L)
TEV N4	7.48 (N)	42.14 (VH)	71.17 (H)	36.227 (VH)	1.53 (VH)	0.682 (VL)
THA IR1	6.59 (N)	48.07 (VH)	71.77 (H)	25.581 (VH)	0.71 (H)	0.911 (VL)
THA IR2	8.02 (SLA)	43.72 (VH)	90.19 (VH)	92.907 (VH)	7.15 (VH)	1.312 (L)
THA IR3	8.44 (SLA)	42.13 (VH)	86.46 (VH)	22.327 (VH)	3.32 (VH)	0.934 (VL)
THA IR4	7.69 (SLA)	57.88 (VH)	73.74 (H)	51.171 (VH)	1.16 (VH)	1.105 (L)
THA N1	6.64 (N)	52.81 (VH)	77.97 (H)	35.019 (VH)	1.59 (VH)	1.363 (L)
THA N2	6.19 (SA)	69.58 (VH)	52.90 (M)	16.111 (H)	1.10 (VH)	1.004 (L)
THA N3	6.09 (SA)	35.17 (H)	41.78 (M)	7.777 (L)	0.21 (L)	0.560 (VL)
THA N4	6.24 (SA)	41.76 (VH)	60.97 (H)	3.785 (VL)	0.12 (L)	0.572 (VL)
THI IR1	6.83 (N)	48.61 (VH)	68.27 (H)	16.276 (H)	0.30 (M)	0.649 (VL)
THI IR2	8.49 (SLA)	48.61 (VH)	81.75 (VH)	1.478 (VL)	0.30 (M)	0.532 (VL)
THI IR3	8.3 (SLA)	36.99 (H)	77.69 (H)	3.423 (VL)	0.49 (M)	0.582 (VL)
THI IR4	6.69 (N)	41.52 (VH)	55.46 (M)	14.147 (M)	0.31 (M)	0.755 (VL)
THI N1	6.57 (N)	39.39 (H)	65.54 (H)	26.448 (VH)	0.48 (M)	0.669 (VL)
THI N2	6.02 (SA)	48.27 (VH)	66.00 (H)	6.920 (L)	0.48 (M)	0.656 (VL)
THI N3	6.8 (N)	43.82 (VH)	69.10 (H)	12.833 (M)	0.46 (M)	0.958 (VL)
THI N4	6.6 (N)	42.85 (VH)	62.44 (H)	6.915 (L)	0.30 (M)	0.667 (VL)

Sample Code	pH H ₂ O	CEC (cmol/kg)	BS (%)	P-Available (ppm)	K-dd (cmol/kg)	C-Org (%)
THV IR1	6.87 (N)	49.29 (VH)	65.15 (H)	9.249 (L)	0.38 (M)	0.690 (VL)
THV IR2	6.7 (N)	36.96 (H)	57.79 (M)	9.823 (L)	0.18 (L)	0.755 (VL)
THV IR3	5.91 (SA)	39.75 (H)	77.01 (H)	15.270 (H)	0.63 (H)	1.001 (L)
THV IR4	6.84 (N)	38.09 (H)	79.37 (H)	32.843 (VH)	1.21 (VH)	0.828 (VL)
THV N1	7.00 (N)	42.16 (VH)	59.76 (M)	6.735 (L)	0.47 (M)	0.435 (VL)
THV N2	6.72 (N)	27.08 (H)	42.15 (M)	1.619 (VL)	0.34 (M)	0.433 (VL)
THV N3	5.88 (SA)	41.97 (VH)	72.23 (H)	24.468 (VH)	0.62 (H)	0.878 (VL)
THV N4	7.29 (N)	36.22 (H)	72.29 (H)	22.880 (VH)	0.46 (M)	0.668 (VL)

Notes: TEV= Typic Endoaquerts; THA= Typic Haplustalfs; THI= Typic Haplustepts; THV= Typic Haplusterts;
IR= Technical Irrigated Paddy Fields; N= Semi-Technical Irrigated Paddy Fields;
VL/L/M/H/VH= Very Low/Low/Moderate/High/Very High,
SA/N/SLA= Slightly Acidic/Neutral/Slightly Alkaline

