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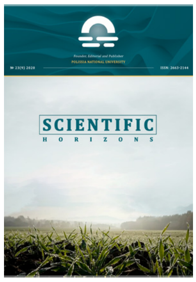

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Soil physical health under different farming systems of rice fields and its effect on rice (*Oryza sativa* L.) productivity

Ganjar Herdiansyah*
Lecturer
Sebelas Maret University
57126, 36 Ir. Sutami, Surakarta, Indonesia
https://orcid.org/0000-0001-5841-4642
Mujiyo Mujiyo
Professor of Pedology and Soil Survey
Sebelas Maret University
57126, 36 Ir. Sutami, Surakarta, Indonesia
https://orcid.org/0000-0002-6161-7771
Aktavia Herawati
Lecturer
Sebelas Maret Universitas
57126, 36 Ir. Sutami, Surakarta, Indonesia
https://orcid.org/0000-0001-5278-8811
Hanindyo Bramastomo
Undergraduate Student
Sebelas Maret University
57126, 36 Ir. Sutami, Surakarta, Indonesia
https://orcid.org/0009-0009-3828-0531

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Abstract. Soil physical health was affected by several factors including farming systems, and the plant growth and soil productivity were directly affected. The study of soil physical health in different farming systems will help manage soil and water used processes. The purpose of this study was to determine the effect of the paddy field management system on soil physical health status, to identify determinants of soil physical health status, and to formulate appropriate management solutions to improve soil physical health. This study employed descriptive, explorative, and survey approaches with purposive sampling methods in soil sampling. The findings showed that the physical health status of soil on paddy fields in the Tirtomoyo District was classified into moderately healthy and healthy categories. Differences in the management system of paddy fields affect soil physical health. Organically managed rice fields have the highest soil physical health value of 76.69. Semi-organic and inorganically managed paddy fields have lower health values of 71.48 and 69.11,

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*Corresponding author

respectively. Soil penetration resistance, soil porosity, and soil texture are determining factors because they can improve indicator conditions and soil physical health values. Efforts can be made to improve soil physical health status by applying organic fertilisers and biochar to paddy fields. Having established the relationship between soil physical health values and rice yield productivity, it is anticipated that farmers and stakeholders will be able to increase crop productivity through improving soil physical condition

Keywords: determinant factors; farming system; organic carbon; rice yield; soil penetration; soil porosity

INTRODUCTION

Soil health is essential in maintaining biodiversity and sustainable agricultural production. Soil health can be defined as the ability of soil to function sustainably in maintaining soil productivity, air, and water quality in the environment, and improving plant, animal, and human health. Soil with good physical conditions such as crumb structure, optimal porosity, and efficient drainage will help maximise the absorption of nutrients and water by plant roots, as well as making soil and plants integrated with each other in adapting to micro and macro climate changes in rice fields, thereby minimising land degradation and the risk of farmer losses (Pahalvi *et al.*, 2021). To achieve agricultural productivity, food security, and environmental sustainability, the physical health of the soil is a crucial aspect that needs to be studied because of its fundamental impact.

The assessment of soil health is investigated in various aspects, including soil physical properties (Simarmata *et al.*, 2020). Poor physical soil health has resulted in various problems in Indonesia. Low soil physical health leads to poor soil structure conditions, such as low percentage of pore space, limited drainage, and water infiltration. This affects plant health and productivity by restricting plant root growth and nutrient uptake. The inundation of rice fields makes the soil aggregate characteristics of rice fields different from those of dry land. The findings of H. Tang *et al.* (2020) show that soil and land processing factors greatly influence soil aggregates in rice fields. Soil health research has developed various methods such as assessment using VSA (Visual Soil Assessment) and vertical soil physical health assessment methods using VNIR, ECa data, and penetration resistance sensors. Research conducted by M. That *et al.* (2020) produced data that soil health on organic land can reduce NO3-, P, K, Mg2+, and increase Ca2+ compared to conventional cultivation systems, while simultaneously increasing soil respiration significantly by 20 times. H. Williams *et al.* (2020) stated that soil health on agricultural land with intensive management is lower than on land without tillage or with minimal tillage. Conservation farming systems and the addition of organic matter can improve the physical health of the soil.

