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The distribution of soil fertility index and its interaction with earthworms density under organic, semi-organic, and inorganic rice fields

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Abstract

Earthworms are soil macrofauna that play a role in maintaining the sustainability of soil use through increasing organic matter and soil fertility. Soil fertility assessment is important to suggest management to create an optimum conditions for plant growth, so it can be maintained the quality and quantity of rice productivity. The purpose of this research was to identify soil fertility index (SFI), the density of earthworms and the relationship between the two under different rice field systems, namely organic, semi-organic, and inorganic. This research also identifies indicators that determine SFI to be able to provide appropriate and efficient strategies in subsequent land management. This method used an exploratory descriptive with a survey approach. Sampling points was taken based on the farming systems (organic, semi-organic, and inorganic rice fields) on flat (0–8%) and sloping (8–15%) slopes. The SFI was determined used the Minimum Soil Fertility Indicator (MSFI). The results showed that differences of rice field farming systems is significantly effects on SFI. The index of soil fertility in the research area is moderate, with the highest SFI in the organic farming system. Soil fertility and earthworms density had a significant positive correlation, that the higher earthworms density, the higher soil fertility. Key indicators were found including organic C, available P, Al saturation, and exchangeable bases which determine SFI. The organic rice field system has the best SFI as well as the highest earthworm population, so we recommend increasing the use of organic materials in the tillages process and expanding the organic rice field system to maintain fertility and the sustainability of soil used for rice production.

1. Introduction

Over the past ten years, the increased population in Tirtomoyo Subdistrict, Indonesia, reached 2.77% (Central Bureau of Statistics, 2021). Muhidin et al. (2018) stated that along with the increase in population, the demand for rice, the staple food commodity, is also increasing (Wahyuti et al., 2023), so the sustainability of rice yield production must be maintained in quality and quantity. In order to maintaining rice productivity, is needed the optimal soil fertility (Mahendratta et al., 2021; Maro'ah et al., 2022). One of the factors that affect plant growth, productivity, and quality is soil fertility (Supriyadi et al., 2021; Syamsiyah et al., 2023). The condition of soil fertility depends on its management (Kome et al., 2018), and impacts on the availability and quantity of soil nutrients (Saosang et al., 2022; Pinandoyo et al., 2023). Soil fertility can be determined by evaluating many characteristics of soil chemical parameters such as research conducted by Bagherzadeh et al. (2018) and Widijanto et al. (2021). In addition, soil biological properties also contribute for improving soil conditions. According to Purba et al. (2022) nutrient availability, especially mineral nutrients for plants can be enhanced by the existence of earthworms in soil. Earthworms greatly contribute to the nutrients cycle and the decomposition of organic matter, so the earthworm density can determine soil fertility (Lele et al., 2021). Earthworm populations can be used to evaluate land conditions, as bioindicators of land sustainability and minimize land degradation due to the application of inorganic systems (Sofo et al., 2020; Widhiyastuti et al., 2023).

Soil fertility assessment is important to suggest land management to create optimum conditions for plant growth (Nguemezi et al., 2020). The soil fertility index (SFI) assessment can be utilized as a source of information on soil fertility data. Soil fertility in an area can be used as a primary reference for planning sustainable agriculture. In addition, information on the categorization of soil fertility levels in an area can be used as a guideline for carrying out fertilization activities in agricultural cultivation (Romadhon and Hermiyanto, 2021). Previous research examined the SFI in two types of rice field farming systems with Entisols soil types, such as those conducted by Prastiwi et al. (2021), which gave the result that the SFI of rice fields with organic farming (0.96) was higher than inorganic farming (with an index of 0.85). In addition, previous studies only examined soil chemical properties, such as research undertaken by Sukristiyonubowo et al. (2019), which produced data showing that the application of the inorganic system in Sambirejo Village, Sragen Regency on Vertisols soil also resulted in lower soil chemical properties compared to the organic system.

The various farming systems of rice field in the research area, Tirtomoyo Sub-district, namely organic, semi-organic, and inorganic farming. The hypothesis of this study is organic farming will resulting the best soil fertility and earthworm densities, cause it has several benefits such as enhances nutrient content, reduces the concentration of heavy metals, and support the growth and reproduction of earthworm, which in turn promotes soil fertility. However, no research has been conducted to describe on the effect of using inorganic, semi-organic, and organic rice field farming systems on soil fertility and earthworm populations in Tirtomoyo District, Wonogiri Regency with Inceptisols soil type. It is necessary to research with the aims to determine the impact of different rice field farming systems on soil fertility index and esrthworm populations. The objectives also to find indicators that determine soil fertility, so that land management recommendations can be given in an effort to improve soil fertility in a sustainable agriculture.

2. Materials and methods

2.1. Research area

This research was conducted in Tirtomoyo Sub-district, Wonogiri Regency, Indonesia, which has a tropical climate with temperature ranges between 21.2°C–24.8°C, annual rain per year is 2250 mm. The geographical location is in 111°0”14.32’ – 111°8”57.39’ E and 7°54”31.45’ – 8°0”54.03’ S. Research conducted in Central Java is necessary because there are ideal rice fields that apply all three types of rice field farming systems while having various geographical conditions. In addition, Central Java is also a substantial rice producer in Indonesia, so it has an important role in food security.

This research used an exploratory descriptive method with a survey approach. Rice fields in this research area are managed by farmers using inorganic, semi-organic, and organic farming systems. Each year, rice fields can be planted with rice for two to three planting periods. This area is located at an altitude of approximately 171 meters above sea level (m asl). The soil type in Tirtomoyo Sub-district is Inceptisols (ICALLRD, 2018). Organic farming of rice field is manage by farmers under the guidance of the Wonoagung Wonogiri Organic Farmers Association (called PPOWW) which has been running since 2020 (information of the fertilizers shown in Table 1). The provision of organic fertilizer (cow manure) is carried out before planting period at

Table 1.
The variants, treatments, type, and properties of fertilizer used.

Farming systems	Variant of fertilizer	Concentration properties	Type	Frequency of treatment
Organic	Organic fertilizer (Octabacter)	10 ml per liter at a dose of 15 liters per hectare	Liquid	1 to 2 times a week
	Biofertilizer containing phosphate solubilizing bacteria (Djagotani)	2 ml per liter	Liquid	1 to 2 times a week
	Cow manure	3–4 tons per hectare	Compact	1 time before planting periode
Semi organic	Cow manure	3–4 tons per hectare	Compact	1 time before planting periode
	Urea	150–200 kg per hectare	Compact	twice in one planting period
	NPK/Phonska fertilizer	50–100 kg per hectare,	Compact	twice in one planting period
	TSP (Triple Super Phosphate)	50–100 kg per hectare	Compact	twice in one planting period
	ZA (Zwavelzure Amonium)	50–100 kg per hectare	Compact	twice in one planting period
	KNO	20 kg per hectare.	Compact	twice in one planting period
Inorganic	Urea	150–200 kg per hectare	Compact	twice in one planting period
	NPK/Phonska fertilizer	50–100 kg per hectare,	Compact	twice in one planting period
	TSP (Triple Super Phosphate)	50–100 kg per hectare	Compact	twice in one planting period
	ZA (Zwavelzure Amonium)	50–100 kg per hectare	Compact	twice in one planting period
	KNO	20 kg per hectare.	Compact	twice in one planting period

dose of 3 up to 4 tons per hectare. After 2 weeks of transplanting, the paddy crops were given liquid organic fertilizer (called *Octabacter*) with a concentration of 10 ml per liter at a dose of 15 liters per hectare and applied once to twice a weeks. In addition, there are rice fields that are treated with liquid biofertilizer containing phosphate solubilizing bacteria (called *Djagotani*) at a concentration of 2 ml per liter.

