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Research Article

A Comparative Study of Soil Fertility in Organic, Semi-Organic, and Conventional Rice Field Farming Systems (Case Study: Nguntoronadi District, Wonogiri, Indonesia)

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Abstract: The soil fertility of rice fields is closely related to rice crop production. The research aims to identify soil fertility under different rice field farming systems, find the key factor of soil fertility, and recommend strategies to improve soil fertility based on the key factor. The research was conducted in Nguntoronadi District, Indonesia, on conventional, semi-organic, and organic rice fields. The research was an exploratory descriptive survey through a field survey approach and soil chemistry and physics analysis. Soil sampling was conducted in 12 Land Map Units (LMUs) with three replicates using purposive sampling methods. Observation indicators include soil pH, organic C, total N, C/N ratio, available P, available K, exchangeable Ca, exchangeable Mg, Cation Exchangeable Capacity (CEC), Base Saturation (BS), Aluminum saturation, soil texture, and worm population density representing soil chemical, physical, and biological properties. Soil fertility is determined using Principal Component Analysis (PCA) and scoring based on the category. The research results show that the level of soil fertility under various rice field farming systems was included in the moderate with ranges of 0.53-0.70, and organic farming has the highest soil fertility. The key factors of soil fertility include pH, organic C, available P, available K, Ca-dd, CEC, and Aluminum saturation. The appropriate management direction is the addition of organic fertilizer in the planting period.

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1. Introduction

Soil fertility is essential for sustainable agriculture and ecosystem health. It directly influences plant growth, nutrient availability, water retention, and environmental sustainability. According to Chirila et al.(2013), soil fertility is a complex process in the constant nutrient cycle between organic and inorganic forms, such as plant and animal residues as waste that enter and release nutrients into the soil and then act as fertilizer and a source of energy for the soil. Soil fertility is achieved through the presence of soil organic matter and the contribution of soil macro and microorganisms (Sofo et al., 2020). In terms of rice production, soil fertility is closely related to the productivity of rice fields. Rice production continues to increase to avoid food insecurity and realize national food security (Soegoto and Sumarauw, 2014; Rohman and Maharani, 2017) because the demand for food needs, especially rice, continues to increase in line with Indonesia's population growth. Good soil fertility will produce good rice for various heritage food product (Azkiyah et al., 2021; Pinandoyo et al., 2023). Increasing agricultural production activities (intensive farming). Adekiya et al. (2018) stated that this is inappropriate because it promotes land degradation. Hailu et al. (2015) stated that continuous management, nutrient loss due to crop transport and erosion events, and leaching are the primary causes of land degradation.

Rice fields are the most significant component of rice production (Arlius et al., 2017; Nurmegawati et al., 2019) and can experience soil fertility degradation due to excessive use of chemical fertilizers and pesticides (Mujiyo et al., 2022). In the research area, farmers and stakeholders use NPK chemical fertilizers such as Urea, TSP, and Phonska to increase essential macronutrients that support the growth and production of rice plants. Based on the data by Pahalvi et al. (2021), Indonesia is one of 13 countries in the world with NPK chemical fertilizer used reaching up to ≥100 kg ha^{-1}. The use of chemical fertilizers tends to have a negative impact on ecological balance (Yolci and Tunçtürk, 2022). Conventional farming uses chemicals during planting, such as fertilizers and pesticides to eradicate pests. The results of Rahman et al. (2020) illustrate that the long-term use of pesticides and chemical fertilizers in the soil in conventional rice field farming showed negative effects. the chemical properties of the soils, such as nitrate, ammonia, SOC, and total N and C compositions, were also significantly decreased. This suggests that the intensive use of pesticides and chemical fertilizers can degrade the biochemical and chemical properties of the soil. Additionally, chemical fertilizers and pesticides produce residue after their use. The resulting residue settles on the ground, evaporates into the air, and is carried away by water flows in irrigation canals. These chemical residues have an impact on contamination, pollute the environment, and increase the potential for soil degradation. The level of land degradation indicates a decrease in soil fertility in various land management systems (Kagabo et al., 2013). Low-energy and low-degradation engineering innovations are needed to increase productivity (Jeon et al., 2021). Appropriate innovations also support the realization of the second goal of the Sustainable Development Goals (SDGs) related to zero hunger by ending hunger, attaining food security, enhancing nutrition, and promoting sustainable agriculture.

Nguntoronadi District, Wonogiri Regency has 1 488 ha of rice fields (Central Bureau of Statistics, 2022) that are managed conventionally, semi-organically, and organically. In the last 5 years based on the data from the Central Bureau of Statistics in 2023, Nguntoronadi District had a harvest area of 2 635.74 ha with a production of 13 803.49 tons, so the average land productivity achieved was around 5.24 tons ha^{-1}. The diverse farming systems of rice fields will affect the level of soil fertility (Sukristiyonubowo et al., 2019), also affect plant secondary metabolites (Khoerunnisa et al., 2022) as an important part of the plant defense system and are currently used as medicine ingredients and food additives and culinary purposes (Azkiyah et al., 2021; Mahendradatta et al., 2021), so an assessment of the soil fertility index is needed. Sukristiyonubowo et al. (2019) stated that organic cultivation has a better soil fertility level than conventional and semi-organic rice fields, especially in the parameters of pH, organic C, total N, available P, and available K with organic rice paddy yields increasing 61% from the previous year. Information on soil fertility status is key to investigating nutrient status, predicting relative soil responses to fertilizer application, and adopting appropriate management strategies (Aytenew and Kibret, 2016). Soil fertility assessment or evaluation is based on nitrogen, phosphorus, and potassium elements, and is affected by soil factors such as soil pH, cation exchangeable capacity, and organic matter content (FAO, 1988; Daksina et al., 2021).

A high level of soil fertility is crucial in rice field farming to improve productivity and strengthen food security, especially in the Nguntoronadi District. Research on soil fertility assessment on a wide range of rice field farming systems in Nguntoronadi District is still limited, so further research is needed to provide information on soil fertility levels in the area with more complete research parameters. The purpose of this research is to measure the degree of soil fertility in various rice field farming systems and to comprehend the impact of land management techniques on soil fertility. Another very important objective is to increase soil fertility at the research site with appropriate land management recommendations based on the key factors of soil fertility. Proper rice field farming advice can then be utilized as a reference for stakeholders to improve farmers' welfare through higher land production and support sustainable integrated agriculture.

2. Material and Methods

2.1. Study area and soil sampling

The research was conducted on conventional, semi-organic, and organic rice fields in Nguntoronadi District, Wonogiri Regency, Central Java Province, Indonesia (Figure 1). The research area has an area of 60.96 km^2 which is geographically located between 7°51'8.71"-7°58'55.90" LS and 110°53'56.59"-111°2'58.78" BT at an altitude of 173 - 410 meters above sea level with regional characteristics in the form of hills and mountains. Land use in Nguntoronadi District includes 1 488 ha of rice fields, 2 213 ha of moorland, 634 ha of state forest, 90 ha of smallholder plantations, 3 379 ha of settlements, and 237 ha of other land uses (Central Bureau of Statistics, 2022).