To further identify the soil fertility indicators that most strongly contributed to the variation in the Soil Fertility Index (SFI), Pearson correlation analysis was conducted between the six soil fertility indicators and SFI values. The results showed that available P had the strongest positive correlation with SFI ($r = 0.836$), followed by organic C ($r = 0.822$), base saturation ($r = 0.736$), exchangeable K ($r = 0.707$), CEC ($r = 0.402$), and pH ($r = 0.243$). These results indicate that available P and organic C were the indicators most strongly associated with variations in SFI in the study area. The strong correlation of available P and organic C with SFI was also consistent with the PCA results, which showed relatively high loading values for these variables. Therefore, available P and organic C can be considered important indicators contributing to the observed variation in soil fertility among the rice fields.

Following the laboratory analysis of soil chemical properties (Table 4), the dataset was analyzed using Principal Component Analysis (PCA) in SPSS. This multivariate statistical approach was employed to identify the key variables explaining the variability of soil fertility characteristics and to determine the Minimum Soil Fertility Indicators (MSFI). The PCA results, including eigenvalues, explained variance, and loading factors for each variable, are shown in Table 5.

Table 5. Results From Principal Component Analysis

Eigen Analysis of The Corelation Matrix		
Eigenvalue	2.768	1.342
Proportion	0.461	0.224
Cumulative	0.461	0.685
Eigenvectors		
Variable	PC1	PC2
pH	0.337	0.731
CEC	0.219	-0.599
BS	0.700	0.413
P-Available	0.884	-0.174
K-available	0.851	0.145
C-Organik	0.782	-0.478

The PCA results showed that PC1 had an eigenvalue of 2.768 and explained 46.14% of the total variance, while PC2 had an eigenvalue of 1.342 and explained 22.37%. Together, the two principal components explained 68.51% of the total variance. Available phosphorus showed the highest loading in PC1 (0.884), while soil pH showed the highest loading in PC2 (0.731). These results indicate that available phosphorus and soil pH were the variables with the strongest contributions to the variation in soil fertility among the selected soil properties.

A total of six soil fertility variables were included in the analysis, namely soil pH, cation exchange capacity (CEC), base saturation (BS), available phosphorus (P-available), exchangeable potassium (K), and soil organic carbon (SOC). PCA was employed to evaluate the relative contribution of each variable to overall soil fertility and to derive weighting factors for the Soil Fertility Index (SFI) calculation. Although P-available and pH showed the highest contributions to the principal components, all six variables were retained in the SFI assessment because they collectively represent the major soil chemical properties controlling nutrient availability, nutrient retention, and soil fertility in paddy fields.

The laboratory analysis results for each soil fertility indicator were subsequently converted into scoring indices (Si) based on the soil fertility criteria established by the Indonesian Center for Agricultural Land Resources Research and Development. The weighting index (Wi) for each indicator was determined from the PCA results and used to calculate the Soil Fertility Index through a weighted scoring approach.

Table 6. Soil Fertility Index Calculation for Typic Endoaquerts

MSFI	Wi	TEV IR				TEV N			
		1	2	3	4	1	2	3	4
pH	0.163	4	3	4	5	5	5	5	5
CEC	0.163	5	5	5	5	5	5	5	5
BS	0.168	5	4	4	4	5	3	4	4
P-available	0.168	5	5	3	2	5	1	5	5

MSFI	Wi	TEV IR				TEV N			
		1	2	3	4	1	2	3	4
K-available	0.168	5	5	4	4	5	3	5	5
SOC	0.168	2	1	1	1	1	1	2	1
cj		4.33	3.83	3.49	3.48	4.33	2.98	4.33	4.16
Smax		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
SFI		0.87	0.77	0.70	0.70	0.87	0.60	0.87	0.83
Class		High	High	Mod	Mod	High	Mod	High	High