In semi-organic system the provision of manure input of 1 to 2 tons per hectare is applied before planting, continues by mineral fertilization. Farmers apply semi-organic and inorganic farming by providing input of different types of fertilizers including; Urea 150–200 kg per hectare, NPK and Phonska fertilizer 50–100 kg per hectare, TSP 50–100 kg per hectare, ZA 50–100 kg per hectare, and KNO 20 kg per hectare. Applying these fertilizers is usually done twice in one planting period when the paddy crops are 7 to 10 days after planting and 21 days after planting.

2.2. Soil sampling and analysis

Sampling was conducted by purposive sampling on organic, semi-organic, and inorganic rice fields based on the sample point map. Soil sampling was carried out by 8 to 15 of december in 2022. Soil sampling was conducted on land mapping unit (LMU) at different rice field farming system in study area (organic, semi-organic, and inorganic) with various slope ranging of 0–8% to 8–15% with each four replications, resulting in a total of 24 soil sampling points (organic in 8 points, semi-organic in 8 points, and inorganic in 8 points). The collection and calculation of earthworm populations were carried out using the PVC sample ring method with a diameter of 20 cm and a ring height of 20 cm and sorted according to technical instructions for identifying earthworms (Suin, 2003; ICALLRD, 2007; Capowiez et al., 2009).

In this study, soil samples were prepared for soil fertility and earthworm density analysis. Soil samples were taken for soil fertility in the form of disturbed soil (sampling at the depth of tillage layer about 1 to 30 cm depth) as much as 1 kilogram soil, while the analysis of earthworm using ring method sampling with a soil volume measuring as 20 cm diameter and height (a total soil volume 6,280 cm^3).

The determination of soil chemical properties was carried out at the Soil Chemistry and Fertility Laboratory with reference to the technical guidelines of the Balittanah (2009). Indicators of soil chemical properties analyzed were soil pH (Electrometry method), soil organic C (Walkley and Black method) (Balittanah, 2009), total N (Kjeldahl method) (Balittanah, 2009), available P

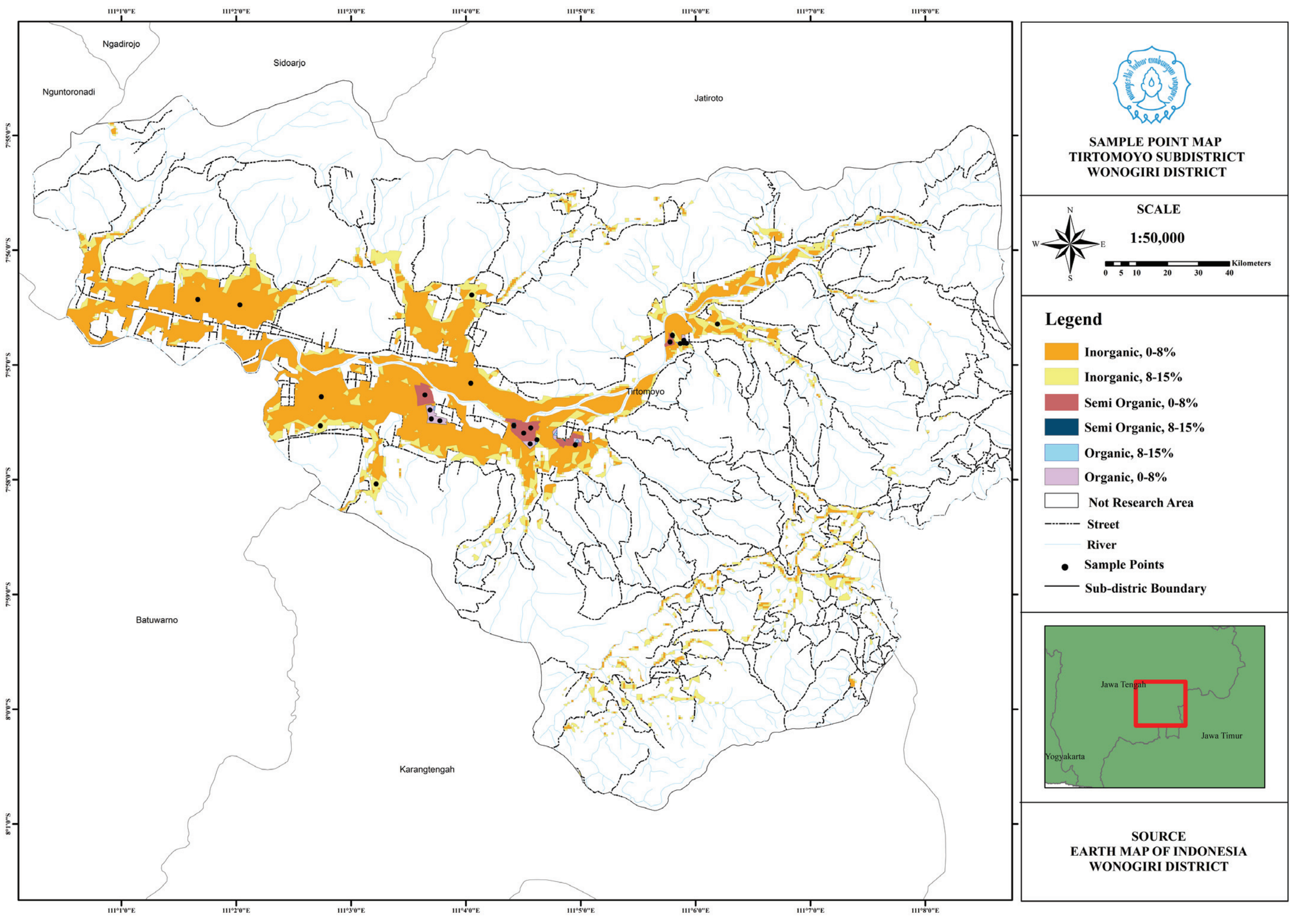

Fig. 1. Location of sampling point

(Olsen method) (Balittanah, 2009), cation exchange capacity (CEC) (1N Ammonium Acetate Extraction method) (Balittanah, 2009), exchangeable bases (1N Ammonium Acetate Extraction method) (Balittanah, 2009), and Al saturation (Potassium Chloride Extraction method).