The continuous use of chemical fertilisers will increase the accumulation of chemical residues in the soil, polluting the soil ecosystem (Rabot *et al.*, 2018). Inorganic farming practices are still quite common in Indonesia, one of which is in the Tirtomoyo District, Wonogiri Regency, Central Java Province. In 2018, Tirtomoyo District became the 4th highest rice-producing area in the Wonogiri Regency and supports the value of rice production in Central Java province (Central Bureau of Statistics, 2022). However, in the last 2 years, in 2021 and 2022, the harvested area and rice production have decreased, with the harvested area decreasing from 1.70 million hectares (in 2021) to 1.69 million hectares (in 2022), and rice production decreasing from 9.62 million tonnes (in 2021) to 9.36 million tonnes (in 2022). This condition necessitates the assessment of the physical health of the soil on rice fields in Tirtomoyo District. Evaluation of the physical health of the soil is expected to maintain and increase rice production in Tirtomoyo District. The study suggests that maintaining soil health is a crucial factor in achieving sustainability goals and should be considered as an ongoing process.

Research conducted by J. Lehmann *et al.* (2020) on soil health highlights the significance of soil health to strike an environmentally and economically sustainable balance. The role of technology and data analysis in advancing soil health is also important. M. That *et al.* (2020) found that soil health in the organic field has an improvement compared to inorganic fields and can economically address global food demands. These researchers assume that the soil farming system will influence the level or status of the soil physical health and impact the productivity of rice crops in rice fields (case study in Tirtomoyo District, Wonogiri, Indonesia). Generally, the physical health of the soil, such as water retention and the structure of rice fields, will be different from other land uses. The other objectives of the study are to find the relationship between the farming system, the physical health of the soil, and the productivity of rice yields, and innovative approaches to establishing the determining factors of the soil physical health. This purpose of this study was to examine how paddy field management affects soil health, identify its determinants, and develop strategies to enhance soil physical well-being.

MATERIALS AND METHODS

Study area description. This study was conducted in Tirtomoyo District, Wonogiri Regency, Central Java Province rice fields. Geographically, Tirtomoyo District is located at 111°0'14.32" – 111°8'57.39" E and 7°54'31.45" – 8°0'54.03"S with an altitude of 150 to 1,100 m above sea level. Hilly areas surround the

Tirtomoyo District, which is divided into two by the Wiroko River (Mujiyo *et al.*, 2018).

Pre-survey. The unit of analysis is based on the Land Map Unit (LMU) overlay results from maps of soil type, slope, rainfall, and rice field farming systems in the Tirtomoyo District using ArcGIS 10.3 software. The soil type found in the area der study is Inceptisols. The slope is categorised into flat (0-8%), sloping (8-15%), slightly steep (15-25%), steep (25-45%), and very steep (>45%) (Fig. 2). Rice field farming systems in Tirtomoyo District consists of organic, semi-organic, and inorganic rice fields (Fig. 1).

