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Evaluating of soil fertility index using a comparative approach: Nutrient Index and Principal Component Analysis in different land uses in Indonesia

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Abstract

This study aims to evaluate the soil fertility index using the Nutrient Index (NI) and Principal Component Analysis (PCA) across different land uses in Mojogedang Subdistrict, Karanganyar Regency, Indonesia. Soil samples were collected using purposive sampling from 14 land map units (LMUs) and analysed in the laboratory for selected soil chemical properties. The laboratory data were processed using the Nutrient Index and Soil Fertility Index methods, with the Minimum Data Set (MDS) derived from correlation analysis and Principal Component Analysis (PCA), followed by scoring to determine the scoring index (Si). According to land-use type, the classification of soil fertility index using two methods yielded different classes in both land uses. The Nutrient Index method showed that the mixed garden had higher soil fertility than the moorland, whereas the values are medium (1.75) and low (1.62), respectively. Meanwhile, the PCA method classified both mixed garden and moorland as medium, with values of 0.54 and 0.51, respectively. However, the soil fertility index for each land map unit differed across land uses. A T-test showed significant differences ($p = 0.000$) between the two methods. The determining factors in the Nutrient Index method are total N and available P, with land use as the main source of variation ($p = 0.002$), while in the PCA method are soil pH, organic carbon, available P, cation exchange capacity (CEC) with soil type ($p = 0.001$) and land use ($p = 0.003$) as the main sources of variation. The study concludes that the PCA method provides a more comprehensive representation of soil fertility conditions by using a broader set of soil indicators. In contrast, the Nutrient Index method is simpler and easier to apply as it utilizes fewer soil parameters. Understanding the different types of land uses and soil characteristics is crucial for enhancing soil fertility and ensuring sustainable agricultural practices.

1. Introduction

The agricultural sector plays an important role in Indonesia's economy and food security, however productivity on dry land is often hampered by declining soil fertility (Hairiah et al., 2025). Mojogedang Subdistrict is located in the Mount Lawu area, which has a volcanic landform. Mount Lawu is an active volcano situated along the ring of fire, at the convergent boundary between the Indian-Australian Plate to the south and the Eurasian Plate to the north (Legowo et al., 2023). This region is dominated by Inceptisols and Alfisols, which are potentially productive but vulnerable to fertility imbalances due to intensive agriculture and limited organic matter content (Oladele, 2019). In dry land areas, such as Mojogedang Subdistrict, agricultural land supports essential crops, including sugarcane, coconut, and robusta coffee (Ismardani, 2024). However, information on the spatial and functional variability of soil fertility in this system is still limited, hindering efforts to develop location-specific management strategies.

Soil fertility is key to agricultural land management, so evaluating it is one way to determine a soil's ability to produce targeted crop yields in its environment. However, the entire world is currently experiencing a decline in soil fertility. Soil fertility decline is a major obstacle to agricultural productivity and global food security, especially in tropical regions where intensive land use and unsustainable management accelerate nutrient leaching (Lal, 2020). Assessing soil fertility is essential to ensure optimal nutrient management, maintain crop yields, and preserve ecosystem services. Several studies have indicated that soil fertility is affected by soil properties, land management, and environmental conditions (Chi et al., 2020). A study by Dewi et al. (2024) found that land cover affects soil

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fertility, particularly through the influence of litterfall, breast height diameter of trees, and tree density. In addition, the earthworm population also contributes to enhancing soil fertility (Suntoro et al., 2023). Mujiyo et al. (2022) reported that altitude significantly affects soil fertility, whereas high altitude contributes to increased cassava productivity. Other studies have explained that macroorganisms, such as termites, play a crucial role in improving soil fertility (Febriani et al., 2025). Moreover, Supriyadi et al. (2018) reported that soil fertility is higher under organic than under inorganic land management, due to soil properties. To improve soil fertility and ensure environmentally sustainable farming practices, it is necessary to understand the agri-environmental characteristics of different land uses and soil types.

Many methods have been developed to evaluate soil fertility (Chaudhry et al., 2024), ranging from nutrient index to advanced multivariate statistical methods such as principal component analysis (Amara et al., 2017; Bagherzadeh et al., 2018). However, each method has limitations in capturing the multidimensional nature of soil properties that influence crop performance. Previous studies have frequently employed the Nutrient Index (NI) method to categorize soil fertility status based on critical soil chemical properties (AbdelRahman et al., 2021; Khadka et al., 2017). While simple and widely applied, the Nutrient Index does not fully account for interactions among soil parameters. Conversely, Principal Component Analysis (PCA) offers a multivariate approach that reduces data complexity while retaining the most informative soil indicators (Mukashema, 2007; Wu et al., 2025). Despite their complementary strengths, comparative applications of NI and PCA for soil fertility assessment in tropical volcanic ecosystems remain scarce. This gap limits both scientific understanding and practical recommendations for sustainable land management.

This study evaluates soil fertility in different land uses within Mojogedang Subdistrict by comparing the Nutrient Index and PCA methods, specifically in mixed gardens and moorlands, across Inceptisols and Alfisols. By integrating the Nutrient Index into a multivariate statistical framework, this study aims to identify the factors that determine soil fertility, provide a robust comparative evaluation of the methods used, and generate recommendations to improve land productivity. This contribution is expected to enhance the development of methodologies for assessing soil fertility and their application in sustainable agricultural management.

2. Materials and methods

2.1. General Conditions of the Study Area

This study was conducted in Mojogedang Subdistrict, Karanganyar Regency, Central Java Province, Indonesia, located in the area: 7°30'20.972"–7°35'56.803"S and 110°56'57.176"–111°3'24.893" E. Mojogedang Subdistrict has an area of 53.31 km^2 with a total dry land area of 3,208.73 ha with an annual rainfall average of 1,200–2,600 mm year^{-1}. This study used purposive sampling of dry land in the mixed garden and moorland across the Mojogedang Subdistrict. Mixed garden is agroforestry system, is a soil management system that combines agricultural plants and forestry. This system is capable of improving productivity in both the long and short term, such as annual plant and horticulture crops (Setiawan et al., 2024). Moorland is dryland agricultural land that relies on rainfall for irrigation or an area with limited water, usually planted with seasonal crops or drought-resistant crops, and uses minimum tillage or no tillage in soil management. These two land uses are distinguished based on the crops planted, management, and fertilization.

2.2. Determining The Land Map Unit and Soil Sample Collection

This research method was conducted by surveying soil characteristics and performing laboratory analyses to describe the actual conditions in the field. The process began with a pre-survey to observe the location and establish land map units (LMUs) while determining sample points through purposive sampling. A land map unit or soil sampling unit is a spatial analysis unit created by overlaying several base maps, such as administrative, geological, slope, landform, soil type, and land use maps, to show similar land characteristics. In this research, LMUs were created using an overlay method from 4 different of sources of map diversity, namely the Indonesian topographic map, soil types (Alfisols and Inceptisols), land use (mixed garden and moorland), rainfall (1292.4 and 2661.92 mm year^{-1}), and land slope (0–8%, 8–15%, 15–25%, 25–45%, >45%). The soil was classify based on the Key of Soil Taxonomy (Soil Survey Staff, 2022), whereas Alfisols is soil that have an accumulation clay in horizon B, called argilic horizon, high of base status and have a combination of an ochric or umbric epipedon, usually located in high rainfall and moderate temperature, while Inceptisols is a developed soil, have one or more pedogenic horizons of alteration. The soil is classified to the order level.