2.3. Data analysis

The results of soil chemical properties that have been obtained are used as indicators of the soil fertility index (Bagherzadeh and Gholizadeh, 2018). The determination of soil fertility index begins with Principal Component Analysis (PCA) and continues with Minimum Data Set (MDS) to produce Minimum Soil Fertility Indicators (MSFI). The analysis is used software (Minitab19). Principal Component Analysis (PCA) is method to reduce the dimensions of the data set, so that the determinants of soil fertility could be identified (Nehrani et al., 2020; Zhan et al., 2020)

The results of classifying parameters on each PC, then selected to become MDS. Furthermore, the selected MSFIs were assessed based on the assessment criteria (shown in Table 2). Indicators in assessing soil fertility focus on the chemical properties of the soil. Scoring index is used to categorize the analysis results into class groups starting from very low, low, moderate, high and very high for the value of each parameter. Scoring indicators will be used in the formula for calculating the soil fertility index.

The SFI assessment is done by dividing the total weight (Sci) by the number of SFI indicators (N) (Mukashema, 2007).

$$\text{SFI} = \frac{Sci}{N} \times 10 \quad (1)$$

Where:
SCi = cj × pc
Cj = wi × si
Pc = 1/nc
SFI (soil fertility index); Sci (scoring indicator); N (total indicator of MSFI); cj (total weight); pc (grade value); wi (weight index); si (scoring index); nc (total value used)

The results obtained are classified into five index of soil fertility (shown in Table 3), which have a value range of 0 ≤ SFI ≥ 1

Earthworm population density was calculated based on the number (2) equation:

$$\text{Earthworm population density} = \frac{\text{a total of earthworms}}{\text{the volume of soil samples}} \quad (2)$$

Source: (ICALLRD, 2007)

The determination of the effect of rice field farming systems on soil chemical properties, soil fertility index and earthworm population density was conducted with one-way ANOVA (Analysis of Variance). If the results were significantly affected by farming systems, then continue with DMRT (Duncan's Multiple Range Test) to determine the average soil chemical properties, soil fertility index, and earthworms population density with the highest value. Correlation tests were conducted to determine the factors or indicators that determine SFI. The correlation between soil fertility index and earthworm population density was determined using Pearson correlation analysis. Regression analysis determined how much the SFI value can change due to the high and low earthworm population density.

Table 2.
Indicator assessment criteria of soil fertility

Indicator	Scoring index (si)				
	1	2	3	4	5
	Very low	Low	Moderate	High	Very high
pH	< 5.5 > 7.5	5.5–6.0	6.0–6.5	6.5–7.5	7.0–7.5
Soil organic 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
Available P (ppm)	< 5	5–10	11–15	16–20	> 20
Available K (me/100 g)	< 10	10–20	21–40	41–60	> 60
CEC (me/100 g)	< 5	5–16	17–24	25–40	> 40
Base saturation (%)	< 20	20–40	41–60	61–80	> 80
Exc. Ca (me/100 g)	<2	2–5	6–10	11–20	> 20
Exc. Mg (me/100 g)	< 0.3	0.4–1	1.1–2.0	2.1–8.0	> 8
Exc. Na (me/100 g)	< 0.1	0.1–0.3	0.4–0.7	0.8–1.0	>1
Al saturation (%)	>40	20–40	11–20	5–10	< 5

Source: (Balittanah, 2009)

Table 3.
Soil Fertility Index classes

SFI Classes	Value
Very low	0.00–0.25
Low	0.25–0.50
Medium	0.50–0.75
High	0.75–0.90
Very high	0.90–1.00

Source: (Bagherzadeh and Gholizadeh, 2018)

3. Results

3.1. The Distribution of Soil Fertilty Index (SFI) of Rice Fields Under Different Farming System

SFI is determined by the analyzed soil chemical parameters. However, only a certain number of parameters are used for practical purposes. Parameter reduction can be done using principal component analysis to produce principal components (PC) and minimum soil fertility indicator (MSFI) that can represent all parameters to determine the soil fertility index (Mukashema, 2007).

Principal components (PCs) that have eigenvalues ≥ 1 were selected in this research. Four principal components (PC 1 to PC 4, shown in Table 4) were obtained based on the principal component analysis, representing 80% of the overall variables. The value of the main component charge is categorized into three categories, namely low (0.3–0.5), medium (0.5–0.75), and high (>0.75) (Liu, 2003). In each PC, the indicator with the highest component load value andwith the highest component load value and significantly correlated with the variable is selected except for the Al saturation indicator, which has the lowest component load value (Mukashema, 2007).

The exchangeable Ca indicator with the highest principal component load value and very closely correlated with organic C, available P, and Al saturation was selected in principal component 1 or PC1. On main component 2, the CEC indicator was selected, which has the highest main component load value with a medium category. On PC3, the available K indicator was selected; on PC4, the exchangeable Mg indicator was selected, which is closely correlated with exchangeable Na. Eight minimum soil fertility indicators, including organic C, available P, Al saturation, exchangeable Ca, cation exchange capacity (CEC), available K, exchangeable Mg, and exchangeable Na can represent the total indicators of soil chemical properties and are then scored whose values are calculated as the scoring index (si) in determining the SFI.

Based on Table 5 which is calculated by equation (1), the SFI in the different applications of rice field farming systems is in the range of 0.59 in inorganic farming to 0.68 in organic farming. The organic, semi-organic, and inorganic rice fields had an average SFI (Fig. 2) of 0.66, 0.63 and 0.59, respectively. Soil fertility in each type of farming system belongs to the same index, which classified as medium.

Based on the result of the research, differences in rice field farming systems had a high significant effect on the soil fertility index of rice fields ($F_{2,23}$= 16.438, $p < 0.010$). The SFI of organically managed rice fields is significantly differs from the other two management systems. In addition, the SFI of semi-organically managed rice fields was also significantly different from the other two farming systems.

The higher soil fertility index of organic rice farming system is caused by higher values of soil chemical properties compared to semi-organic and inorganic farming systems. Selected parameters in Minimum Soil Fertility Indicators (Organic C, Available P, Al saturation, Exchangeable Ca, Available K, Exchangeable Mg, Exchangeable Na, CEC) were significantly different in each rice field farming system (Figs. 3–10).

Table 4.
Principal component analysis (PCA) results

Eigenvalue	5.0877	1.46	1.1638	1.0839
Proportion	0.463	0.133	0.106	0.099
Cumulative	0.463	0.595	0.701	0.800
Variable	PC1	PC2	PC3	PC4
pH	0.256	–0.326	0.013	–0.552
Organic C	**0.364**	–0.026	–0.320	0.008
Available P	**0.359**	–0.074	–0.301	–0.172
Total N	0.180	0.119	–0.673	0.110
CEC	0.249	**0.656**	0.141	–0.077
Al saturation	**–0.377**	–0.151	–0.170	0.197
Exchangeable Mg	0.251	0.187	–0.043	**0.594**
Exchangeable Ca	**0.394**	0.078	0.119	–0.038
Available K	0.312	–0.047	**0.381**	–0.100
Exchangeable Na	0.247	–0.163	0.380	0.399
Base Sturation (BS)	0.246	–0.591	–0.023	0.293

Source: Statistic analysis
Remark: the number written in bold is chosen as the PC indicator.