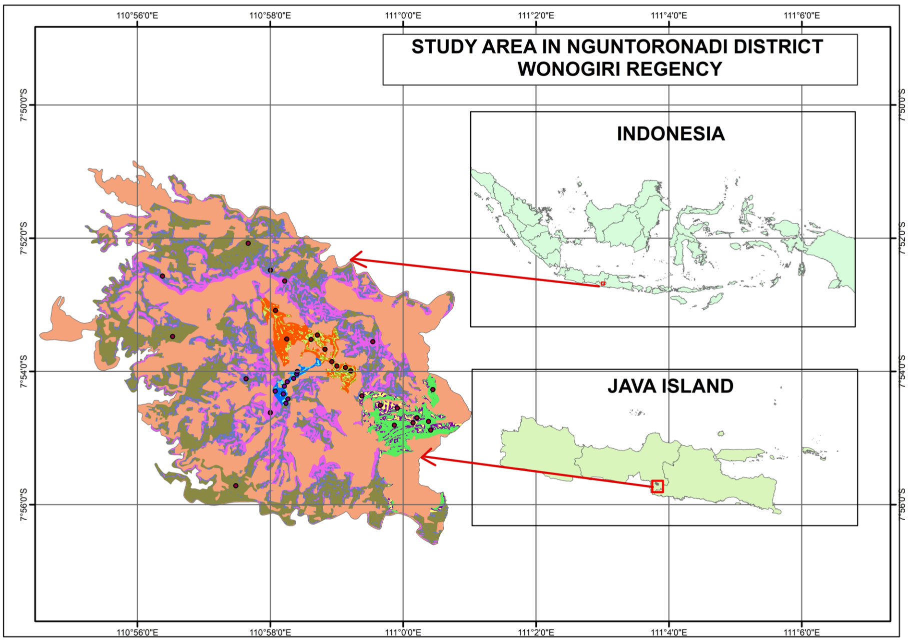

Figure 1. Study area.

The farming system of rice fields in the research location consists of three farming systems, including conventional rice fields, semi-organic rice fields, and organic rice fields. In the field survey stage, based on the information we got from farmers and local rice field stakeholders, it was discovered that fertilization in conventional rice fields is urea fertilizer 100-150 kg ha^{-1}, phonska fertilizer 100-150 kg ha^{-1}, and phosphorus fertilization with TSP fertilizer 50 kg ha^{-1}. Fertilizers used in semi-organic rice fields are organic fertilizer of 1 ton ha^{-1} as a base fertilizer before planting, urea fertilizer of 100 kg ha^{-1}, and liquid organic fertilizer (LOF) of 10 L ha^{-1}. Fertilization in organic rice fields is 3-6 ton ha^{-1} of organic fertilizer and liquid organic fertilizer (LOF) 15 L ha^{-1}. The farming of organic rice fields has been started since 2014 under the auspices of Gapoktan Beji Makmur, which passed the organic certification test in 2017 and was recertified in 2020 for the scope of rice, crops, and fertilizers with the basic reference of SNI 6729: 2016 by Lembaga Sertifikasi Organik Seloliman (LeSOS).

The research was conducted using an exploratory descriptive survey method through a field survey approach and the results of laboratory analysis of soil chemistry and physics. Soil sampling was conducted based on purposive sampling (Lenaini, 2021) in a composite manner at a depth of 0-30 cm. Soil sampling points were based on land map units (LMUs) obtained from overlaying the Indonesian landform map (RBI) of Nguntoronadi District, Wonogiri Regency, and thematic maps. The thematic map represents the diversity of the research location, including a map of rice field farming systems, a soil map, a slope map, and a rainfall map. Soil types at the research site are mostly Inceptisols and Entisols in the eastern part with the geological formation of Qvu. The slope is about 0-8%, 8-15%, 15-25%, and 25-45%. The average rainfall is about 2250 mm per year. The survey area consists of 12 LMUs with 3 replicates, so the total sample points are 36 as shown in Figure 2.

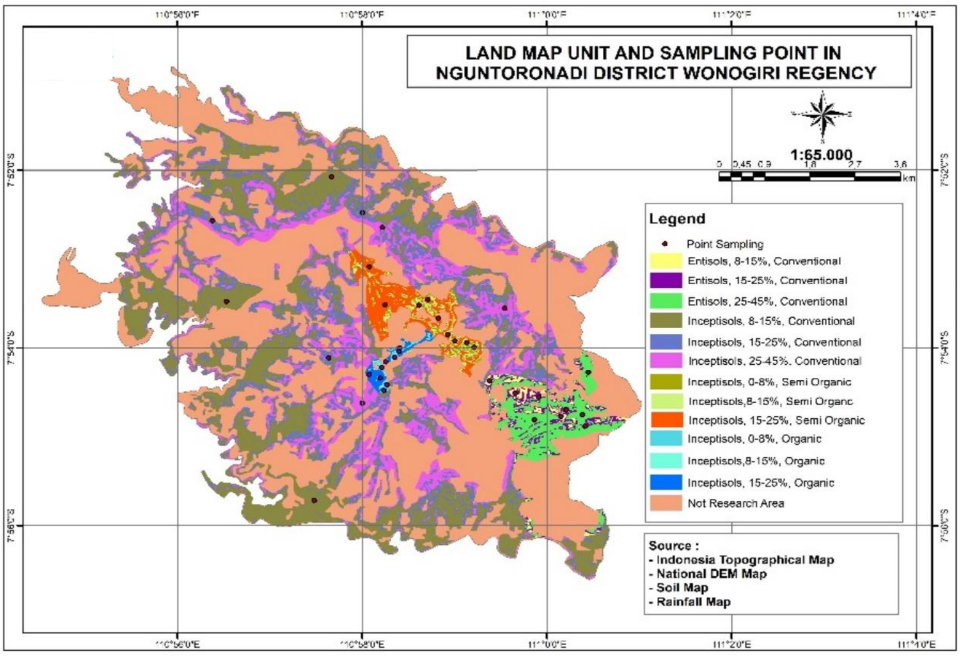

Figure 2. Land map unit and sampling point.

2.2. Soil analysis

Soil sample analyses were conducted at the Chemistry and Soil Fertility Laboratory and Soil Conservation and Physics Laboratory, Faculty of Agriculture, Sebelas Maret University. Soil chemical analysis included soil pH (electrometric method), organic C (Walkley and Black method), total N (Kjeldahl method), C/N ratio, available P (Olsen method), available K (extraction NH_4OAc 1N), exchangeable Ca (extraction NH_4OAc 1N), exchangeable Mg (extraction NH_4OAc 1N), Cation Exchangeable Capacity (extraction NH_4OAc 1N), base saturation (extraction NH_4OAc 1N), and Aluminium saturation (KCl saturation) (Soil Research Institute, 2009). Analysis of soil physics is soil texture (pipette method) (Center for Research and Development of Agricultural Land Resources, 2007). Worm density population observation (PVC ring sample) was conducted directly in the field (Center for Research and Development of Agricultural Land Resources, 2006).