Based on the overlay results, 14 land map units were identified. The distribution of the location land map unit was shown in Fig. 1, and the characteristics of each LMU were explained in Table 1. Each LMU was repeated three times with different sampling points to represent the entire LMU, resulting in a total of 42 soil samples collected. Subsequently, field surveys and soil sampling were conducted for laboratory analysis. Soil samples were collected at a 0–120 cm depth using a soil auger, and then soil characteristics were described according to horizon boundaries. Samples were then collected at 0–30 cm for soil analysis in the laboratory.

2.3. Soil Laboratory Analysis

The soil analyses conducted include soil pH H_2O (1:5) (FAO, 2021), soil texture using pipette method (Eviati et al., 2023), organic carbon using Walkley-Black rapid titration method (Walkley and Black), total nitrogen (Kjeldahl), available phosphorus using $NaHCO_3$ extractable P (pH 8.5) (Olsen), available potassium NH_4O_{Ac} extractable K (Chapman), cation exchange capacity, extract of NH_4O_{Ac} 1M, pH 7 (Chapman), base

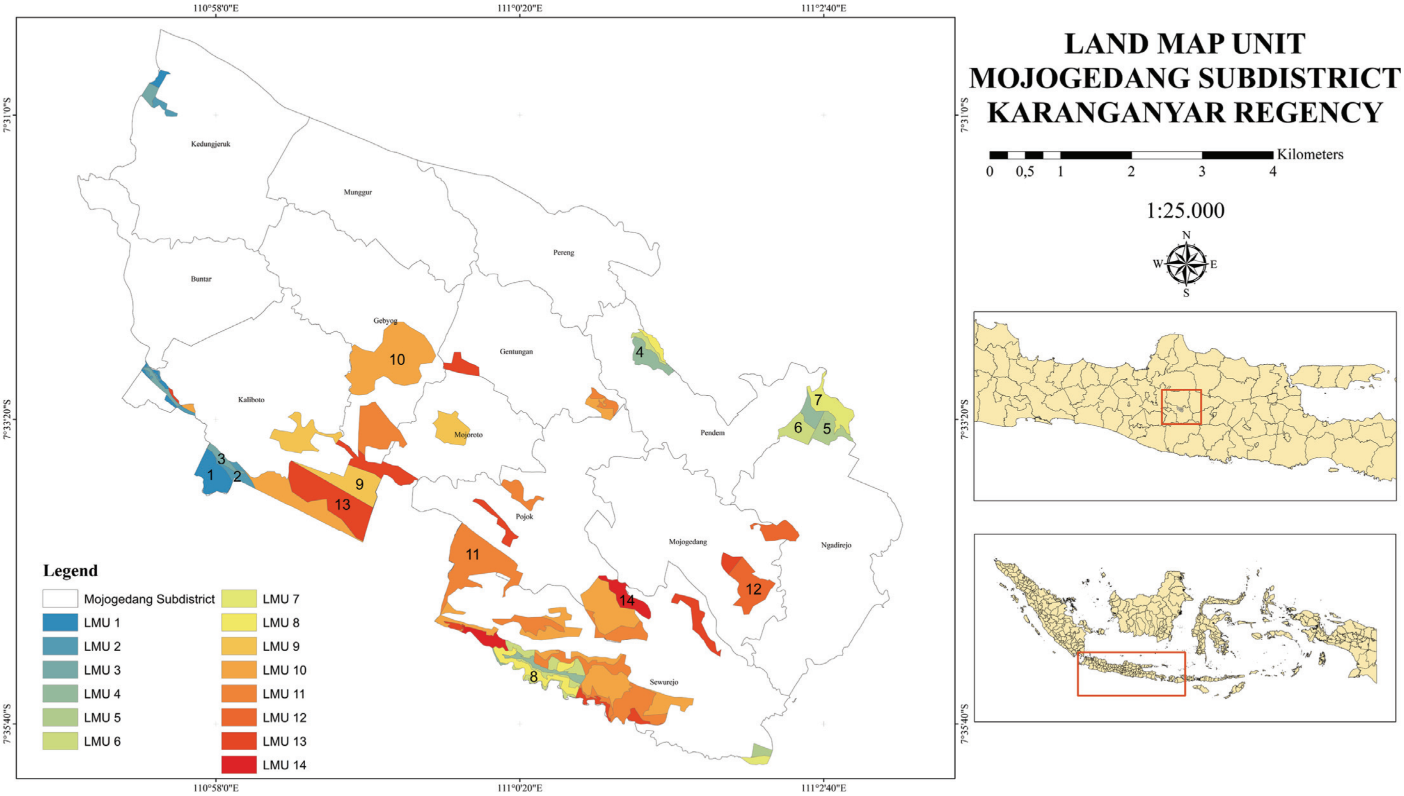


Fig. 1. The distribution of land map unit in the study area

Table 1
The characteristics of each land map unit

LMU	Soil Type	Land Use	Slope (%)	Rainfall (mm/year)	Area (ha)
1	Alfisols	Moorland	8–15	1292.4	21.38
2	Alfisols	Moorland	15–25	1292.4	14.44
3	Alfisols	Moorland	25–45	1292.4	13.92
4	Inceptisols	Mixed Garden	8–15	1292.4	21.56
5	Inceptisols	Mixed Garden	8–15	2661.92	13.45
6	Inceptisols	Mixed Garden	15–25	1292.4	22.97
7	Inceptisols	Mixed Garden	15–25	2661.92	26.32
8	Alfisols	Mixed Garden	25–45	1292.4	16.65
9	Inceptisols	Moorland	0–8	1292.4	72.50
10	Inceptisols	Moorland	8–15	1292.4	187.38
11	Alfisols	Moorland	15–25	1292.4	162.61
12	Inceptisols	Moorland	15–25	2661.92	10.24
13	Inceptisols	Moorland	25–45	1292.4	85.40
14	Inceptisols	Moorland	>45	1292.4	18.26
	Total area				687.08

saturation extract of NH_4O_{Ac} 1M, pH 7 (Chapman), exchangeable Ca, extract of NH_4O_{Ac} 1M, pH 7 (Chapman), exchangeable Mg, extract of NH_4O_{Ac} 1M, pH 7 (Chapman), exchangeable Na, extract of NH_4O_{Ac} 1M, pH 7 (Chapman), available Fe, DTPA-extractable method, using Atomic Absorption Spectrophotometer (AAS).

The soil characteristics in each land map unit was presented in Table 2.