Notes: IR= Technical Irrigated Paddy Fields; N= Semi-Technical Irrigated Paddy Fields; Mod= Moderate

Table 7. Soil Fertility Index Calculation for Typic Haplustalfs

MSFI	Wi	THA IR				THA N			
		1	2	3	4	1	2	3	4
pH	0.163	4	5	5	5	4	4	4	4
CEC	0.163	5	5	5	5	5	5	4	5
BS	0.168	4	5	5	4	4	3	3	3
P-available	0.168	5	5	5	5	5	4	2	1
K-available	0.168	4	5	5	5	5	5	2	2
SOC	0.168	1	2	1	2	2	2	1	1
cj		3.83	4.49	4.33	4.33	4.16	3.83	2.65	2.65
Smax		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
SFI		0.77	0.90	0.87	0.87	0.83	0.77	0.53	0.53
Class		High	High	High	High	High	High	Mod	Mod

Notes: IR= Technical Irrigated Paddy Fields; N= Semi-Technical Irrigated Paddy Fields; Mod= Moderate

Table 8. Soil Fertility Index Calculation for Typic Haplustepts

MSFI	Wi	THI IR				THI N			
		1	2	3	4	1	2	3	4
pH	0.163	5	5	5	4	4	4	5	4
CEC	0.163	5	5	4	5	4	5	5	5
BS	0.168	4	5	4	3	4	4	4	4
P-available	0.168	4	1	1	3	5	2	3	2
K-available	0.168	3	3	3	3	3	3	3	3
SOC	0.168	1	1	1	1	1	1	1	1
cj		3.65	3.32	2.98	3.15	3.49	3.15	3.48	3.15
Smax		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
SFI		0.73	0.66	0.60	0.63	0.70	0.63	0.70	0.63
Class		Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod

Notes: IR= Technical Irrigated Paddy Fields; N= Semi-Technical Irrigated Paddy Fields; Mod= Moderate

Table 9. Soil Fertility Index Calculation for Typic Haplusterts

MSFI	Wi	THV IR				THV N			
		1	2	3	4	1	2	3	4
pH	0.163	5	5	4	5	5	5	3	5
CEC	0.163	5	4	4	4	5	4	5	4
BS	0.168	4	3	4	4	3	3	4	4
P-available	0.168	2	2	4	5	4	1	5	5
K-available	0.168	3	2	4	5	3	3	4	3
SOC	0.168	1	1	2	1	1	1	1	1
cj		3.32	2.82	3.66	3.99	3.48	2.82	3.66	3.66
Smax		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
SFI		0.66	0.56	0.73	0.80	0.70	0.56	0.73	0.73
Class		Mod	Mod	Mod	High	Mod	Mod	Mod	Mod

Notes: IR= Technical Irrigated Paddy Fields; N= Semi-Technical Irrigated Paddy Fields; Mod= Moderate

Soil Fertility Index of Rice Fields with Different Soil Types

The Soil Fertility Index (SFI) values of paddy fields in Tikung District varied among soil types and irrigation systems, indicating differences in soil chemical quality and nutrient availability. The calculated SFI values ranged from 0.53 to 0.90 and were classified into two fertility categories, namely moderate and high (Tables 6–9). These variations demonstrate that soil fertility is influenced by the interaction between inherent soil characteristics and land management practices, particularly irrigation and fertilization.

The relatively high Soil Fertility Index observed in several sampling sites was closely associated with high cation exchange capacity (CEC) values (Trigunasih et al., 2023). CEC is an important indicator of soil fertility because it reflects the ability of soil colloids to retain and exchange nutrient cations required for plant growth. Soils with high CEC generally have a greater capacity to store nutrients such as Ca^{2+} , Mg^{2+} , K^{+} , and NH_4^{+} , thereby reducing nutrient losses through leaching and increasing nutrient use efficiency. Consequently, higher CEC values contribute positively to nutrient availability and overall soil fertility status.