2.3. Data analysis

Data analysis consists of determining the soil fertility index and key factor indicators of soil fertility in this research. The soil fertility index is determined by calculating the score, PCA, and index. Meanwhile, the key factor indicator is determined using a statistical test, namely Pearson's correlation.

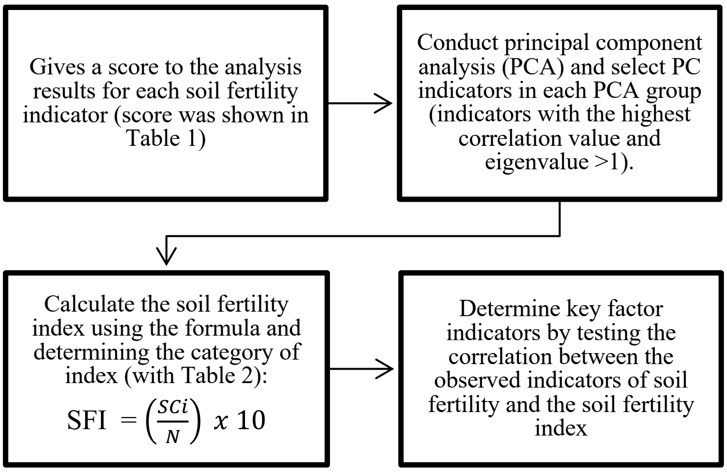

Figure 3. Data analysis stages.

2.3.1. Soil fertility index (SFI)

The soil fertility index was determined utilizing the Statistical Package for the Social Sciences (SPSS) and Minitab software. The soil fertility index was determined based on Pearson Correlation Analysis followed by Principal Component Analysis (PCA) to produce in Minimum Soil Fertility Indicator (MSFI). Minimum Soil Fertility Indicator (MSFI) is the outcome of Principal Component Analysis (PCA), where the major component or Principal Component (PC) employed has the highest eigenvalue >1 and is correlated. The indicators with the highest value and are correlated with the highest value are selected as MSFI indicators, except Aluminum is chosen from the lowest value (Mukashema, 2007). MSFI that met the criteria were then scored based on the results of the score of the Soil Research Center (2009) as shown in Table 1.

Table 1. Score index of soil fertility index (SFI)

Indicators	**Score**				
	1 (VL)	**2 (L)**	**3 (M)**	**4 (H)**	**5 (VH)**
Texture	C, S	LS, SiC	CL, SL	SiL, Si, SiCL	L
pH	<5.5 and >7.5	5.5-6.0	6.0-6.5	6.5-7.5	7.0-7.5
Organik C (%)	<1	1-2	2-3	3-5	>5
Total N (%)	<0.1	0.1-0.2	0.21-0.5	0.51-0.75	>0.75
C/N	<5	5-10	11-15	16-25	>25
Available P (ppm)	<5	5-10	11-15	16-20	>20
Available K (me $100g^{-1}$)	<0.1	0.1-0.3	0.4-0.5	0.6-1.0	>1
Exchangeable Ca (me $100g^{-1}$)	<2	2-5	6-10	11-20	>20
Exchangeable Mg (me $100g^{-1}$)	<0.3	0.4-1	1.1-2.0	2.1-8.0	>8
CEC (me $100g^{-1}$)	<5	5-16	17-24	25-40	>40
BS (%)	<20	20-40	41-60	61-80	>80
Al Saturation (%)	<5	5-10	10-20	20-40	>40

Source: Lal (1994), Soil Research Institute (2009), Mukashema, (2007).
Remark: VL (Very Low), L (Low), M (Moderate), H (High), VH (Very High), C (Clay), S (Sandy), LS (Loamy Sand), SiC (Silty Clay), CL (Clay Loam), SL (Sandy Loam), SiL (Silty Loam), Si (Silt), SiCL (Silty Clay Loam), and L (Loam).

The scoring results are then applied to the calculation of the soil fertility index using the following formula (Mukashema, 2007).

$$\text{SFI} = \left(\frac{SCi}{N}\right) x\ 10 \tag{1}$$

Remark :

$$SC_i = c_j\ x\ p_c \tag{2}$$

$$C_j = W_i\ x\ S_i \tag{3}$$

$$p_c = \frac{1}{nc} \tag{4}$$

Where; SFI is the soil fertility index, SCi represents the scoring indicator, N is the number of indicator MSFI, c_j is the class number which varies from 1 to j, p_c represents the probability of the class, n_c is the number of classes, Wi is weight index and Si is scoring index. The results of the SFI assessment are classified based on Table 2.

Table 2. Classification of the soil fertility index

Fertility İndex Value	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).

2.3.2. Key factors of soil fertility index (SFI)

Analysis of Variance (ANOVA) statistical testing was utilized to assess the effect of diversity sources such as rice field farming systems, slopes, soil types, and rainfall on soil fertility index values. If it has a real influence, Duncan's Multiple Range Test (DMRT) is used to assess the true difference in influence. Key factors of the soil fertility index were obtained from Pearson Correlation Analysis between indicators and soil fertility index values that were significantly correlated. Key factors are used as the basis for the direction of improvement or recommendations for proper management of rice fields to improve the status of soil fertility.

3. Results and Discussion

3.1. Study area and soil sampling

Soil fertility indicators are parameters that can be utilized in defining soil fertility indices. In addition to soil chemical properties, physical, and biological properties are also linked to soil fertility. The results of laboratory analysis (Table 3) show that rice field soils in the study area have a pH between 6.4-6.87 including in the category of slightly acidic (5.6-6.5) to neutral (6.6-7.5) (Soil Research Institute, 2009). The average pH value in conventional rice fields tends to be slightly acidic at 6.51 compared to semi-organic and organic rice fields which have neutral pH of 6.8 and 6.84. The application of urea fertilizer can contribute to soil acidity because dissolved urea reacts with water to produce carbonic acid (H_2CO_3). Furthermore, ammonium applied to soil undergoes nitrification, producing nitrites and nitrates that release H^+ ions and lower pH (Yamsil et al., 2022). Increased soil pH increases the availability of basic cations such as K, Ca, Mg, and Na. Meanwhile, Al, Fe, and Mn levels, which frequently bind basic cations, will decrease (Fitria and Soemarno, 2022).