Table 5.
SFI result

LMU (Farming system, slope)	Scoring of SFI								cj	nc	pc	Sci	N	SFI	Average
	Organic C	Available P	Al saturation	Exc. Ca	CEC	Av. K	Exc. Mg	Exc. Na							
(Organic, 0–8%)	2	1	5	3	2	2	3	2	2.498	5	0.2	0.500	8	0.62	0.66
	2	1	5	3	2	2	3	2	2.498	5	0.2	0.500	8	0.62	
	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
	2	1	5	3	2	2	4	2	2.560	5	0.2	0.512	8	0.64	
(Organic, 8–15%)	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
(Semi Organic, 0–8%)	2	1	5	3	2	2	3	2	2.498	5	0.2	0.500	8	0.62	0.63
	2	1	5	2	3	2	3	2	2.520	5	0.2	0.504	8	0.63	
	2	1	5	3	2	2	3	2	2.498	5	0.2	0.500	8	0.62	
	2	1	5	3	3	2	4	2	2.727	5	0.2	0.545	8	0.68	
(Semi-Organic, 8–15%)	2	1	5	3	3	2	3	2	2.665	5	0.2	0.533	8	0.67	
	2	1	5	2	3	2	3	2	2.520	5	0.2	0.504	8	0.63	
	2	1	5	2	2	2	3	2	2.354	5	0.2	0.471	8	0.59	
	2	1	5	3	2	2	3	2	2.498	5	0.2	0.500	8	0.62	
(Inorganic, 0–8%)	2	1	5	2	2	2	3	2	2.354	5	0.2	0.471	8	0.59	0.59
	2	1	5	2	2	2	4	2	2.416	5	0.2	0.483	8	0.60	
	2	1	5	2	2	2	2	2	2.292	5	0.2	0.458	8	0.57	
	2	1	5	2	2	2	3	2	2.354	5	0.2	0.471	8	0.59	
(Inorganic, 8–15%)	2	1	5	2	2	2	4	2	2.416	5	0.2	0.483	8	0.60	
	2	1	5	2	2	2	3	2	2.354	5	0.2	0.471	8	0.59	
	2	1	5	2	2	2	3	2	2.354	5	0.2	0.471	8	0.59	
	2	1	5	2	2	2	4	2	2.416	5	0.2	0.483	8	0.60	

Remark: Exc. Ca (Exchangeable Ca), CEC (cation exchange capacity), Av. K (Available K), Exc. Mg (Exchangeable Mg), Exc. Na (Exchangeable Na), cj (Sum of weights or cumulative from 1 to j, determined from the sum of each weight index multiplied by each scoring index (wi × si)), nc (Number of classes is the number of scoring classifications used), pc (Probability class is the chance of the number of scoring classifications used (1/nc)), Sci (sum of MSFI weights), N (number of MSFI).

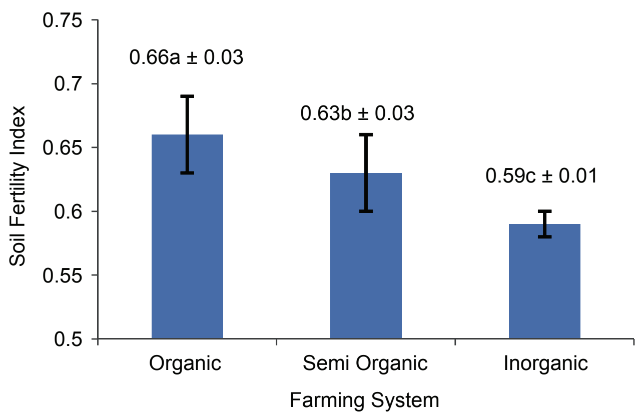

Fig. 2. Average soil fertility index under different rice field farming systems in research area

Remark: Different letters indicate significantly different results at the 95%.

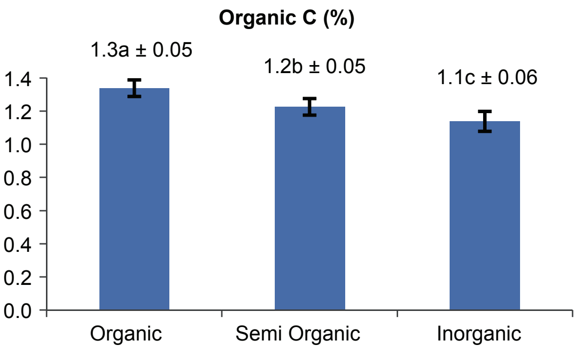

Fig. 3. The distribution of Organic C under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

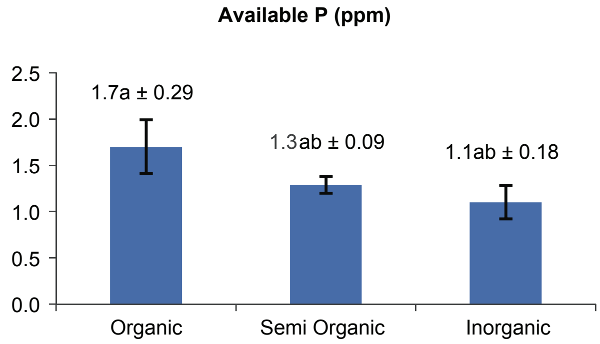

Fig. 4. The distribution of Available P under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

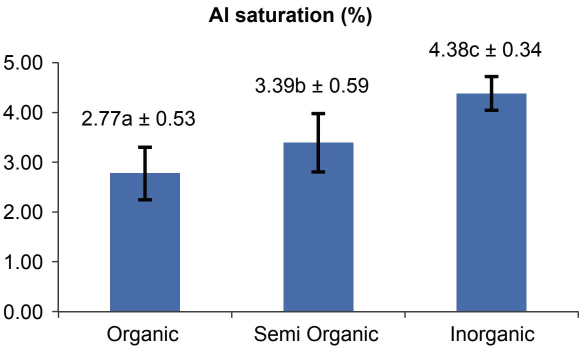

Fig. 5. The distribution of Al saturation under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

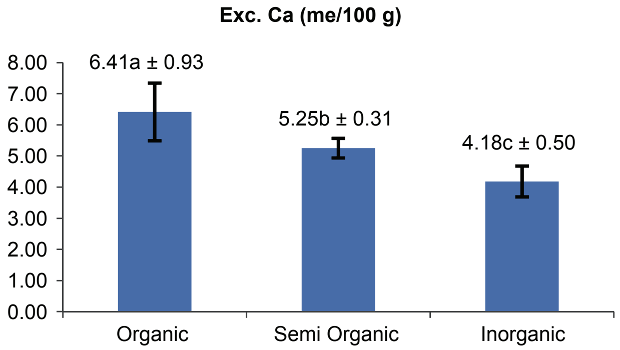

Fig. 6. The distribution of Exchangeable Ca saturation under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