Table 2
The characteristics of soil in each land map unit (LMU)

LMU	Soil sample	pH H_2O	Tot-N (%)	Av. P (ppm)	Av. K ($cmol^+kg^{-1}$)	OC (%)	CEC ($cmol^+kg^{-1}$)	BS (%)
1	1	7.1	0.13	4.33	0.12	1.23	27.54	15.47
	2	6.7	0.15	3.93	0.12	1.11	20.10	21.20
	3	6.7	0.19	4.39	0.11	1.08	14.17	25.77
2	4	6.9	0.20	4.00	0.13	1.15	19.29	25.67
	5	7.2	0.24	4.48	0.11	1.15	14.82	29.02
	6	5.6	0.22	4.10	0.07	1.06	14.91	22.54
3	7	6.6	0.37	3.84	0.09	1.17	21.64	20.20
	8	6.8	0.42	3.40	0.07	1.14	20.13	19.15
	9	7.0	0.60	4.21	0.08	1.08	17.71	21.92
4	10	6.3	0.51	5.26	0.13	0.99	12.02	30.29
	11	6.1	0.56	5.09	0.11	1.04	8.69	37.51
	12	6.1	0.48	5.21	0.14	1.01	11.74	31.78
5	13	6.2	0.79	5.26	0.13	1.08	11.65	22.75
	14	6.2	0.68	5.01	0.12	1.18	24.84	11.42
	15	5.5	0.71	5.13	0.12	1.05	16.30	13.75
6	16	6.3	0.55	5.00	0.14	1.01	13.01	29.08
	17	6.5	0.49	4.88	0.14	1.08	22.29	17.46
	18	6.2	0.55	5.05	0.13	1.03	20.23	18.44
7	19	6.0	0.54	5.04	0.14	1.15	10.73	39.36
	20	6.3	0.58	4.71	0.14	1.19	13.81	30.09
	21	5.8	0.53	5.09	0.15	1.08	7.80	48.76
8	22	6.2	0.54	4.74	0.12	1.16	21.90	12.18
	23	6.6	0.58	4.34	0.12	1.09	15.34	18.01
	24	6.0	0.50	5.18	0.14	1.15	16.47	18.88
9	25	5.3	0.38	4.58	0.10	1.19	21.97	22.49
	26	6.7	0.61	4.47	0.11	1.17	15.57	28.31
	27	5.7	0.35	4.21	0.11	1.17	13.65	30.93
10	28	6.8	0.31	4.18	0.10	1.12	24.41	17.35
	29	5.7	0.46	4.66	0.10	1.06	8.78	50.55
	30	6.1	0.41	3.99	0.10	0.99	15.39	20.48
11	31	7.0	0.24	4.27	0.11	1.04	16.22	25.65
	32	6.0	0.20	3.89	0.11	1.05	12.00	33.68
	33	6.0	0.16	4.67	0.11	1.06	19.55	20.94
12	34	7.0	0.25	4.49	0.09	1.06	15.49	18.46
	35	6.4	0.29	3.59	0.09	1.15	16.44	17.25
	36	6.7	0.23	4.66	0.09	0.99	8.37	49.42
13	37	6.8	0.18	3.46	0.10	1.09	17.63	10.67
	38	6.8	0.21	3.28	0.10	1.07	12.37	7.37
	39	6.1	0.43	3.20	0.12	1.01	12.27	15.11
14	40	5.7	0.18	3.14	0.11	0.97	11.71	34.21
	41	5.8	0.27	2.50	0.10	1.01	15.14	17.87
	42	5.9	0.19	3.13	0.11	1.09	6.09	47.10
Mean		**6.3**	**0.39**	**4.33**	**0.11**	**1.09**	**15.72**	**24.97**
SD		**0.48**	**0.18**	**0.69**	**0.02**	**0.07**	**4.94**	**10.73**

Table 2
The characteristics of soil in each land map unit (LMU) (continued)

LMU	Soil sample	Exc. Na ($cmol^{+}kg^{-1}$)	Exc. Ca ($cmol^{+}kg^{-1}$)	Exc. Mg ($cmol^{+}kg^{-1}$)	Av. Fe (ppm)	Sand (%)	Silt (%)	Clay (%)	Texture
1	1	0.46	0.09	3.59	0.20	31.88	26.91	41.21	C
	2	0.52	0.06	3.56	0.19	31.36	36.88	31.76	CL
	3	0.18	0.05	3.32	0.16	25.79	58.58	15.63	SiL
2	4	0.28	0.04	4.50	0.16	49.73	31.45	18.82	L
	5	0.38	0.03	3.79	0.19	31.14	51.08	17.78	SiL
	6	0.54	0.02	2.73	0.18	49.73	29.42	20.85	L
3	7	0.23	0.06	4.00	0.15	18.11	51.22	30.67	SiCL
	8	0.13	0.04	3.65	0.17	40.45	31.30	28.25	CL
	9	0.10	0.02	3.67	0.18	23.01	52.42	24.57	SiL
4	10	0.49	0.02	3.00	0.13	7.67	30.82	61.51	C
	11	0.06	0.02	3.07	0.21	15.28	38.59	46.13	C
	12	0.52	0.07	3.00	0.14	21.39	50.90	27.71	CL
5	13	0.41	0.02	2.09	0.22	3.27	57.47	39.26	SiCL
	14	0.36	0.02	2.35	0.22	4.68	59.87	35.45	SiCL
	15	0.31	0.02	1.81	0.14	18.27	30.96	50.77	C
6	16	0.17	0.02	3.46	0.12	31.32	25.98	42.70	C
	17	0.25	0.04	3.46	0.14	21.91	41.57	36.52	CL
	18	0.09	0.03	3.50	0.13	16.51	53.89	29.60	SiCL
7	19	0.16	0.02	3.93	0.15	17.43	61.91	20.66	SiL
	20	0.10	0.02	3.90	0.17	15.53	60.99	23.48	SiL
	21	0.07	0.04	3.55	0.24	16.47	62.62	20.91	SiL
8	22	0.03	0.01	2.51	0.11	27.34	36.42	36.24	CL
	23	0.01	0.04	2.60	0.20	22.84	40.00	37.16	CL
	24	0.01	0.01	2.97	0.18	21.50	26.30	52.20	C
9	25	0.45	0.02	4.37	0.13	8.15	10.28	81.57	C
	26	0.22	0.05	4.02	0.13	56.55	3.13	40.32	SC
	27	0.13	0.02	3.97	0.19	27.12	45.36	27.52	CL
10	28	0.07	0.04	4.03	0.13	19.24	76.19	4.57	Si
	29	0.23	0.02	4.09	0.20	10.43	9.27	80.30	C
	30	0.13	0.01	2.91	0.19	17.44	20.14	62.42	C
11	31	0.08	0.05	3.91	0.12	18.88	38.51	42.61	C
	32	0.11	0.02	3.82	0.16	14.33	39.60	46.07	C
	33	0.17	0.04	3.79	0.14	24.94	22.88	52.18	C
12	34	0.13	0.03	2.61	0.19	6.29	8.34	85.37	C
	35	0.10	0.01	2.63	0.12	4.86	28.79	66.35	C
	36	0.10	0.01	3.93	0.15	26.51	40.39	33.10	CL
13	37	0.09	0.02	1.67	0.13	16.02	35.05	48.93	C
	38	0.10	0.04	0.67	0.17	13.75	9.06	77.19	C
	39	0.08	0.05	1.61	0.17	15.55	37.38	47.07	C
14	40	0.07	0.01	3.82	0.18	12.75	33.20	54.05	C
	41	0.20	0.01	2.39	0.16	14.00	31.17	54.83	C
	42	0.18	0.02	2.55	0.19	14.50	30.34	55.16	C
Mean		**0.20**	**0.03**	**3.21**	**0.17**	**21.05**	**37.30**	**41.65**	
SD		**0.15**	**0.02**	**0.84**	**0.03**	**11.95**	**16.71**	**19.02**	

Explanations: Tot-N (total nitrogen); Av. P (available phosphorus), Av. K (available potassium), OC (organic carbon), CEC (cation exchange capacity), BS (base saturation), Exc. Na (exchangeable natrium), Exc. Ca (Exchangeable calsium), Exc. Mg (exchangeable magnesium), Av. Fe (available Fe), C (clay), SiL (silty loam), L (loam), SiCL (silty clay loam), CL (clay loam); SC (sandy clay); SD (standard deviation)

2.4. The calculation of soil fertility index using Nutrient Index

The Nutrient Index method was first introduced by Parker et al., (1951) and is widely used today to determine the nutrient index that determines soil fertility. Laboratory analysis results are scored based on the nutrient index scoring in Table 3 (Abdehvand et al., 2024). The Nutrient Index is divided into three classes: low, medium, and high then multiplied by 1, 2, and 3, respectively. For example, the soil sample in LMU 1 soil sample 1 has pH H_2O value of 7.1; total nitrogen 0.13%; available P 4.33 ppm, it means that the LMU 1 has a score 2 for soil pH and 1 for total nitrogen and available P. The sum of the obtained numbers is divided by 100 to calculate the fertility index using Equation 1.

$$Nutrient\ \ Index = \frac{\{(1\,x\,A)\ +\ (2\,x\,B) + (3\ x\ C)\}}{TNS} \qquad \text{Equation 1}$$

Where
A = number of low-category soil samples; B = number of medium-category soil samples; C = number of high-category soil samples; and TNS = total number of soil samples.