Organic rice fields have the highest average organic C content of 2.75%, ranging from 2.42 to 3.18%, which is influenced by incorporating organic matter into the soil in the form of compost and straw harvest wastes. The addition of organic fertilizer (compost, manure, and green manure) improves organic C (Fitria and Soemarno, 2022; Syamsiyah et al., 2023). The range value of organic C in conventional rice fields was 0.84 to 1.85% and in semi-organic rice fields, it was 1.31%. The low organic C is due to the lack of organic matter returning to the soil such as straw left over from harvesting, which is often burned or used as animal feed. Meanwhile, the total N content in various rice field farming systems is low, with values between 0.12-0.2%. Nitrogen in the soil is one of the factors that improve plant productivity (Suminto et al., 2023). Conventional rice fields have more total N than organic rice fields because N from inorganic fertilizers can deliver N directly to plants, whereas N from organic fertilizers is released slowly, therefore the response is slower (Herdiansyah et al., 2022). The C/N ratio in conventional and semi-organic rice fields has a C/N value ranging from 6.10-10.02 which is classified as a low category, while organic rice fields have the highest C/N ratio value of 16.23-21.1 which is ideal in the decomposition process. Organic fertilizers increase soil qualities in terms of physical, chemical, and microbial activity (Kipcakbitik and Sensoy, 2023). Research by Ostrowska and Porębska (2014) showed that the C/N ratio in addition to being related to organic C is also related to soil N content where too high N input, especially from fertilizers, causes a lower C/N ratio compared to organic farming with abundant organic matter input.

Organic rice fields have higher P (6.18 ppm), K (0.63 me $100g^{-1}$), Ca (12.96 me $100g^{-1}$), and Mg (1.87 me $100g^{-1}$) than semi-organic rice field farming systems (P (5.34 ppm), K (0.55 me $100g^{-1}$), Ca (10.62 me $100g^{-1}$), and Mg (1.86 me $100g^{-1}$)), and conventional rice fields (P (2.38 ppm), K (0.53 me $100g^{-1}$), Ca (10.66 me $100g^{-1}$) and Mg (1.86 me $100g^{-1}$)). Organic matter sources such as compost, straw, and legume green manure crops will improve soil chemical properties such as macronutrients N, P, K, Ca, Mg, and S because of their ability to release P fixation by Al, Fe or Mn (Sukristiyonubowo et al., 2019). Analysis of BS in various rice field farming systems is included in the moderate level with an average value of BS in conventional rice fields at 43.35%, semi-organic rice fields at 43.76%, and organic rice fields at 43.60%. This is related to the leaching of base cations supported by the research of Aytenew and Kibret (2016), which states that the loss of base cations due to runoff causes increased acidity and decreased soil fertility.

The CEC value in various land farming systems is included in the high value because it is in Inceptisols and Entisols soils, classified as young soils and dominated by clay textures. Soil that is still young and supported by a relatively neutral pH and clay-dominated soil texture will increase the CEC value (Pinatih et al., 2015). However, the highest CEC value is found in organic rice fields at 39.87 me $100g^{-1}$ due to the colloidal content of organic matter that can contribute a negative charge to soil colloids. The role of organic matter as a colloid can increase the capacity of absorption and cation exchange (Prasetiyo et al., 2015), which also increases the concentration of K in the soil (Roy et al., 2016). Al saturation at the research site is considered very low ranging from 3.20-5.27% with organic rice fields having the lowest average Al saturation value of 3.57%. The low Al saturation in the organic rice field farming system is due to the high content of organic matter that in decomposition, will release fulvic acid, humic acid, and organic acids that bind Al through the mechanism of binding Al-monomer (Al^{3+}) to a stable chelate complex (Muzaiyanah and Subandi, 2016).

Texture as an indicator of soil physics at the research site is dominated by clay and clay loam textures. According to Islam et al. (2021), soil texture affects the available water capacity of soil in rice farming because of its ability to hold and absorb water so that water can be available to plants. Worm population density as a supporting bioindicator showed the highest density in organic rice fields at 0.11 L^{-1} because organic matter content affects the metabolic activity of soil organisms (Supriyadi et al., 2020). According to Lou et al. (2022), soil organic matter is the most abundant organic carbon source and has an ecological impact on soil fauna, particularly earthworms that mineralize soil organic matter components.

3.2. Soil fertility index

The soil fertility index is a functional indicator in soil fertility assessment that provides information and appropriate management recommendations for sustainable agriculture. The results of PCA analysis (Table 4) show that the principal components (PC) that meet the requirements are PC 1 to PC 4. Zhang et al. (2018) stated that PCs that become the Minimum Soil Fertility Indicator (MSFI) have an eigenvalue ≥1 or a cumulative percentage of at least 60%. The four PCs have a cumulative presentation of 80.1%, showing the main components' confidence levels. Indicators with the highest value and correlated with the highest value are selected as MSFI indicators, except Aluminum is selected from the lowest value (Mukashema, 2007). Indicators selected as MSFI are pH, organic C, C/N, exchangeable Ca, CEC, Al saturation, BS, total N, exchangeable Mg, and available K.

The level of soil fertility at the study site (Table 5) based on the classifications of Bagherzadeh et al. (2018) was included in the moderate category with a value ranging from 0.53 to 0.70. LMU 1, 2, and 3 have an average SFI of 0.54 which is conventional rice fields farming on Entisols soil, while LMU 4, 5, and 6 with conventional rice field farming on Inceptisol soil have an average SFI of 0.56. SFI in both soil types with conventional rice field farming systems has a value with a slight difference. This could occur because Entisols and Inceptisols soils have similarities, namely undeveloped soils with diverse parent materials (Helmi et al., 2016) so the weathering process runs slowly.

Table 3. Analysis of soil fertility ındicators in various farming systems of rice fields in the study area