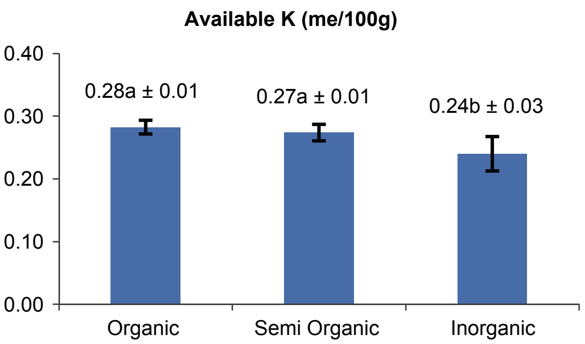

Fig. 7. The distribution of Available K under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

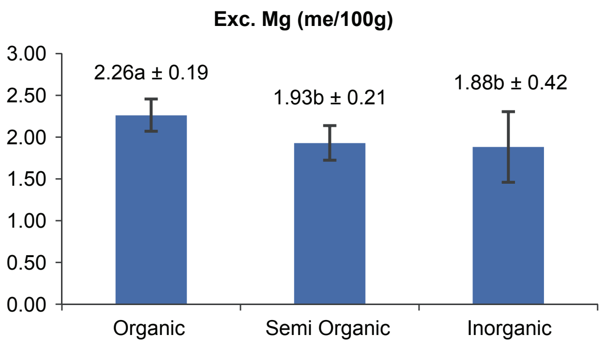

Fig. 8. The distribution of Exchangeable Mg under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

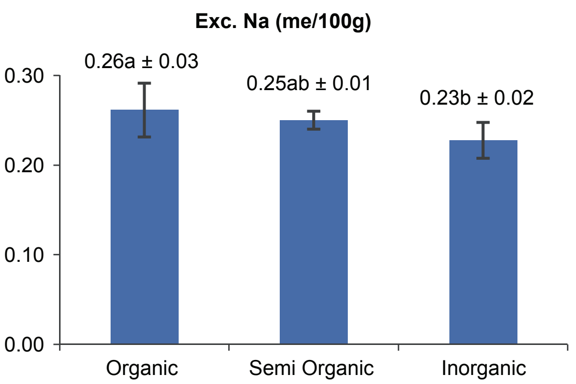

Fig. 9. The distribution of Exchangeable Na under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

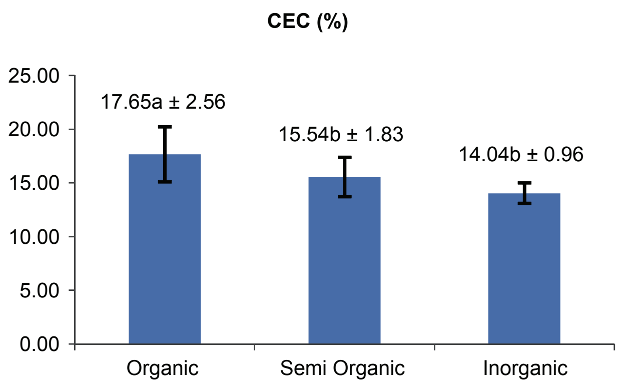

Fig. 10. The distribution of CEC under different farming systems. Remark: Different letters indicate significantly different result at the 95%.

3.2. Key Indicator of Soil Fertility Index (SFI)

Based on the research result, some soil chemical properties are correlated with SFI, including organic C, available P, available K, CEC, Exc. Mg, Exc. Ca, Exc. Na, and Al saturation (Table 6). In this research, it consider the key indicator determines the level of soil fertility. The regression equation presented in Figs. 11–18 describes the relationship between the condition of each key indicator to the level of soil fertility.

Table 6.
Correlation between SFI with soil chemical properties

	pH	Organic C	Available P	Total N	CEC	Al St.	Exc. Mg	Exc. Ca	Available K	Exc. Na	BS
Organic C	0.472*										
Available P	0.543**	0.757**									
Total N	0.065	0.416*	0.362								
CEC	0.075	0.428*	0.327	0.230							
Al St.	–0.575**	–0.638**	–0.638**	–0.234	–0.628**						
Exc. Mg	0.016	0.428*	0.346	0.233	0.433*	–0.442*					
Exc. Ca	0.440*	0.697**	0.640**	0.246	0.647**	–0.715**	0.428*				
Available K	0.353	0.504*	0.380	0.074	0.370	–0.610**	0.184	0.647**			
Exc. Na	0.201	0.349	0.243	0.027	0.210	–0.433*	0.350	0.427*	0.441*		
Base Saturation	0.393	0.434*	0.442*	0.121	–0.270	–0.274	0.359	0.502*	0.396	0.398	
SFI	0.223	**0.627****	**0.502***	0.113	**0.812****	**–0.676****	**0.556****	**0.692****	**0.528****	**0.406***	0.043

Remark: * = significant correlation at 0.05 level, ** = significant correlation at 0.01 level (key indicator written in bold)