The results of the calculation are then categorized according to Table 4.

2.5. The calculation of soil fertility index using Principal Component Analysis

Principal Component Analysis (PCA) is a linear reduction method with a simple theory of statistics, commonly used in statistical analysis. The result of PCA is a new variable called principal components (PC) obtained from the linear combination of the original variables. The first component (PC1) is the component with the dominant or greater variation, while the second component (PC2) is calculated below the first component with the largest possible inertia (Emami et al., 2024). The indicators selected as Minimum Data Set (MDS) had a significant correlation and an eigenvalue greater than 1. MDS is a minimum data set for determining the soil parameters that influence soil fertility. The probability classes (pc) are determined using Equation 2 by dividing the number of SFI classes (five classes). Soil samples that have undergone laboratory testing are then scored based on the BPSI Tanah dan Pupuk (2023) (Table 5). Wi represents an index weight derived from the proportion divided by the cumulative, and Si represents the indicator score. The total weighted score of all MDS (cj) was calculated by multiplying Wi and Si (Equation 3). Sci is the MDS weighted, obtained by multiple Equation 2 and Equation 3 (Equation 4). The calculation of SFI value was obtained through dividing of Sci by the total indicator number of MDS and multipling by 10, as shown in Equation 5 (Mukashema, 2007).

Table 3
Nutrient index scoring

Indicator	Unit	Score		
pH	–	< 6.0 (acidic)	6.1–8.0 (neutral)	>8.0 (alkaline)
Organic Carbon	%	<0.5 (low)	0.5–0.75 (medium)	>0.75 (high)
Total Nitrogen	kg ha^{-1}	<280 (low)	280–560 (medium)	>560 (high)
Available P	ppm	<10 (low)	10–25 (medium)	>25 (high)
Available K	cmol^{+}kg^{-1}	<110 (low)	110–280 (medium)	>280 (high)
Exc. Ca	cmol^{+}kg^{-1}	<1.5 (low)	1.5–4.5 (medium)	>4.5 (high)
Exc. Mg	cmol^{+}kg^{-1}	<1.5 (low)	1.5–4.5 (medium)	>4.5 (high)
Available Fe	ppm	<0.2 (low)	0.2–0.6 (medium)	>0.6 (high)
Nutrient Index	Index	I	II	III

Source: Abdehvand et al. (2024)

Table 4
Nutrient index range

Nutrient Index	Range	Description
I	< 1.67	Low
II	1.67–2.33	Medium
III	> 2.33	High

Source: Parker et al., (1951)

$$Pc = \frac{1}{nc} \qquad \text{Equation 2}$$

$$cj = Wi\ x\ Si \qquad \text{Equation 3}$$

$$Sci = cj\ x\ pc \qquad \text{Equation 4}$$

$$SFI = \left(\frac{Sci}{N}\right)\ x\ 10 \qquad \text{Equation 5}$$

Where
SFI = soil fertility index; *Sci* = MDS weighted; *N* = the total number of MDS indicators; *Pc* = Probability class; *cj* = total weighted score; *wi* = weighted index; *Si* = scoring index; *nc* = Number of classes.

Table 5
Soil fertility indicator scoring

Indicator	Unit	Score				
		1	2	3	4	5
pH	–	<4.5 and > 8.5	4.5–5.5	7.5–8.5	5.5–6.5	6.5–7.5
Organic Carbon	%	<1	1–2	2–3	3–5	>5
Total Nitrogen	%	<0.1	0.1–0.2	0.21–0.5	0.51–0.75	>0.75
Available P (Olsen)	ppm	<5	5–10	11–15	16–20	>20
Available K	$cmol^+kg^{-1}$	<0.1	0.1–0.3	0.4–0.5	0.6–1.0	>1
Cation Exchange Capacity (CEC)	$cmol^+kg^{-1}$	<5	5–16	17–24	25–40	>40
Exc. Ca	$cmol^+kg^{-1}$	<2	2–5	6–10	11–20	>20
Exc. Mg	$cmol^+kg^{-1}$	<0.3	0.4–1.0	1.1–2.0	2.1–8.0	>8
Exc. Na	$cmol^+kg^{-1}$	<0.1	0.1–0.3	0.4–0.7	0.8–1.0	>1
Base Saturation	%	<20	20–40	41–60	61–80	>80
Texture*	%	C, S	SiC, SL	CL, SL	SiL, Si, SiCL	L

Source: Eviati et al., (2023); *Lal (1994)

The calculation results are then categorized according to Bagherzadeh et al., (2018) in Table 6.

Table 6
Soil fertility index category classes

Soil Fertility Index	Value
Very Low (VL)	0.00–0.25
Low (L)	0.25–0.50
Medium (M)	0.50–0.75
High (H)	0.75–0.90
Very High (VH)	0.90–1.00

Source: Bagherzadeh et al., (2018)

2.6. Statistical Analysis

There are several statistical analyses to evaluate the soil fertility. The t-test is used to compare the significance ($p<0.05$) of the Nutrient Index and Principal Component Analysis (PCA) methods in determining the soil fertility index. The Analysis of Variance (ANOVA) test is used to determine the effect of the source of diversity (soil type, land use, rainfall, and slope) on the soil fertility index using the Principal Component Analysis and Nutrient Index methods at significance ($p<0.05$). The Pearson Correlation test is used to determine the correlation between soil characteristics and the soil fertility index, and to identify the determining factors of the soil fertility index. All of statistical analysis was conducted with Minitab Software.

3. Results and discussion

3.1. Chemical soil properties

The interaction of chemical properties determines soil fertility in mixed gardens and moorlands. Soil pH ranged between 5.3–7.2, indicating slightly acidic to neutral conditions. Such conditions are generally suitable for nutrient availability, yet localized acidity may limit P and certain micronutrients (Asfaw and Zewudie, 2021). Similar conditions are reported in tropical volcanic soils elsewhere (Lal, 2020), where weathering and leaching tend to depress soil pH and nutrient retention. Nitrogen content ranged from 0.13% to 0.79%. The average value in mixed gardens (0.57%) was higher than in moorlands (0.29%), which can be attributed to denser vegetation cover and greater organic matter decomposition. This finding aligns with Yates et al. (2016), who observed that vegetation density and microbial activity enhance N cycling. As nitrogen is essential for vegetative growth, this distinction explains why mixed gardens have a relatively higher soil fertility than moorlands.