Soil type	Farming Systems	LMU	pH	Org-C (%)	Total N (%)	C/N	Available P (ppm)	Available K (ppm)	Exc-Ca (me 100g^{-1})	Exc-Mg (me 100g^{-1})	CEC (me 100g^{-1})	BS (%)	Al Saturation (%)	Texture	Worm population density (individuals L^{-1})
Entisols	Conventional	1	6.41±0.11	1.85±0.07	0.19±0.03	9.93±1.58	2.17±0.30	0.48±0.05	10.31±1.01	1.81±0.10	31.75±2.36	42.07±0.52	4.23±0.59	CL	0.00±0.00
		2	6.40±0.55	1.14±0.05	0.16±0.15	6.95±0.59	0.47±0.15	0.55±0.05	10.36±0.15	1.87±0.15	33.04±0.34	41.57±1.30	4.63±0.47	C	0.05±0.09
		3	6.56±0.08	0.84±0.08	0.19±0.28	4.52±0.37	2.33±0.28	0.51±0.05	9.88±0.19	1.86±0.21	31.04±0.18	45. 90±0.56	5.27±0.19	C	0.05±0.09
Inceptisols		4	6.59±0.05	1.26±0.13	0.18±0.60	7.07±1.09	6.38±0.60	0.54±0.05	11.99±1.66	1.73±0.21	33.14±2.39	44.18±1.57	4.95±0.66	C	0.11±0.09
		5	6.53±0.18	1.17±0.02	0.12±0.30	10.02±2.12	2.20±0.30	0.51±0.03	10.54±0.66	1.74±0.11	32.99±1.14	41.36±1.25	4.26±0.33	CL	0.05±0.00
		6	6.56±0.25	0.87±0.08	0.15±0.10	6.10±1.64	0.74±0.10	0.58±0.04	10.88±1.05	2.16±0.33	35.05±1.95	45.04±1.20	3.61±0.07	C	0.11±0.09
	Semi-organic	7	6.85±0.05	1.08±0.01	0.14±0.37	7.84±0.90	5.38±0.37	0.57±0.03	10.91±1.26	1.70±0.14	34.37±1.76	44.33±2.49	4.57±0.66	C	0.05±0.09
		8	6.71±0.06	1.43±0.10	0.19±0.76	7.60±0.39	5.43±0.76	0.57±0.07	10.58±1.62	1.83±0.22	34.31±3.04	45.80±1.95	4.88±0.81	C	0.11±0.09
		9	6.84±0.03	1.43±0.12	0.20±0.65	7.25±0.62	5.20±0.65	0.52±0.02	10.39±0.28	2.04±0.16	33.13±0.45	41.15±0.24	4.53±0.05	CL	0.11±0.09
	Organic	10	6.79±0.03	2.42±0.34	0.15±0.53	16.23±1.56	6.31±0.53	0.62±0.02	12.88±0.70	1.73±0.18	37.42±1.13	44.92±0.47	3.20±0.11	C	0.11±0.18
		11	6.87±0.04	2.64±0.19	0.14±1.46	19.25±3.48	6.37±1.46	0.66±0.01	13.12±0.46	1.70±0.21	41.53±2.50	42.65±0.60	3.62±0.44	C	0.05±0.09
		12	6.86±0.04	3.18±0.17	0.16±0.16	21.10± 4.39	5.87±0.16	0.62±0.03	12.87±1.13	2.17±0.28	40.65±2.81	43.24± 1.95	3.89±0.56	C	0.16±0.16

Table 4. Results of PCA to determine MSFI

Variable	PC1	PC2	PC3	PC4
Eigenvalue	5.3629	1.5538	1.4058	1.2936
Proportion	0.447	0.129	0.117	0.108
Cumulative	0.447	0.576	0.694	0.801
pH	0.268	0.047	-0.265	-0.209
Organic C	0.349	-0.319	0.127	-0.206
Total N	-0.167	0.138	0.274	-0.664
C/N	0.366	-0.344	0.01	0.037
Available P	0.261	-0.043	-0.343	-0.536
Available K	0.371	0.255	0.073	0.069
Exchangeable Ca	0.389	0.148	0.007	-0.019
Exchangeable Mg	-0.008	0.115	0.751	-0.104
CEC	0.409	0.023	0.155	0.037
BS	0.066	0.674	-0.029	-0.144
Al saturation	-0.316	0.007	-0.304	-0.271
Texture	-0.124	-0.449	0.187	-0.269

Remark: the number written in bold is selected as the PC in each PC group.

Table 5. Results of soil fertility index calculation

Farming System	LMU	Point	Indicator Scoring										cj	nc	pc	SCI	N	SFI	SFI Average	Class
			pH	Org-C	C/N	Ca	CEC	Al	BS	N	Mg	K								
		1	3	2	2	3	4	1	3	3	3	3	2.72	5	0.2	0.54	10	0.54		
	1	2	3	2	3	3	4	1	3	2	3	3	2.74	5	0.2	0.55	10	0.55		
		3	4	2	2	4	4	1	3	2	3	3	2.83	5	0.2	0.57	10	0.57		
		4	4	2	2	3	4	1	3	2	3	3	2.74	5	0.2	0.55	10	0.55		
	2	5	4	2	2	3	4	1	3	2	3	3	2.74	5	0.2	0.55	10	0.55		
		6	2	2	2	3	4	2	3	2	3	3	2.65	5	0.2	0.53	10	0.53		
		7	3	1	1	3	4	2	3	3	3	3	2.63	5	0.2	0.53	10	0.53		
Conventional	3	8	4	1	1	3	4	2	3	2	3	3	2.65	5	0.2	0.53	10	0.53		
		9	4	1	1	3	4	2	3	2	3	3	2.65	5	0.2	0.53	10	0.53		
		10	4	2	2	4	4	1	3	2	3	3	2.83	5	0.2	0.57	10	0.57	0.55	Moderate
	4	11	4	2	2	3	4	2	3	3	3	3	2.91	5	0.2	0.58	10	0.58		
		12	4	2	2	4	4	2	3	2	3	3	2.93	5	0.2	0.59	10	0.59		
		13	3	2	2	3	4	1	3	2	3	3	2.65	5	0.2	0.53	10	0.53		
	5	14	3	2	3	3	4	1	3	1	3	3	2.67	5	0.2	0.53	10	0.53		
		15	4	2	2	4	4	1	3	2	3	3	2.83	5	0.2	0.57	10	0.57		
		16	3	1	1	4	4	1	3	2	4	3	2.63	5	0.2	0.53	10	0.53		
	6	17	4	1	2	4	4	1	3	2	3	4	2.88	5	0.2	0.58	10	0.58		
		18	3	1	2	3	4	1	3	2	4	3	2.63	5	0.2	0.53	10	0.53		
		19	4	2	2	4	4	1	3	2	3	4	2.97	5	0.2	0.59	10	0.59		
	7	20	4	2	2	3	4	1	3	2	3	3	2.74	5	0.2	0.55	10	0.55		
		21	4	2	2	3	4	2	3	2	3	3	2.83	5	0.2	0.57	10	0.57		
		22	4	2	2	3	4	2	3	2	3	3	2.83	5	0.2	0.57	10	0.57		
Semi-organic	8	23	4	2	2	3	4	2	3	2	3	3	2.83	5	0.2	0.57	10	0.57	0.57	Moderate
		24	4	2	2	4	4	1	3	2	3	4	2.97	5	0.2	0.59	10	0.59		
		25	4	2	2	3	4	1	3	3	4	3	2.89	5	0.2	0.58	10	0.58		
	9	26	4	2	2	3	4	1	3	2	4	3	2.81	5	0.2	0.56	10	0.56		
		27	4	2	2	3	4	1	3	2	3	3	2.74	5	0.2	0.55	10	0.55		
		28	4	3	4	4	4	1	3	2	3	3	3.11	5	0.2	0.62	10	0.62		
	10	29	4	3	4	4	4	1	3	2	3	4	3.25	5	0.2	0.65	10	0.65		
Organic		30	4	3	4	4	4	1	3	2	3	4	3.25	5	0.2	0.65	10	0.65		
		31	4	3	4	4	5	1	3	2	3	4	3.34	5	0.2	0.67	10	0.67		
	11	32	4	3	4	4	4	1	3	2	3	4	3.25	5	0.2	0.65	10	0.65	0.66	Moderate
		33	4	3	4	4	5	1	3	2	3	4	3.34	5	0.2	0.67	10	0.67		
		34	4	4	4	4	5	1	3	2	4	4	3.51	5	0.2	0.70	10	0.70		
	12	35	4	4	4	4	4	1	3	2	3	3	3.21	5	0.2	0.64	10	0.64		
		36	4	4	4	4	5	1	3	2	4	4	3.51	5	0.2	0.70	10	0.70		