Among the evaluated soil types, Typic Endoaquerts (TEV) exhibited the highest soil fertility status, with SFI values ranging from 0.60 to 0.87. Most TEV sampling sites were classified as high fertility. This condition was associated with consistently high scores for cation exchange capacity (CEC), base saturation (BS), available phosphorus, and exchangeable potassium. Vertic soils such as Typic Endoaquerts are characterized by a high clay content dominated by expanding clay minerals, which provide a large surface area and high nutrient retention capacity (Singh et al., 2025). This characteristic was reflected in the consistently high CEC values observed in the study area. Consequently, these soils are capable of storing and supplying essential nutrients more effectively than other soil types (Hamzah et al., 2024). Nevertheless, relatively low soil organic carbon scores limited the maximum SFI values, indicating that organic matter remains an important factor in improving overall soil fertility (Zeng et al., 2026). Base saturation is another important indicator influencing soil fertility status in Typic Endoaquerts. High base

saturation values indicate that exchange sites are predominantly occupied by basic cations, resulting in favorable conditions for nutrient uptake by plants (Zhang et al., 2023). The combination of high CEC and high base saturation enhances nutrient retention and availability, contributing to the high fertility status observed in this soil type (Bouajila et al., 2023).

The Typic Haplustalfs (THA) soils showed SFI values ranging from 0.53 to 0.90. Most sites under technical irrigation were classified as high fertility, whereas several semi-technical irrigation sites were categorized as moderate fertility. The highest SFI value (0.90) was observed at THA IR2, reflecting favorable soil chemical conditions, including high nutrient availability and base saturation. In contrast, the lower SFI values recorded at THA N3 and THA N4 were mainly attributed to reduced available phosphorus, exchangeable potassium, and soil organic carbon. These findings suggest that nutrient depletion and insufficient organic matter inputs may limit soil fertility in certain Haplustalf areas, particularly where water management is less intensive (Rizki et al., 2024). Available phosphorus was identified as one of the most influential variables affecting soil fertility status. Phosphorus plays a crucial role in root development, tillering, and grain formation in rice plants (Vijay et al., 2026). Sites with higher phosphorus availability generally exhibited higher SFI values, indicating that phosphorus management remains essential for maintaining soil fertility and sustaining rice productivity (Dutta et al., 2024).

The SFI values of Typic Haplustepts (THI) ranged from 0.60 to 0.73, and all sampling sites were classified within the moderate fertility category. Compared with the other soil types, THI exhibited relatively uniform SFI values, indicating similar fertility conditions across sampling locations. The moderate fertility status was primarily associated with low organic carbon content and moderate levels of exchangeable potassium. In addition, several sites recorded low available phosphorus scores, which further reduced the overall fertility index. These results indicate that soil fertility improvement in Typic Haplustepts should focus on increasing organic matter inputs and enhancing phosphorus availability through appropriate fertilization strategies (Gao et al., 2023).

Similarly, Typic Haplusterts (THV) exhibited SFI values ranging from 0.56 to 0.80. Most sites fell within the moderate fertility category, while THV IR4 reached the high fertility category with an SFI value of 0.80. The higher fertility status at THV IR4 was associated with greater phosphorus and potassium availability compared with other THV sites. Conversely, lower SFI values observed at THV IR2 and THV N2 were related to reduced nutrient availability and low organic carbon content. Although Haplusterts generally possess a high nutrient retention capacity due to their clay-rich nature, limited organic matter content remains a major constraint affecting soil fertility (Mesele et al., 2024). Differences in Soil Fertility Index among soil types were largely related to variations in soil mineralogy and clay content (Afu et al., 2024). Vertisol-derived soils such as Typic Endoaquerts and Typic Haplusterts generally possess greater nutrient retention capacity due to the dominance of expanding clay minerals. These characteristics allow the soil to store and supply nutrients more effectively than soils with lower clay activity, resulting in higher fertility levels (Kome et al., 2019).