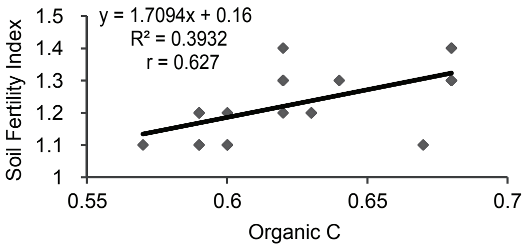

Fig. 11. Relationship between Organic C and SFI

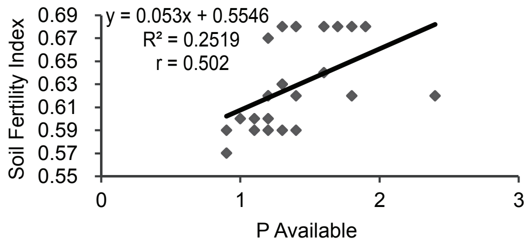

Fig. 12. Relationship between P Available and SFI

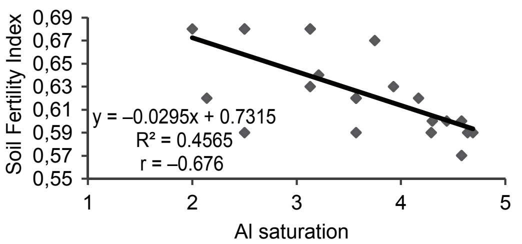

Fig. 13. Relationship between Al saturation and SFI

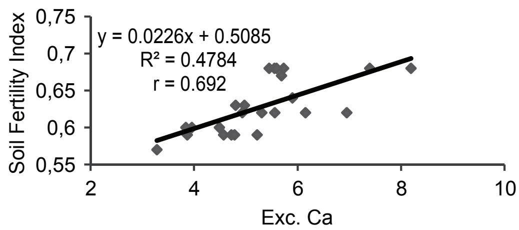

Fig. 14. Relationship between exchangeable Ca and SFI

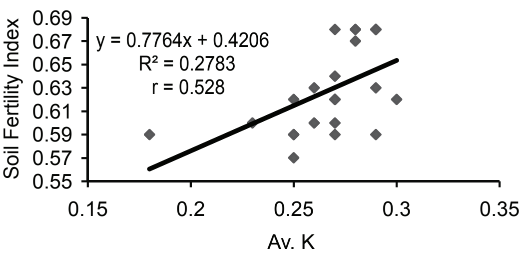

Fig. 15. Relationship between SFI Av. K and SFI

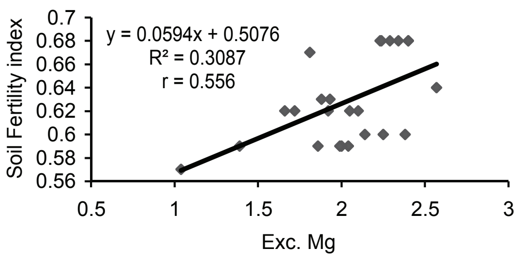

Fig. 16. Relationship between exchangeable Mg and SFI

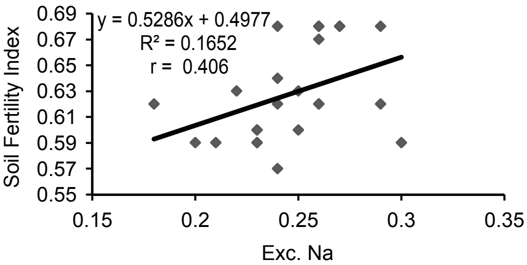

Fig. 17. Relationship between exchangeable Na and SFI

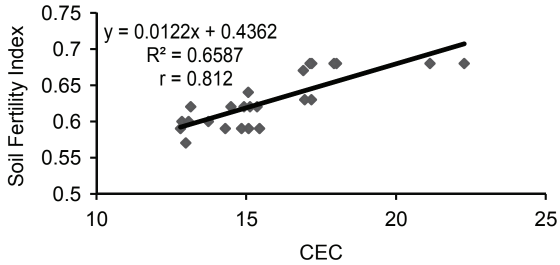

Fig. 18. Relationship between CEC and SFI

3.3. The distribution of earthworms population density under different farming systems of rice field

Earthworms were found in rice fields with all three management systems which is calculated based on the equation (2). Determination of earthworm population density was done by dividing the number of earthworm populations found by the area or volume of soil samples taken. The use of volume units is more recommended in muddy rice fields. The diameter and height of the PVC ring used were 20 cm referring to ICALLRD (2007). The population density of earthworms varied, ranging from 0.00 individuals per liter to 0.48 individuals per liter (shown in Fig. 19). The average population density of rice worms managed organic was 0.22 individuals per liter of soil. In rice field's soil with semi-organic farming has an average population of 0.14 individuals per liter of soil. The average population found in rice soil managed inorganic is as much as 0.08 individuals per liter soil.

The results of this study indicate that the presence of soil biota also supports soil fertility conditions, include several soil properties called key indicator (shown in Table 7). The presence of earthworms was significantly positively correlated to pH (r=0.428), soil C-organic content (r=0.425), P available (r=0.489), and CEC (r = 0.414). Earthworm population density was also significantly positively correlated with soil fertility index (r=0.582), means soil with high biota density also has high soil fertility, especially in pH, C organic content, P availability and cation exchange capacity (CEC), and vice versa.

Based on the results of statistical analysis, soil organic C has a value of R^2 or the coefficient of determination of 18.05%, which means that the soil organic C has an effect of 18.05% on the earthworms population density under various kinds of management with the regression equation (3):

$$y = 0.5943x – 0.5863 \qquad (3)$$

Remark: y = Earthworms population density
x = Soil organic C

Based on equation (3), the regression coefficient is positive. This means that an increase in the soil organic C under various farming systems, the earthworms population density will also increase. The earthworms population density will increase by

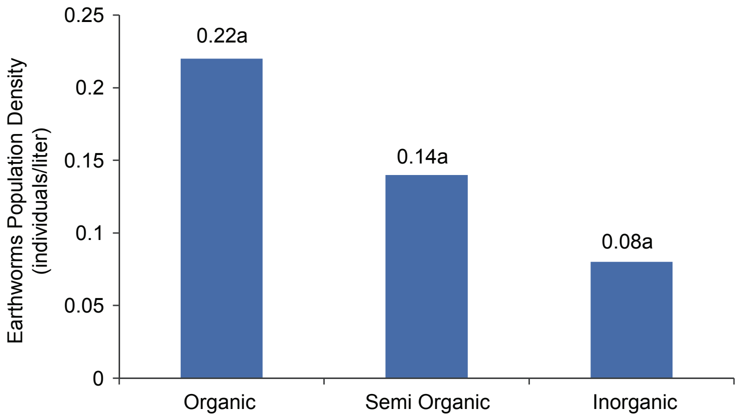

Fig. 19. Population density of earthworms in various rice field farming systems in research area

Table 7.
Correlation of earthworm population with soil chemical properties and SFI

	pH	Organic C	P Av.	Total N	CEC	Al st.	Exc. Mg	Exc. Ca	K Av.	Exc. Na	BS	SFI
Earthworm Population	**0.428***	**0.425***	**0.489***	0.057	**0.414***	**–0.471***	0.147	0.270	0.362	0.022	0.146	**0.582****

Remark: * = significant correlation at the 0.05 level, ** = significant correlation at the 0.01 level

0.5943 if there is an increase of 1% of soil organic C in various rice field farming systems. Soil fertility, pH, soil organic carbon, P available, CEC and earthworm population density showed high values in organic farming. Organic fertilizers applied to the rice fields will play a crucial role in soil. Organic and biofertilizers act as a catalyst for the growth and activity of soil microorganisms by enhancing nutrient availability (such as nitrogen, phosphorus, potassium, sulfur, and zinc), suppressing harmful pathogens, stimulating indigenous microorganisms, and also releasing plant growth stimulants (Mącik et al., 2020) such as phytohormones which also known as plant growth regulators (PGRs) and leads to increased root length and growth (Amara et al., 2015)

Based on the results of statistical analysis, earthworm population density has a value of R^2 or the coefficient of determination of 33.93%, which means that the density of earthworm population has an effect of 33.93% on the SFI of rice fields with various kinds of management with the regression equation (4):

$$y = 0.60551 + 0.1527x \quad (4)$$

Remark: y= SFI
x= Earthworms population density

Based on equation (4), the regression coefficient is positive. This means that every time there is an increase in the population density of earthworms under various management systems, the SFI will also increase. The SFI will increase by 0.1527 if there is an increase of 1 individuals/litre of earthworms in various rice field management systems.