Organic rice fields (LMU 10, 11, and 12) have the highest average soil fertility index value of 0.66 compared to semi-organic rice field farming systems (LMU 7, 8, and 9) of 0.57 and conventional (LMU 1, 2, 3, 4, 5, and 6) of 0.55. Map of soil fertility index rice fields in Nguntoronadi District, Wonogiri Regency as shown in Figure 2. The high value of the soil fertility index (SFI) in organic rice fields indicates that the provision of organic inputs will improve soil fertility status. This is corroborated by El-Mogy et al. (2020) assertion that organic farming will restore, preserve, and improve soil physiochemistry and biology, thereby increasing crop production. The higher the organic matter in the soil, the more fertile it will be. Conversely, the lower the organic matter content, the lower the soil fertility (Hanafiah, 2013). The application of organic materials can increase optimal soil fertility for crop management with sustainable agricultural yields and better production quality (Mutammimah et al., 2020). Conventional agriculture dependent on fertilizers and pesticides for crop production reduces fertility due to nutrient loss from erosion and leaching (Roy et al., 2016). Using chemical fertilizers in disproportionately high concentrations can also lead to nutrient imbalances in the soil that can cause other nutrient deficiencies (Mujiyo et al., 2022).

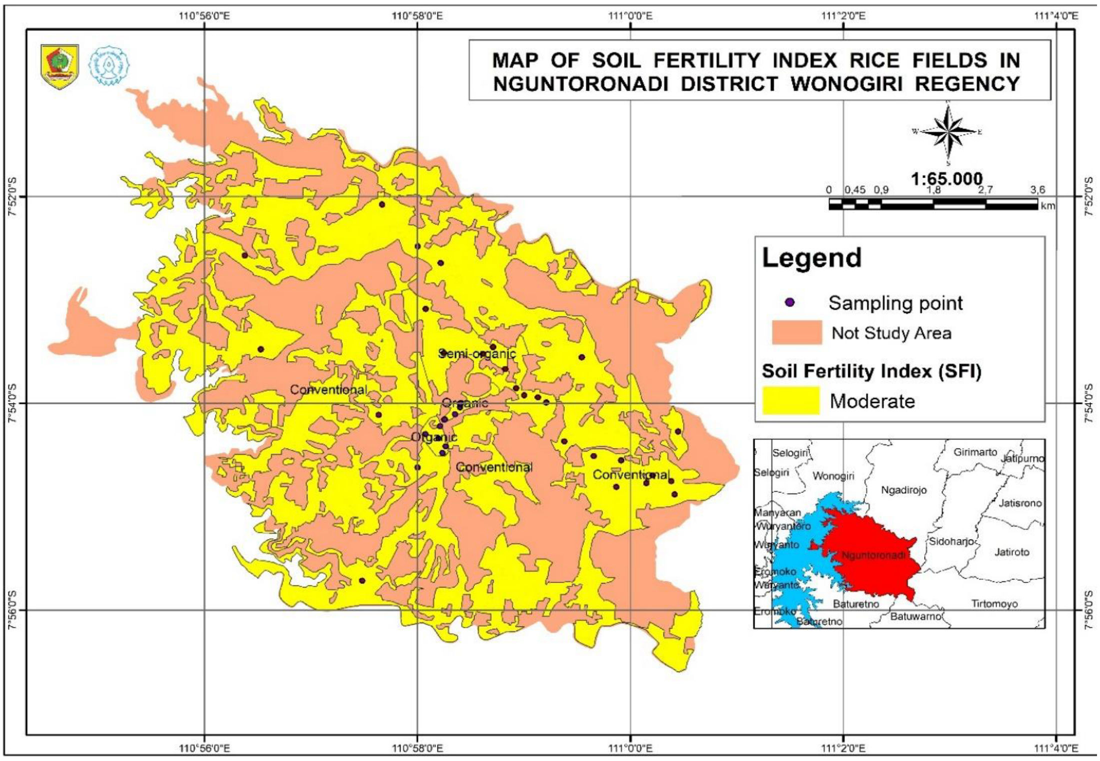

Figure 4. Map of soil fertility index.

3.3. The distribution and effects of different rice fields farming systems on SFI

The results of the ANOVA analysis showed that the farming system of rice fields had a very significant effect on soil fertility (p-value<0.01). According to Sukristiyonubowo et al. (2019), organic, semi-organic, and conventional farming systems affect soil chemical and physical fertility. Furthermore, Duncan's Multiple Range Test (DMRT) analysis was performed in Figure 5. Based on Figure 5. shows that the three rice field farming systems (conventional, semi-organic, and organic) have significant differences (not followed by the same letter) with each other. The organic rice field farming system has the highest value and differs from conventional and semi-organic farming systems. In contrast, conventional rice fields have the lowest SFI value and are significantly different from semi-organic and organic rice fields. Although conventional, semi-organic, and organic rice field farming systems are still in the same SFI class moderate, organic rice fields have a considerable difference in SFI values from other farming systems due to organic rice fields that have been cultivated for 8 years so that they affect higher soil fertility levels. This is similar to the findings of Das et al. (2017) that organic farming practices will gradually improve soil properties by increasing carbon storage in the soil and long-term

N, P, and K availability (Pambayun et al., 2023). According to Reeve et al. (2016), organic systems have been proven to increase chelate microelements, buffer soil pH, and increase cation exchangeable capacity, influencing the availability of adequate plant nutrients and reducing leaching potential.

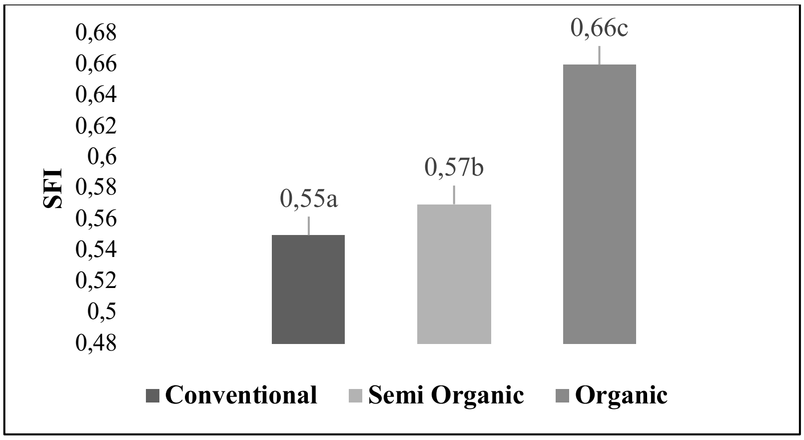

Figure 5. Soil fertility index (SFI) under different rice field farming systems.