Available phosphorus was low across both land uses, averaging 5.00 ppm in mixed gardens and 3.96 ppm in moorlands. These values fall below the critical threshold for optimal crop productivity, highlighting P deficiency as a major constraint. Low P is often associated with fixation by Fe and Al oxides in volcanic soils and limited organic matter turnover (Peńa et al., 2025). Compared with studies in other volcanic regions, P deficiency appears to be a consistent challenge, suggesting that organic amendments and phosphate fertilization are crucial management strategies. Potassium levels were also deficient, ranging from 0.07 to 0.15 $cmol^+ kg^{-1}$, with averages of 0.13 $cmol^+ kg^{-1}$ in mixed gardens and 0.10 $cmol^+ kg^{-1}$ in moorlands. The low potassium status is most likely due to leaching processes under high rainfall, as reported by Lu et al. (2022). Since K is critical to crop quality and stress resistance, its scarcity underscores the need for targeted K management. Together with low P, this deficiency underscores the vulnerability of both land uses to macronutrient imbalances.

Organic carbon content averaged 1.09%, with slightly higher values in mixed gardens (up to 1.23%). Organic matter not only contributes directly to nutrient supply but also regulates microbial activity and soil structure (Zhang et al., 2025). The relatively higher organic carbon in mixed gardens is consistent with higher N levels, as both are closely linked through litter decomposition and mineralization. This relationship strengthens the role of vegetation management in sustaining fertility. CEC values ranged from 7.8 to 27.54 $cmol^{+}kg^{-1}$, averaging 15.12 $cmol^{+}kg^{-1}$ in mixed gardens and 16.05 $cmol^{+}kg^{-1}$ in moorlands, which indicates moderate capacity to retain nutrients. However, base saturation remained low (<30%), with very low Ca (0.02–0.03 $cmol^{+}kg^{-1}$) and Mg content in the mixed garden, at 3.01 $cmol^{+}kg^{-1}$, while in the moorland it is 3.32 $cmol^{+}kg^{-1}$. The average Na content in both the mixed garden and the moorland is 0.2 $cmol^{+}kg^{-1}$, which falls within the low category, reflecting high leaching intensity and insufficient nutrient replenishment (Awoonor et al., 2025). These patterns are typical of leached volcanic soils and impose severe constraints on crop growth, particularly for Ca-demanding crops such as coffee and coconut. Micronutrient Fe^{3+} was also found to be very low (1.13–2.42 ppm). While excessive Fe is often toxic, low Fe availability can limit enzyme functions and chlorophyll synthesis. The low Fe levels observed in both land uses further illustrate the systemic fertility limitations of these soils.

Overall, mixed gardens demonstrated relatively better fertility due to higher N and organic C, but both land uses exhibited critical deficiencies in P, K, Ca, and base saturation. These parameters emerged as key drivers of soil fertility variation, as confirmed by their weights in both the Nutrient Index and PCA analyses. The combination of conventional fertility indices and multivariate analysis provides a more comprehensive understanding of fertility status, offering a scientific basis for site-specific nutrient management strategies.

3.2. Soil Fertility Index

The soil fertility index is used as a reference to determine the soil fertility potential for crop development. Soil fertility evaluation uses the nutrient index principle to identify which nutrients are used to determine the fertility index. Nutrients in the soil are used to assess soil fertility by examining their relationship with the natural and chemical properties of the soil. Soil fertility index using PCA methods, based on results from the Minimum Data Set (MDS), determines the main components with a consistent spatial relationship between soil indicators (Chen et al., 2021). The calculation uses Equation 5. The class of soil fertility index for each land map unit using the nutrient index is shown in Table 7, the Principal Component Analysis method is shown in Table 8, and the distribution of the soil fertility index is shown in Figure 2.

Based on Table 7, the soil fertility index using the Nutrient Index method shows that the mixed garden has an average index value (1.72) and the moorland has a low average index value (1.62). It is indicates that the soil fertility index in mixed gardens is higher than that of moorlands. The differences in index values are attributed to variations in land use, soil management, and the types of cultivated commodities. The mixed garden has the shade of main trees, resulting in higher organic matter accumulation than moorland. Ali et al., (2025) noted that land use with dense vegetation cover significantly provides higher biomass in the upper soil layer. Zhu et al., (2025) also stated that land with dense vegetation, such as forests, gardens, or mixed gardens, compared to other land uses, has higher soil organic matter content. Based on Table 8, it is known that on moorland, LMUs 1 and LMUs 3 has the highest SFI value of 0.57, which is classified as medium, while the lowest is found in LMUs 13 with an SFI value of 0.46, which is classified as low. For the mixed garden, LMU 6 has the highest value of 0.57, which falls into the medium category, while LMU 7 has the lowest value of 0.52, which falls into the medium category. However, overall, mixed garden land has an average SFI value of 0.54, which falls into the medium category, while moorland has an average SFI value of 0.51, which falls into the medium category. It can be seen that the mixed garden has a higher SFI than the moorland. In both mixed garden and moorland, if not managed properly, it will reduce productivity or soil fertility (Kharal et al., 2018).

Table 7
The class of soil fertility index using the Nutrient Index

LMU	Scoring Index								TNS	Index Value								Nutrient Index
	pH	N	P	K	OC	Fe	Ca	Mg		pH	N	P	K	OC	Fe	Ca	Mg	
1	2	1	1	1	3	2	1	2	42	2.00	1.00	1.00	1.00	3.00	1.33	1.00	2.00	1.54 (Low)
	2	1	1	1	3	1	1	2	42									
	2	2	1	1	3	1	1	2	42									
2	2	2	1	1	3	1	1	3	42	1.67	2.00	1.00	1.33	3.00	1.00	1.00	2.33	1.67 (Medium)
	2	2	1	1	3	1	1	2	42									
	1	2	1	2	3	1	1	2	42									
3	2	3	1	1	3	1	1	2	42	2.00	3.00	1.00	1.33	3.00	1.00	1.00	2.00	1.79 (Medium)
	2	3	1	1	3	1	1	2	42									
	2	3	1	2	3	1	1	2	42									