The average SFI under technical irrigation ranged from 0.66 to 0.90, whereas semi-technical irrigation produced values ranging from 0.53 to 0.87, indicating a

tendency toward higher fertility under technical irrigation management. This trend was particularly evident in Typic Endoaquerts and Typic Haplustalfs soils, where most technically irrigated sites were classified as highly fertile. Adequate and stable water supply under technical irrigation likely promotes nutrient dissolution, transport, and uptake by plants while reducing nutrient losses caused by water stress (Zebua et al., 2026). Furthermore, improved irrigation management may enhance fertilizer use efficiency and support microbial activity involved in nutrient cycling (Ren et al., 2023). In contrast, semi-technical irrigation systems often experience fluctuations in water availability, which can negatively affect nutrient dynamics and contribute to lower fertility indices (Purwadi & Mindari, 2025). In paddy ecosystems, water management plays a critical role in regulating nutrient mobility and nutrient availability (Xu et al., 2026). Adequate irrigation promotes nutrient dissolution and transport within the soil solution, thereby facilitating nutrient uptake by rice plants. Stable water availability may also enhance microbial activity involved in nutrient cycling and organic matter decomposition, contributing to improved soil fertility (Gurmu, 2019).

The results also indicate that soil organic carbon was the most consistent limiting factor across all soil types. The low soil organic carbon content may be attributed to the continuous removal of crop residues, intensive cultivation practices, and the limited application of organic amendments in paddy fields (Goswami et al., 2020). Despite generally favorable values of CEC, base saturation, phosphorus, and potassium, the low organic carbon content recorded at many sampling sites reduced the overall SFI values. Soil organic matter plays a crucial role in improving soil structure, increasing nutrient retention, enhancing microbial activity, and maintaining long-term soil productivity (Hussain et al., 2023). Therefore, increasing organic matter inputs through the application of compost, manure, crop residues, or other organic amendments is essential for sustaining soil fertility in paddy fields (Haque et al., 2021). The low organic carbon content observed in many sampling locations may be associated with intensive cultivation practices and limited organic matter inputs. Continuous rice cultivation without sufficient incorporation of organic amendments can gradually reduce soil organic matter reserves. Therefore, the application of compost, manure, green manure, or crop residues should be encouraged to improve soil quality and maintain long-term agricultural sustainability.

Overall, the ranking of soil fertility based on SFI was Typic Endoaquerts and Typic Haplustalfs exhibited higher fertility levels than Typic Haplusterts and Typic Haplustepts. This pattern reflects differences in soil mineralogy, nutrient retention capacity, and management practices among the soil types (Adhikari et al., 2015). The findings demonstrate that the Soil Fertility Index is an effective tool for integrating multiple soil chemical properties into a single quantitative measure, thereby facilitating the evaluation and comparison of soil fertility conditions across different soil types and irrigation systems. The use of the Soil Fertility Index provides a comprehensive approach for evaluating soil fertility because it integrates several soil chemical properties into a single quantitative indicator (Chaudhry et al., 2024). This approach allows for easier comparison among locations and facilitates the identification of limiting factors affecting soil productivity. Consequently, SFI can serve as an effective tool for supporting site-specific soil fertility management and sustainable agricultural

planning. The information obtained from this study can serve as a scientific basis for developing site-specific soil fertility management strategies aimed at improving the sustainability and productivity of rice cultivation in Tikung District, Lamongan Regency.