4. Discussion

4.1. The Distribution of Soil Fertility Index (SFI) of Rice Fields Under Different Farming Systems

The SFI has different values depending on the soil's chemical properties. According to Chen et al. (2020) soil chemical properties are influenced by several factors among them are natural factors and human factors. Topography, climate, and soil formation are natural factors that cause differences in soil chemical properties. Humans can affect soil chemical properties through irrigation, fertilization, soil management, and plant species selection. Bagherzadeh and Gholizadeh (2018) categorized the soil fertility index into five classes: very low (0.00–0.25), low (0.25–0.50), medium (0.50–0.75), high (0.75–0.90), and very high (0.90–1.00).

In the research area, the highest average SFI is found in organic rice fields, with an index of 0.66. The middle average SFI found in semi-organic rice fields managed with the system has an index of 0.63. The lowest average SFI is found in inorganic rice fields systems with an index of 0.59. The higher SFI in organic farming rice fields than inorganic is in line with the findings of research undertaken by Prastiwi et al. (2021). According to Widijanto et al. (2021) the high and low soil fertility index depends on the soil management carried out and the chemical properties of the soil. The application of organic materials as input in agricultural production can increase the SFI compared to without the use of organic materials, in line with the data from the research conducted. It is because organic fertilizers contain more nutrients and there is an increase in better soil physicochemical conditions, such as enhancing CEC, availability of nutrients for plants, and soil health. According to Akhmad et al. (2018), Meilani et al. (2023), and Wisnubroto et al. (2021) the availability of macronutrients such as high N and P in the soil can enhance soil fertility and affect the high productivity of plants.

The land characteristics factor in the form of slope did not impact the soil fertility index in the research area (p-value = 0.419, $p > 0.05$). This result can be caused by the rice fields' terracing system on sloping area (>0%). According to Surjandari et al. (2021), terracing is a form of conservation construction as an effort to reduce the slope. The purpose of terraces is to minimize surface runoff, the erosion of soil, and increase water absorption. The reduction of slope length on terraced land can minimize surface flow. As a result, nutrient loss due to surface flow can be minimized (Mustikasari et al., 2018).

4.2. Key indicators of Soil Fertility Index (SFI)

Indicators significantly correlated with the soil fertility index can also be shown to be indicators that determine soil fertility (Mujiyo et al., 2022). The highly significant positive correlation between organic C and soil fertility index (r=0.627) indicates that the higher the organic C value in rice soil, the higher the SFI. Gunawan et al. (2019) stated that soil organic C can serve to enhance soil properties, so the value of soil organic C can affect soil fertility.

In addition to organic C, another indicator that determines soil fertility is available P. Based on the analysis result, there is a significant correlation between available P and soil fertility. Based on the analysis result, there is a significant positive correlation between the value of available P and the soil fertility index (r = 0.502) which means that an increase will follow any increase in the value of available P in the SFI. According to Widijanto et al. (2021) the soil available P indicator is also included in the indicator determining the SFI. According to Penn and Camberato (2019) stated that high soil pH increases soil and plant P uptake, but decreases the availability of soluble P in the soil. P nutrients can be available to plants if the soil pH is around 6–7. At pH < 6 the availability of P nutrients becomes low because it can be bound with Al and at pH >7 the availability of P nutrients also becomes low because it can be bound with Ca.

Another indicator that determines soil fertility is Al saturation. The Al saturation value is highly significantly negatively correlated with the soil fertility index (r = –0.676) which means that the higher the Al saturation value, the lower the soil fertility index. Al saturation value is important in assessing soil fertility. According to Baquy et al. (2018) besides being a limiting factor in plant growth, the presence of Al in the soil can also affect the availability of nutrients needed by plants, such as P, K, Ca, and Mg. The presence of Al can bind P nutrients. The high value of P nutrient availability can occur if the activity of Al^{3+} ions decreases.

Exchangeable bases are also a determining factor of the soil fertility index. According to Baquy et al. (2018), exchangeable bases, such as Ca and K can reduce the Al content that can poison plants. These nutrients not only play an important role in plant growth but also in determining soil fertility. Gunawan et al. (2019) also stated that the balance of soil fertility is also determined by exchangeable bases such as calcium, magnesium, and sodium. Exchange bases can affect the availability of other nutrients, such as nutrient P.

Soil cation exchange capacity (CEC) is also significantly correlated with the soil fertility index (r = 0.812) which means that the higher the cation exchange capacity value, the higher the SFI. The significance of this correlation makes the cation exchange capacity indicator one factor that determines the SFI. Jawang (2021) states that cation exchange capacity is an indicator that plays a role in determining soil fertility because this indicator determines the provision of nutrients for plants. The amount of cations that plants can exchange and absorb is determined by the amount of soil colloids. Soil with a high cation exchange capacity value makes many nutrients available to plants.

4.3. The distribution of earthworms population density under different farming systems of rice field

The average tendency for the highest earthworm population density was found in organically managed rice fields although not significantly different from the other two management systems. This can be caused by the higher organic matter content of organic rice fields compared to semi-organic and inorganic rice field, which is supported by a close positive correlation between soil organic C content and earthworm population density. According to Edwards and Arancon (2022) earthworm populations are effected by organic matter content because earthworms survive by eating organic matter.

The rice field farming systems was not significant to the number of earthworm populations. There is no significant difference in the three types of rice field farming systems that several things can cause. Based on the results of research conducted by Afgani et al. (2018), the application of agrochemicals such as Urea fertilizer or nitrogen fertilizer and without Urea fertilizer (0 kg/ha) had earthworm density that were not significantly different. Long et al. (2017) also stated that the input of fertilizers, such as Urea fertilizer on clay soil has a small effect on earthworm populations, for example, there is only 1 earthworm death in the application of a dose of Urea 200mg/kg of soil. According to Werdhyastuti et al. (2018), earthworms are more susceptible to the input of agrochemicals such as synthetic pesticides that can be toxic to them so that they can reduce the worm population. However, based on the results of interviews at the research site, especially with farmers who manage their rice fields inorganically, farmers very rarely spray synthetic pesticides and have never given synthetic pesticide inputs during the planting period when sampling was carried out, so that earthworm population density was not significantly affected by the application of different rice field farming systems. In addition to these factors, the period of implementation of organic management at the research site, which has only been implemented for approximately 2 years, since 2020, also has the potential to have an impact on the research results obtained. According to Chabert and Sarthou (2020) and Kurniawan et al. (2023) on agricultural land, changes to the management system take several years to create an ecological balance and provide services to the land ecosystem.

4.4. The relationship between earthworms population and soil fertility

The abundance of earthworms is positively correlated to soil C-organic content (r = 0.425). The higher content of soil organic matter, the higher the number of earthworm populations. An increase in organic matter content support the growth and abundance of earthworms population. Organic matter content was supported as a source of food for earthworms, also provide a stable environment as they consume plant material and create casts form differently sized aggregates. A similar outcome by research findings by Angst et al. (2017) showed that the stabilization of organic matter in the soil greatly determines earthworm populations, especially in decomposition activities.