Table 7 – continue
The class of soil fertility index using the Nutrient Index

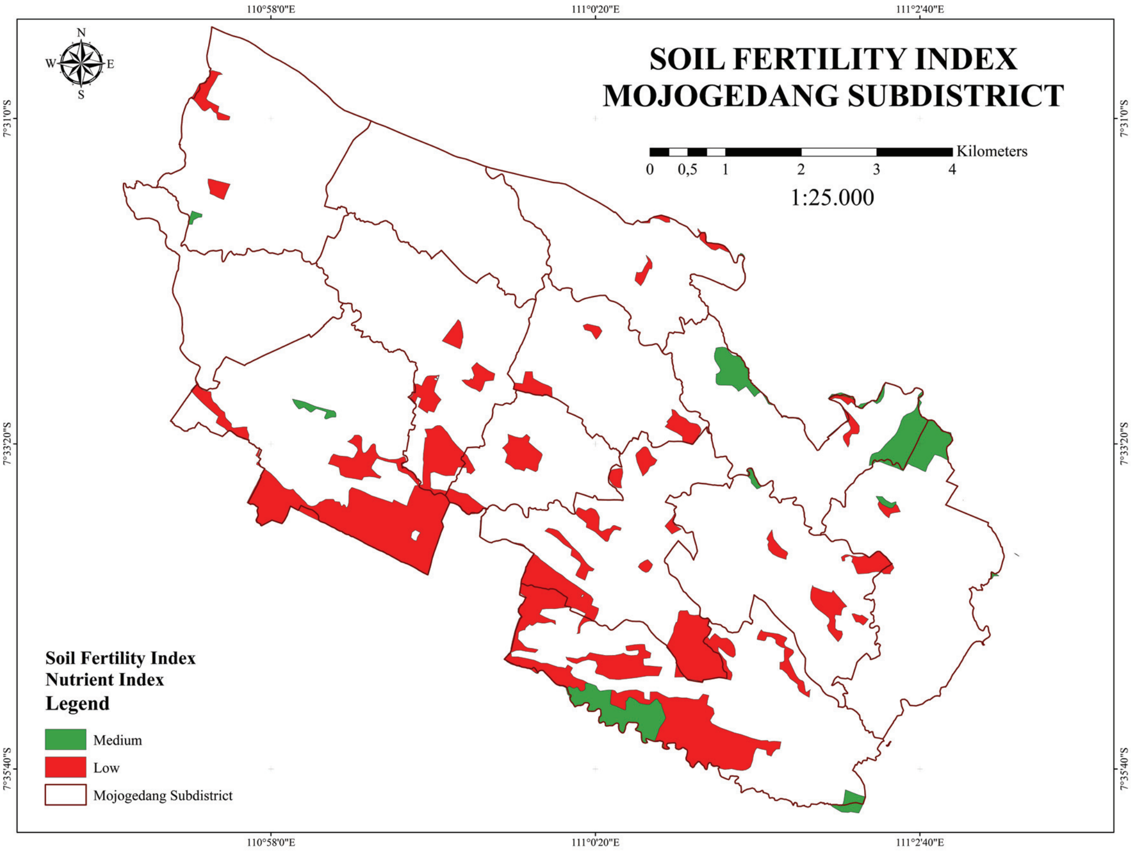
LMU	Scoring Index								TNS	Index Value								Nutrient Index
	pH	N	P	K	OC	Fe	Ca	Mg		pH	N	P	K	OC	Fe	Ca	Mg	
4	2	3	1	1	3	1	1	2	42	2.00	3.00	1.00	1.00	3.00	1.33	1.00	2.00	1.79 (Medium)
	2	3	1	1	3	2	1	2	42									
	2	3	1	1	3	1	1	2	42									
5	2	3	1	1	3	2	1	2	42	1.67	3.00	1.00	1.00	3.00	1.67	1.00	2.00	1.79 (Medium)
	2	3	1	1	3	2	1	2	42									
	1	3	1	1	3	1	1	2	42									
6	2	3	1	1	3	1	1	2	42	2.00	3.00	1.00	1.00	3.00	1.00	1.00	2.00	1.75 (Medium)
	2	3	1	1	3	1	1	2	42									
	2	3	1	1	3	1	1	2	42									
7	1	3	1	1	3	1	1	2	42	1.33	3.00	1.00	1.00	3.00	1.33	1.00	2.00	1.71 (Medium)
	2	3	1	1	3	1	1	2	42									
	1	3	1	1	3	2	1	2	42									
8	2	3	1	1	3	1	1	2	42	1.67	3.00	1.00	1.00	3.00	1.33	1.00	2.00	1.75 (Medium)
	2	3	1	1	3	2	1	2	42									
	1	3	1	1	3	1	1	2	42									
9	1	3	1	1	3	1	1	2	42	1.33	3.00	1.00	1.00	3.00	1.00	1.00	2.00	1.67 (Medium)
	2	3	1	1	3	1	1	2	42									
	1	3	1	1	3	1	1	2	42									
10	2	2	1	1	3	1	1	2	42	1.67	2.67	1.00	1.00	3.00	1.00	1.00	2.00	1.67 (Medium)
	1	3	1	1	3	1	1	2	42									
	2	3	1	1	3	1	1	2	42									
11	2	2	1	1	3	1	1	2	42	1.33	2.00	1.00	1.00	3.00	1.00	1.00	2.00	1.54 (Low)
	1	2	1	1	3	1	1	2	42									
	1	2	1	1	3	1	1	2	42									
12	2	2	1	1	3	1	1	2	42	2.00	2.00	1.00	1.33	3.00	1.00	1.00	2.00	1.67 (Low)
	2	2	1	2	3	1	1	2	42									
	2	2	1	1	3	1	1	2	42									
13	2	2	1	1	3	1	1	2	42	2.00	2.33	1.00	1.00	3.00	1.00	1.00	1.67	1.63 (Low)
	2	2	1	1	3	1	1	1	42									
	2	3	1	1	3	1	1	2	42									
14	1	2	1	1	3	1	1	2	42	1.00	2.00	1.00	1.00	3.00	1.00	1.00	2.00	1.50 (Low)
	1	2	1	1	3	1	1	2	42									
	1	2	1	1	3	1	1	2	42									

Explanations: LMU (Land Map Unit), pH (soil pH H_2O), N (Total Nitrogen), P (Available P), K (Available K), OC (Organic Carbon), Fe (Available Fe), Ca (Exc. Ca), Mg (Exc.Mg), TNS (total number of soil samples)

Table 8
The class of soil fertility index using the Principal Component Analysis

LMU	Scoring Index						cj	nc	Pc	Sci	N	SFI	Average
	pH	P	OC	CEC	Ca	Mg							
1	5	1	2	4	1	4	1.89	5	0.2	0.38	6	0.63	0.57 (Medium)
	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	
	5	1	2	2	1	4	1.53	5	0.2	0.31	6	0.51	
2	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	0.52 (Medium)
	5	1	2	2	1	4	1.53	5	0.2	0.31	6	0.51	
	4	1	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
3	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	0.57 (Medium)
	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	
	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	
4	4	2	1	2	1	4	1.55	5	0.2	0.31	6	0.52	0.53 (Medium)
	4	2	2	2	1	4	1.62	5	0.2	0.32	6	0.54	
	4	2	2	2	1	4	1.62	5	0.2	0.32	6	0.54	
5	4	2	2	2	1	3	1.51	5	0.2	0.30	6	0.50	0.54 (Medium)
	4	2	2	3	1	4	1.80	5	0.2	0.36	6	0.60	
	4	2	2	2	1	3	1.51	5	0.2	0.30	6	0.50	
6	4	2	2	2	1	4	1.62	5	0.2	0.32	6	0.54	0.57 (Medium)
	5	1	2	3	1	4	1.71	5	0.2	0.34	6	0.57	
	4	2	2	3	1	4	1.80	5	0.2	0.36	6	0.60	
7	4	2	2	2	1	4	1.62	5	0.2	0.32	6	0.54	0.52 (Medium)
	4	1	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
	4	2	2	2	1	4	1.62	5	0.2	0.32	6	0.54	
8	4	4	2	3	1	4	1.64	5	0.2	0.33	6	0.55	0.53 (Medium)
	5	4	2	2	1	4	1.53	5	0.2	0.31	6	0.51	
	4	3	2	2	1	4	1.62	5	0.2	0.32	6	0.54	
9	2	3	2	3	1	4	1.5	5	0.2	0.30	6	0.50	0.50 (Low)
	5	4	2	2	1	4	1.53	5	0.2	0.31	6	0.51	
	4	3	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
10	5	3	2	3	1	4	1.71	5	0.2	0.34	6	0.57	0.51 (Medium)
	4	3	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
	4	3	1	2	1	4	1.39	5	0.2	0.28	6	0.46	
11	5	3	2	2	1	4	1.53	5	0.2	0.31	6	0.51	0.51 (Medium)
	4	2	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
	4	2	2	3	1	4	1.64	5	0.2	0.33	6	0.55	
12	5	3	2	2	1	4	1.53	5	0.2	0.31	6	0.51	0.49 (Low)
	4	3	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
	5	3	1	2	1	4	1.46	5	0.2	0.29	6	0.49	
13	5	2	2	3	1	3	1.6	5	0.2	0.32	6	0.53	0.46 (Low)
	5	2	2	2	1	1	1.2	5	0.2	0.24	6	0.40	
	4	3	2	2	1	3	1.35	5	0.2	0.27	6	0.45	
14	4	2	1	2	1	4	1.39	5	0.2	0.28	6	0.46	0.48 (Low)
	4	3	2	2	1	4	1.46	5	0.2	0.29	6	0.49	
	4	2	2	2	1	4	1.46	5	0.2	0.29	6	0.49	