3.4. Key factor indicators

Key factors of soil fertility are indicators that are significantly correlated with the results of the soil fertility index. The key factors become the basis for appropriate recommendations to improve soil fertility in rice fields of the study area. Indicators selected as key factors include pH (r=0.59, P-value<0.01, N=36), organic C (r=0.878, P-value<0.01, N=36), available P (r=0.651, P-value<0.01, N=36), available K (r=0.732, P-value<0.01, N=36), Exchangable-Ca (r=0.831, P-value<0.01, N=36), CEC (r=0.875, P-value<0.01, N=36), and Aluminum saturation (r=-0.57, P-value<0.01, N=36). The research results show that key factor indicators of soil fertility found in the research area are positively correlated with soil fertility. This value explains that the higher the key factor indicator value includes organic C (Figure 6), CEC (Figure 7), Exchangable Ca (Figure 8), Available K (Figure 9), Available P (Figure 10), pH (Figure 11), and Aluminum saturation (Figure 12), the higher the soil fertility level.

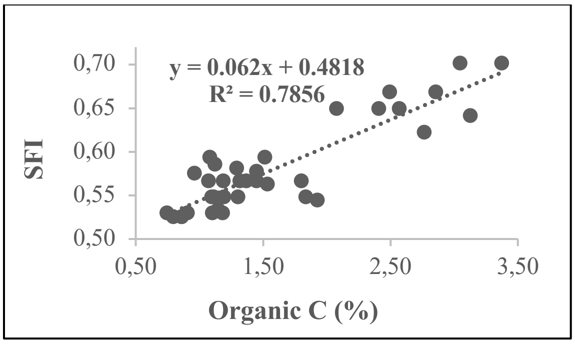

Figure 6. The correlation of organic carbon and soil fertility.

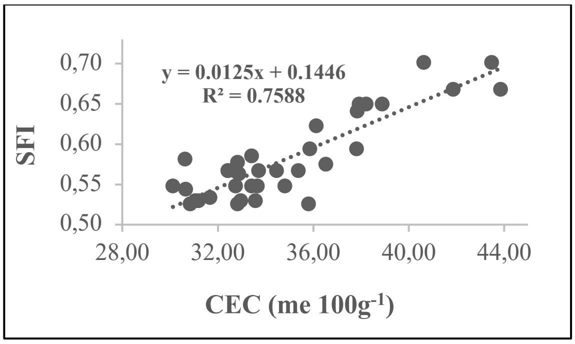

Figure 7. The correlation of CEC and soil fertility.

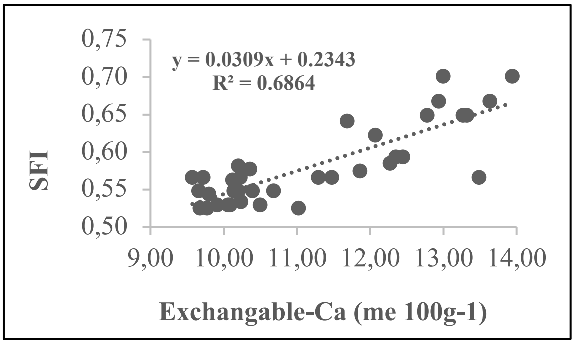

Figure 8. The correlation exchangable-Ca and soil fertility.

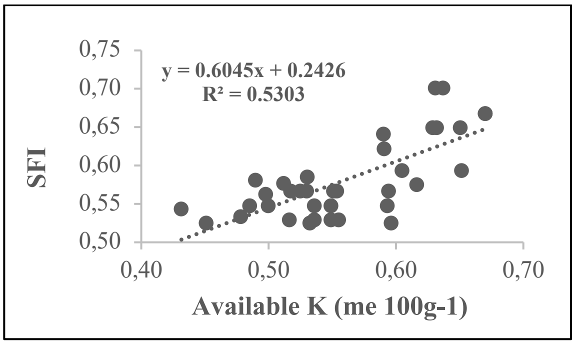

Figure 9. The correlation available K and soil fertility.

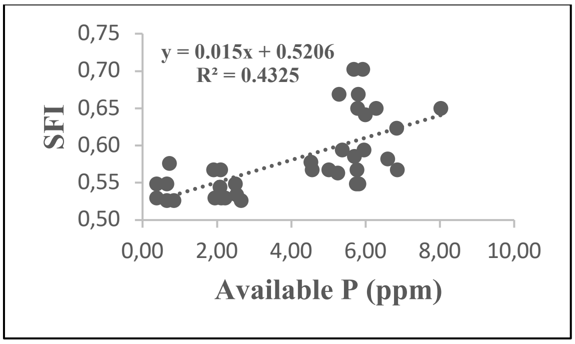

Figure 10. The correlation of available P and SFI.

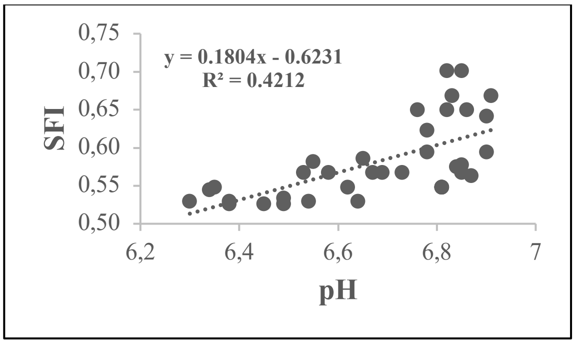

Figure 11. The correlation of pH and soil fertility.

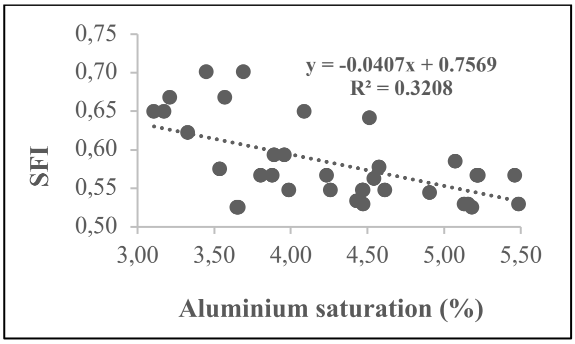

Figure 12. The correlation of Aluminium saturation and soil fertility.