Based on the correlation test, in addition to being significantly positively related to soil organic carbon, earthworm population density is also significantly positively correlated with available P content (r = 0.489). Rice fields with a high fertility index content also has a high available P content. Statistically, the highest soil fertility is in organic rice fields compared to semi-organic and inorganic rice fields. High soil fertility values are also related to high earthworm populations, so we conclude in this case study that earthworms population density is related to available P content.

In agreement with the findings of research undertaken by Li et al. (2019) which produced data showing that the presence of earthworms can have a good effect compared to the no presence of earthworms, which can enhance soil nutrients availability, such as available phosphorus and total nitrogen in the soil. Research conducted by Cheng et al. (2021) showed the data of the changes in earthwoms mass and the impact of earthworms on soil fertility under cadmium (Cd) contaminant soil. Earthworm activities contribute to the decomposition of organic matter and nuttrient cycling, increasing soil nitrogen, phosphorus, and potassium (Nurhidayati et al., 2021). Residues from earthworm activity supply nutrients to microbes in the soil, which then release dissolved phosphate so that phosphorus availability increases. Indirectly, it shows that earthworms can enhance soil fertility by promoting nitrogen mineralization and increasing the levels of readily available phosphorus.

The earthworm population density under different rice field farming systems was also significantly correlated with the soil fertility index (r = 0.582). The higher the earthworms population density, the higher the soil fertility index. Earthworms can enhance soil nutrients availability that plants need. The findings of research conducted by Cheng et al. (2021) also stated that the presence of earthworms can increase soil fertility through their mechanism of increasing available P, total soil N, and available K. Apart from increasing nutrient availability the presence of earthworms can increase other soil fertility parameters, such as the soil CEC value. In addition, according to Ahmed and Al-Mutairi (2022) earthworms have several ways to improve soil fertility. For example, by carrying nutrients into deeper soil layers.

Based on the research result, differences in rice field slopes do not significantly impact the density of earthworm populations (p-value = 0.653, $p > 0.05$). A non-significant effect of slope on earthworm population density can be caused by organic C levels on each slope that are not significantly different due to the presence of vegetation or the same soil cover, namely in the form of rice plants. According to Edwards and Arancon (2022) earthworm populations are effected by organic matter content because earthworms survive by eating organic matter that can be used as a source of food.

Climatic conditions and soil moisture are relatively similar on each slope, which can also cause earthworm populations to not differ significantly. Briones and Schmidt (2017) stated that soil conditions more influence the presence of earthworms as a place for earthworms to live, such as temperature, soil pH (>5.5), and soil texture. Another reason is that soil pH on various slopes of rice fields is also not significantly different. Various slopes of rice fields have a pH above 6, so that earthworms can continue their lives.

4.5. Recommendations on strategies for improving soil properties and increasing soil fertility of the sustainable agriculture

Based on the findings of this research such as soil chemical properties, soil fertility index, and earthworm population density, better management of rice fields is still needed so that rice field soil fertility can increase and be sustainable. Increased soil fertility is intended to support good and sustainable rice productivity. According to Reganold and Wacher (2016) by the application of organic farming, we will not only achieve sustainability of the agricultural system. Organic farming also reduces agricultural waste, providing benefits for soil health and the environment (Mujiyo et al., 2022).

Based on the determinants of soil fertility, indicators of organic C, available P, cation exchange capacity, exchangeable bases need to be increased and indicators of Al saturation need to be decreased. According to He et al. (2018) organic C is the core parameter of soil fertility. The more organic C input, the more soil fertility will increase. Soil organic C concentration can be increased by further improving the quality and quantity of organic fertilizer inputs in rice fields. Organic materials such as cow manure can be composted before being applied as organic fertilizer.

Another indicator that needs to be improved is the level of soil available P. Increasing P nutrients can be done by applying fertilizer inputs that contain P nutrients. We recommend type of fertilizer is manure. Research conducted by (Panhwar et al., 2020) showed that the biochar and biofertilizer application treatment resulted in available P content in the soil (32.43 mg/kg), bacterial population (7.23 $\log_{10}$ CFU per gram), straw husk residues (0.15%), and rice grains (0.32%) with the highest values compared to the application limestone and control.

The value of soil cation exchange capacity ranged from 13.08 me/100 g of soil (low) in inorganic farming to 22.27 me/100 g of soil (medium) in organic farming, while according to the research results of (Domingues et al., 2020) show that biochar provides a positive effect with one application, namely high soil CEC results which may be due to the separation of carbon lamellae during pyrolysis through oxidation of cross-linked C atoms. There are management recommendations that farmers can follow, that is by providing input of organic materials with higher quality and quantity. Research by (Karanja et al., 2019) compared the CEC content with the application of compost made from chicken manure and donkey manure. The soil with the highest CEC value, namely 25.25 ± 2.90 Cmol/kg) was produced by compost treatment made from chicken manure and was much higher and different compared to the control treatment and donkey manure ($p = 0.005$). This is because humic acid as the main component of compost plays a role in binding positively charged multivalent ions.

Soil exchange bases are in the low category and there is Al saturation in the very low category. The content of soil exchange bases can be increased and Al saturation can be reduced by applying organic matter to rice fields. The study by Slavich et al. (2013) found that the application of manure biochar (FM) increased total pasture productivity by 11% and improved the agronomic nitrogen use efficiency by 23%. It also reduced soil acidity but did not significantly affect the pH-dependent soil cation exchange capacity (CEC).

The ratio of C and N influences the quality of organic fertilizer. The applied manure should have a C/N ratio value of not more than 20 and not less than 12 (Afonso et al., 2021). According to Trivana and Pradhana (2017) the ratio of organic carbon to nitrogen contained in organic matter is the proportion between the high and low content of carbon elements and the high and low content of nitrogen elements. Microorganisms need the elements carbon and nitrogen to sustain their lives. Reduced microorganism activity can occur if the C/N ratio value is high so that the time required for composting is also longer and the quality of the compost produced is also lower. Otherwise, if the C/N ratio is too low or excess nitrogen cannot be assimilated, it can be denitrified.

Organic materials to be applied should already have perfect maturity. According to Hanuf et al. (2020) perfectly ripe organic matter has physical characteristics of being dark brown, no odor, crumbly structure, room temperature, and a maximum C per N ratio of 20. The maturity of organic matter can be accelerated by adding bioactivators and by chopping straw.

5. Conclusions

Determining soil fertility in various rice farming systems by assessing soil chemical aspects and evaluating the condition of sustainable land use using earthworm bioindicators is important for obtaining information on soil fertility data to provide appropriate management recommendations to create optimal conditions for sustainable plant growth. In conclusion, different rice field management systems have a very real impact on

SFI, but do not have a significant impact on earthworm population density. However, it was found that there was a very significant relationship between soil fertility and earthworm population density. Management recommendations that can be given to increase the soil fertility index include providing organic material input of higher quality and quantity. Therefore, farmers and paddy field stakeholders who implement inorganic management systems must be able to gradually switch to implementing semi-organic or organic farming systems to increase earthworm population density and soil fertility index in a sustainable manner so that soil productivity can increase sustainably as well.

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