Explanations: LMU (land map unit), pH (soil pH H_2O), P (Available P), OC (organic carbon), CEC (cation exchange capacity), Ca (Exc. Ca), Mg (Exc.Mg), cj (total weighted score (wi × si)), nc (number of classes), pc (probability class (1/nc)), Sci (MDS weights), N (the total number of MDS indicators), SFI (soil fertility index)



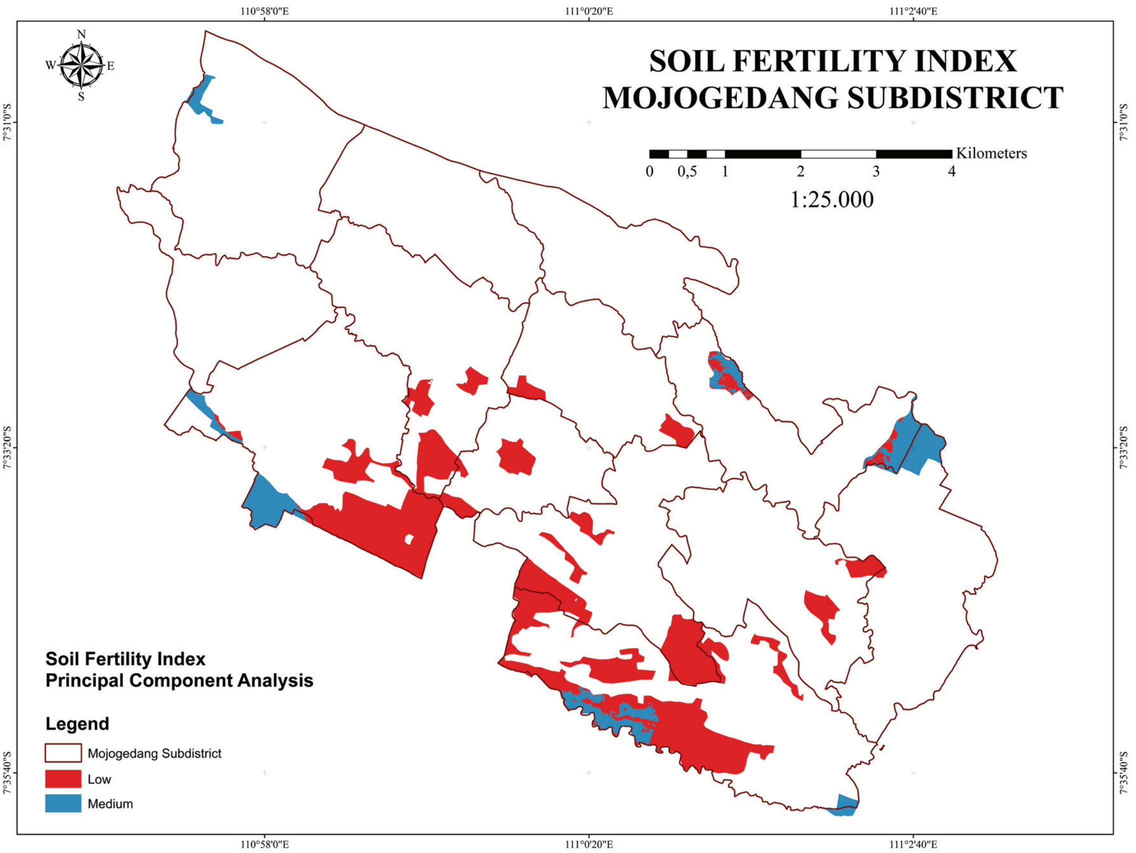


Fig. 2. The distribution of soil fertility index according to Nutrient index method (a) and Principal Component Analysis method (b).

The t-test is used to compare the Nutrient Index and Principal Component Analysis (PCA) methods to determine any significant differences in the soil fertility index results. Based on Table 9, the One-Sample T-Test showed that both the Nutrient Index (NI) and Principal Component Analysis (PCA) methods produced fertility index values significantly different from zero (NI: $t = 64.931$, $p < 0.05$; PCA: $t = 57.879$, $p < 0.05$). The mean value of NI (1.676) was slightly higher than PCA (1.564), and both confidence intervals excluded zero, confirming the significance. These results indicate that NI and PCA provide statistically different fertility index estimates. NI tends to yield higher values due to its categorical scoring system, while PCA integrates multiple soil parameters into components that compress variability. This explains the significant difference found in the paired comparison test.

Table 10 presents the results of the ANOVA test comparing the sources of diversity (soil type, land use, rainfall,and slope) with the soil fertility index using the PCA (Principal Component Analysis) and NI (Nutrient Index) methods. This test is conducted as a step in identifying the determining factors of the soil fertility index. Based on Table 10, it can be seen that only land use variability ($p=0.002$) shows a statistically significant difference in both of two methods, as the p-value is less than 0.05. This is because the Nutrient Index directly evaluates soil fertility based on the availability of nutrients such as N, P, K, organic C, and pH, which are strongly influenced by land management practices (Awoonor et al., 2024). For instance, the mixed garden soils usually receive higher and more consistent inputs of organic or inorganic fertilizers compared to moorland, which tends to be less intensively managed. Such differences in management practices lead to clear variations in nutrient content, thereby influencing the fertility index calculated using the Nutrient Index approach.

In contrast, the Principal Component Analysis (PCA) method revealed that both soil type and land use significantly affected the soil fertility index. . Unlike the Nutrient Index, PCA reduces a wide range of soil chemical parameters into a set of principal components, allowing it to capture management-related differences and inherent soil characteristics (Arumugam et al., 2025). Soil type inherently influences fertility through factors such as clay content, mineralogy, solum depth, and weathering intensity. For example, Inceptisols generally have lower natural fertility compared to Alfisols (Pal et al., 2025), and these differences are reflected in the principal components extracted by PCA. Thus, PCA is more sensitive in detecting the effect of soil type, in addition to land use variability. These findings suggest that the Nutrient Index primarily emphasizes management-induced differences in soil fertility, while PCA provides a broader perspective by integrating both management factors (land use) and pedogenetic factors (soil type).

Table 11 showed the correlation test between the soil parameters and the soil fertility index. The aim of the correlation analysis is to identify the determining factors of soil fertility index in the tested parameters. A positive correlation indicates that the values of the two variables are directly proportional, while a negative correlation indicates that the two variables are inversely proportional and are opposite. Based on the correlation results in Table 11, the Nutrient Index method shows significant correlations with parameters such as total nitrogen (N) ($r = 0.741^{**}$) and available phosphorus (P) ($r = 0.486^{**}$). In contrast, the Principal Component Analysis method shows correlations with parameters such as pH ($r = 0.321^{*}$), organic carbon (C-organic) ($r = 0.408^{**}$), available phosphorus (P) ($r = 0.378^{*}$), cation exchange capacity (CEC) ($r = 0.639^{*}$), magnesium (Mg) ($r = 0.381^{*}$), and texture ($r = -0.466^{**}$). ANOVA test was then conducted to determine the effect on diversity, which has significantly different effects, namely soil type and land use. ANOVA test results for soil type on Nutrient Index correlation parameters can be seen in Table 12. The ANOVA test results for soil type and land use on the Principal Component Analysis correlation parameter can be seen in Table 13.