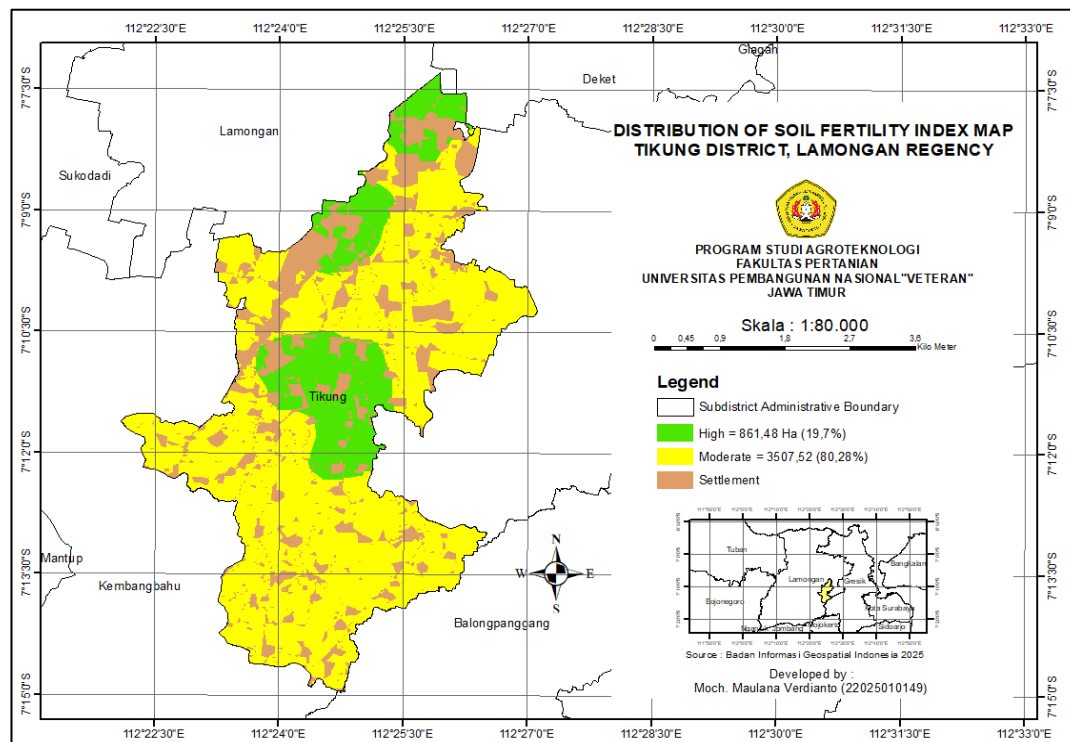


Figure 2. Distribution of Soil Fertility Index Map

Based on the Soil Fertility Index Distribution Map of Tikung District, Lamongan Regency, the soil fertility status of the paddy fields was classified into two categories, namely high and moderate fertility. The spatial distribution indicates that the moderate fertility class dominates the study area, while the high fertility class is distributed in several locations, particularly in the central and northern parts of Tikung District.

Table 10. Soil Fertility Index Distribution Area

Class Soil Fertility Index	Area (Ha)	%
High	861.48	19.70
Moderate	3507.52	80.28

The spatial analysis revealed that the high fertility class covers an area of 861.48 ha, representing 19.7% of the total study area. In contrast, the moderate fertility class occupies 3,507.52 ha, accounting for 80.28% of the total area. These results indicate that the majority of paddy fields in Tikung district are characterized by a moderate level of soil fertility, while only a smaller proportion exhibits high fertility status.

CONCLUSION

The Soil Fertility Index (SFI) effectively characterized the fertility status of paddy fields under different soil types and irrigation systems in Tikung district, Lamongan Regency. The calculated SFI values ranged from 0.53 to 0.90, indicating moderate to high fertility levels across the study area. Typic Endoaquerts and Typic Haplustalfs generally showed relatively higher fertility conditions than Typic Haplusterts and Typic Haplustepts. Technical irrigation generally showed higher SFI values than semi-technical irrigation, indicating the importance of adequate water management in maintaining soil fertility. Spatial analysis showed that 80.28% of the paddy-field area was classified as moderate fertility, while 19.7% was classified as high fertility. Soil organic carbon was identified as the most consistent limiting factor across the study area, despite generally favorable CEC, base saturation, available phosphorus, and exchangeable potassium values. The contribution of this study is the integration of soil type, irrigation system, SFI assessment, and spatial analysis to provide site-specific information on soil fertility conditions in Tikung District. The resulting fertility distribution and identification of limiting factors can serve as a basis for developing more targeted soil management strategies, particularly through increasing organic matter inputs using compost, manure, crop residues, or other suitable organic amendments to support sustainable rice production.

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