The content of organic C will increase with the addition of organic matter, the increase in organic C will be directly proportional to the increase in CEC (r= 0.750), available P (r=0.559), and pH (0.392). Organic C content in conventional rice fields is very low to low due to the absence of added organic matter, semi-organic rice fields are low due to the provision of organic matter that is not optimal, and organic C content in organic rice fields is moderate. Organic matter requires the addition of microbes to facilitate the decomposition or release of minerals, thus making nutrients more available to roots in an early stage for sustainable plant growth (Ossai et al., 2022). Soil pH is very crucial in soil fertility because it involves the availability of other nutrients. The optimal pH range is 5.5 – 6.5 ensures that the nutrients in the soil are available for uptake by the rice plants. If the pH deviates from this range, it can lead to nutrient deficiencies or toxicities, affecting the overall fertility of the soil (Johnson et al., 2019).CEC is determined by organic matter content. Soils with higher organic matter content generally have higher CEC values (Sihi et al., 2017). The lack of soil organic matter results in a low pH so that H^+ ions are firmly bound to active groups and positively charged groups ($-COOH^{2+}$ and $-OH^{2+}$), as a consequence negatively charged colloids become low and CEC decreases. Conversely, in high pH conditions, OH^- dissolves and binds H^+ released from organic groups increasing negative charges ($-COO^-$ dan $-O^-$) and CEC (Irawan et al., 2021).

The increase in organic C will reduce Aluminum saturation so that soil acidity decreases and increases the soil fertility index. Aluminum saturation negatively affects soil fertility by causing multiple nutrient deficiencies (Zhao and Shen, 2018). Aluminum saturation in organic rice fields is lower than in conventional and semi-organic rice fields. Organic matter undergoing decomposition produces organic acid compounds that can bind and reduce Al metal cations in acidic soils and can increase soil fertility and pH (Farrasati et al., 2019). In organic rice fields, the CEC is high due to the humification of organic material so that soil colloids increase and soil fertility also increases (Jawang, 2021). In addition, increasing soil CEC will increase the availability of K and Ca and protect against leaching. Organic rice fields have the highest CEC compared to other rice field farming systems so the quantity of available K and exchangeable Ca is also higher. The increase in available K and Ca-dd in the soil is due to the soil's ability to bind K and the clay content in the soil. High clay content has a large surface area, so the CEC becomes larger, increasing the ability to hold K and Ca from leaching (Jawang, 2021). High soil fertility is related to the availability of K^+ which plays an important role in crop yields. Organic farming will increase the efficiency of P availability (Adamtey et al., 2016) and increase the fertility of agricultural land. Organic C with the mechanism of inhibiting P binding by metal ions (Fe and Al) through the production of organic acids, humic acids, fulvic acids, and organic leachates (Li et al., 2021) can increase P availability.

3.5. Land management recommendation as a strategy to maintain soil fertility

Proper management can enhance soil properties so that fertility increases (Mutiara and Bolly, 2019) which is an important factor in determining plant growth and yield (Pinatih et al., 2015). Organic agriculture systems are recommended for rice field management in the study area because they have a higher soil fertility index than conventional and semi-organic rice fields. This is linked to the availability of organic matter inputs, which will improve the soil fertility index. Integrated soil fertility management considers site-specific conditions biotic and physio-chemical factors, and administrative aspects (Abukari and Abukari, 2020). In addition, organic farming can be the main road to socio-economic and ecologically sustainable development by avoiding or excluding synthetic inputs and utilizing crop rotation, crop residues, manure, organic waste, natural rock minerals, and crop protection.

Sources of organic matter that can be applied in rice field management are compost, liquid organic fertilizer (LOF), manure, biochar, green fertilizer, and biofertilizer. Compost comes from crop residues and animal waste that undergo a biological decomposition process by microorganisms with or without bio-activators such as EM4 (effective microorganism 4) technology, which accelerates the composting process (Dahlianah, 2015) and increases the total N, available P, and K (Viandari et al., 2022) and enhanced soil quality recovery (Kurniawan et al., 2023). Compost is generally in the form of solid organic fertilizer, while liquid organic fertilizer is commonly referred to as liquid organic fertilizer (LOF). The advantages of liquid organic fertilizer are that it has the potential to improve soil fertility because the nutrients are easily decomposed and quickly available to plants, reduce farming costs, and save on environmental problems (Arfarita et al., 2020).

Using organic fertilizers such as manure and vermicompost can raise the relative water content by up to 75%, aid in plant water absorption, and increase nutrition, resulting in optimal plant vegetative growth (Rahimi et al., 2023). Manure not only contains macronutrients needed by plants but can also maintain the balance of nutrients in the soil. Animal manure contains complete nutrients and is relatively available to plants because organic matter has gone through a complete transformation quickly. Animal manure contains complete and relatively available nutrients for plants consisting of 26.2 kg ton^{-1} N, 4.5 kg ton^{-1} P, 13 kg ton^{-1} K, 2.2-13.6 kg ton^{-1} S, 5.3-16.28 kg ton^{-1} Ca, and 3.5-12.8 kg ton^{-1} Mg (Suntoro et al., 2018). Biochar is a carbon product derived from biomass pyrolysis in an anaerobic environment that is beneficial for soil fertility by decreasing soil acidity, increasing CEC, and nutrient availability (Diatta et al., 2020). Green fertilizers are green plants that can increase the physical and biochemical structure of the soil, reduce nutrient losses due to leaching, increase water holding capacity, increase carbon absorption, increase nitrogen fixation, and increase organic matter content (Iderawumı and Kamal, 2022). Organic fertilizers combined with biological agents can produce high-quality fertilizers that can increase soil fertility and support soil productivity (Mujiyo et al., 2022). Organic farming also helps to reduce greenhouse gas emissions, ensuring a more sustainable environment for the future (Angon et al., 2022; Suwardi et al., 2023)

Conclusion

Intensive farming of rice fields to meet food needs with the addition of chemical fertilizers and pesticides causes land degradation. This land degradation indicates a decrease in soil fertility in rice fields. In fact, rice field soil fertility is required for rice plant productivity. Thus, research is necessary to analyze soil fertility to determine the soil fertility level in various rice field farming systems used for rice production and management recommendations based on key soil fertility factors. The research results show that the soil fertility level in the research area is moderate, with an index value range of 0.55 to 0.66. Differences in rice field farming systems affect the level of soil fertility. Organic farming has the highest soil fertility with an index of 0.66, and conventional farming has the lowest fertility compared to the others with an index of 0.55. The key indicators of soil fertility are pH (R^2=0.4212), organic C (R^2=0.7856), available P (R^2=0.4325), available K (R^2=0.5303), exchangeable Ca (R^2=0.6864), CEC (R^2=0.7588), and Aluminum saturation (R^2=0.3208). Suitable management recommendations for rice fields in the area are through the implementation of organic farming systems with the addition of organic materials such as compost, liquid organic fertilizer (LOF), manure, biochar, green fertilizer, and biological fertilizer. In addition, organic farming recommendations support the implementation of sustainable integrated agriculture by increasing soil fertility. Increased soil fertility has a clear impact on enhancing rice crop productivity and achieving food security.

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