Based on Table 12, the ANOVA results for soil type and land use on the correlation parameters of the Nutrient Index method indicate that land use has a significant effect, with

Table 9
Comparison of two methods of soil fertility index

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
PCA	14	1.5643	.10113	.02703
NI	14	1.6764	.09660	.02582

One-Sample Test
Test Value = 0

	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
PCA	57.879	13	0.000	1.56429	1.5059	1.6227
NI	64.931	13	0.000	1.67643	1.6207	1.7322

Explanations: significance level at 5% (p<0.05)

Table 10
The effect of source of diversity on the soil fertility index

Source of Diversity	p-value	
	Nutrient Index	Principal Component Analysis
Soil Type	0.356	0.001
Land Use	0.002	0.003
Rainfall	0.291	0.249
Slope	0.073	0.551

Explanations: significance level at 5% (p<0.05).

significance values for nitrogen (N) (p= 0.000) and available phosphorus (P) (p= 0.000). According to Table 13, the ANOVA results for soil type and land use on the correlation parameters of the Principal Component Analysis method show that soil type has a significant effect on pH (p= 0.008), organic carbon (p=. 0.028), cation exchange capacity (CEC) (p=0.032), and texture (p= 0.000). Meanwhile, land use has a significant effect on available phosphorus (P) (p= 0.000) and texture (p= 0.006). Therefore, the determining factors of the soil fertility index using the Nutrient Index method are total nitrogen and available phosphorus. Moreover, the determining factors of the soil fertility index using the Principal Component Analysis method are pH, organic carbon, available phosphorus, cation exchange capacity, and texture.

According to the determining factors, it can be concluded that land uses and soil types have impacted the soil fertility index through the physical and chemical soil properties. The addition of organic matter can be done to improve soil fertility in both mixed garden and moorland. This aligns with the research (Yang et al., 2024) which states that adding organic matter can improve soil fertility because organic matter contains macro and micro nutrients. Biochar can also be added to upland fields because it has the potential to improve soil fertility (Ahmed et al., 2017). Specific nutrient addition can be done through fertilization based on the determining factors obtained. According to Kebalo et al., (2025) balanced fertilization is used to provide a mixture of macro and micro nutrients in appropriate doses, both organic and inorganic fertilizers. The Nutrient Index method is considered more specific in measuring soil fertility indices for each research parameter. According to Ahamad et al., (2021), NI provides fertility codes for each location, enabling recommendations for fertilization based on fertility levels. The study by Abdel-Fattah et al., (2021) states that PCA is a method used to reduce the number of variables by identifying the most significant variables in a dataset.

Tabel 11
The correlation of soil parameters and soil fertility index

	pH	OC	N	P	K	CEC	Ca	Mg	Na	BS	Fe	Texture
OC	0.220											
N	–0.227	0.052										
P	–0.103	0.082	0.609**									
K	–0.164	0.023	0.400**	0.546**								
CEC	0.337*	0.532**	0.064	0.002	0.117							
Ca	0.431**	0.146	–0.230	–0.058	0.161	0.218						
Mg	0.073	0.250	–0.131	0.208	0.033	0.138	0.083					
Na	–0.071	0.126	–0.038	0.210	0.044	0.196	0.297	0.052				
BS	0.279	–0.230	–0.018	0.196	0.155	0.722**	0.102	0.490**	0.036			
Fe	–0.048	0.068	0.084	0.002	0.032	–0.252	0.036	–0.119	0.056	0.240		
Texture	–0.290	–0.237	–0.101	–0.175	–0.197	–0.168	–0.178	–0.351*	–0.032	–0.083	–0.028	
NI	0.191	0.129	0.741**	0.456**	0.178	0.109	0.033	–0.035	–0.038	–0.110	0.151	–0.258
PCA	0.321*	0.408**	0.150	0.378*	0.210	0.639**	0.222	0.381*	0.201	–0.159	–0.036	–0.466**

Explanations: pH (soil pH H_2O), OC (organic carbon), N (total nitrogen), P (Available P), K (available K), CEC (cation exchange capacity), Ca (Exc. Ca), Mg (Exc.Mg), Na (exc. Na), BS (base saturation), Fe (available Fe), NI (Nutrient Index), PCA (Principal Component Analysis), *significance level at 5% (p<0.05), ** significance level at 1% (p<0.01).

Table 12
ANOVA results of soil type and land use on nutrient index correlation parameters diversity

Diversity	P-value	
	N	P
Land Use	0.000	0.000

Explanations: N (Total Nitrogen), P (Available P), significance level at 5% (p<0.05).

Table 13
ANOVA results of soil type and land use on principal component analysis correlation parameters

Diversity	pH	P-value				
		OC	P	CEC	Mg	Texture
Soil Type	0.008	0.028	0.408	0.032	0.157	0.000
Land Use	0.600	0.501	0.000	0.762	0.621	0.006

Explanations: pH (soil pH H_2O), P (Available P), CEC (Cation Exchange Capacity), OC (Organic Carbon), Mg (Exc.Magnesium), significance level at 5% (p<0.05).

4. Conclusions

In conclusion, the study demonstrated that evaluating soil fertility index using the Nutrient Index and Principal Component Analysis in the mixed garden and moorland revealed different classes. The Nutrient Index approach showed that the mixed garden was more fertile than the moorland, whereas the values are medium (1.75) and low (1.62), respectively. Meanwhile, the PCA method classified both mixed garden and moorland as medium, with values of 0.54 and 0.51, respectively. The soil fertility index for each land map unit, on the other hand, revealed a separate class for each land use. A T-test showed significant differences (p = 0.000) between the two methods. The calculation of the NI method, based on specific nutrient thresholds, identified that phosphorus, potassium, iron, and calcium are in the low category, magnesium and pH are in the medium category, while organic carbon and nitrogen are in the high category. The determining factors in the NI method are total N and available P, with land use as the main source of variation. In contrast, the PCA method integrated a broader set of soil chemical and physical parameters into a multivariate model, producing a soil fertility index that more holistically captured the fertility status, with soil pH, organic carbon, available P, and CEC as the determining factors, with soil type and land use as the main sources of variation. These values reflect the spatial heterogeneity and complexity of fertility patterns better than the univariate NI approach. PCA is appropriate for comprehensive soil fertility diagnostics, especially in diverse and multi-parameter landscapes, as it captures the interactions between multiple soil attributes. Its strength lies in its capacity to reduce data complexity while maintaining meaningful distinctions across fertility gradients. The Nutrient Index method is simpler and easier to apply as it utilizes fewer soil parameters. This research contributes to the growing body of knowledge advocating for multivariate approaches in soil fertility assessment. It suggests that while traditional index-based methods remain relevant, integrative statistical techniques, such as PCA, should be adopted more widely to support evidence-based decision-making in soil management and sustainable agriculture planning.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Aktavia Herawati – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft; **Rahayu** – Conceptualization, Investigation, Methodology, Supervision; **Ganjar Herdiansyah** – Investigation, Validation, Data curation, Supervision, Validation, Writing – review & editing; **Mujiyo** – Conceptualization, Investigation, Supervision, Validation**; Enriko Dzaki Pradana** – Investigation, Writing – review & editing. All authors read and approved the final manuscript.

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