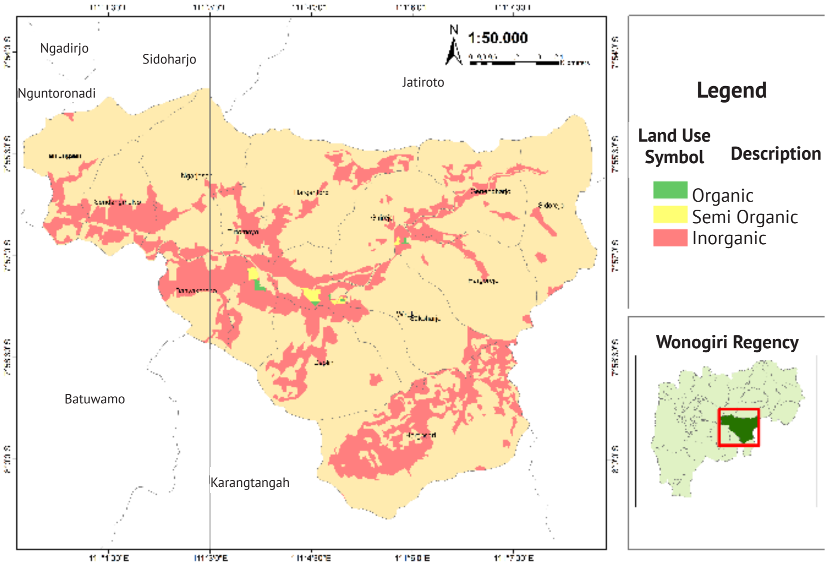

***Figure 1**. Map of rice fields farming system*
***Source:** Indonesian Seamless Digital Elevation Model (DEM)*

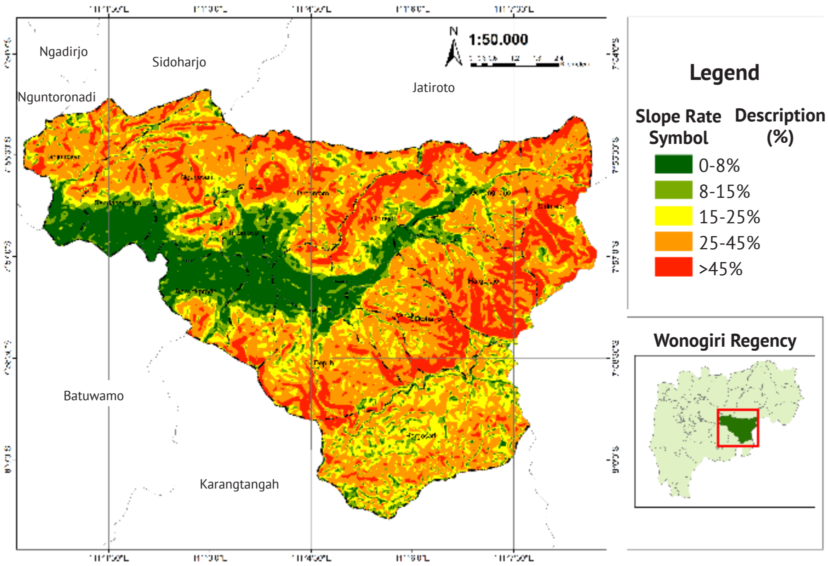

***Figure 2**. Map of slope*
***Source:** Indonesian Seamless Digital Elevation Model (DEM)*

Purposive sampling methods were arranged to determine the sample points for each LMU. It is proportional and in a representative area. This study investigated 30 sample points from the results of 10 LMU with 3 replicates (Fig. 3). Land characteristics for each LMU are presented in Table 1. Soil samples were taken at rooting depth (1-20 cm) for each point, which were then used for laboratory analysis. Parameters of soil effective depth, soil penetration resistance, and crop productivity were carried out directly in the field. Soil effective depth was measured using the soil drill method, penetration resistance – using the penetrometer method, and crop productivity – using the 1×1 m *ubinan* method (Arinta & Lubis, 2018).

***Table 1**. Characteristics of LMU in the area under study*

Soil Type	Farming Systems	Rainfall (mm year^{-1})	The degree of Slope (%)
Inceptisols	Inorganic	2,119.9	0-8%
Inceptisols	Inorganic	2,119.9	8-15%
Inceptisols	Inorganic	2,119.9	15-25%
Inceptisols	Inorganic	2,119.9	25-45%
Inceptisols	Inorganic	2,119.9	>45%
Inceptisols	Organic	2,119.9	0-8%
Inceptisols	Organic	2,119.9	8-15%
Inceptisols	Semi organic	2,119.9	0-8%
Inceptisols	Semi organic	2,119.9	8-15%
Inceptisols	Semi organic	2,119.9	15-25%

***Source**: secondary data (Digital map and field survey)*

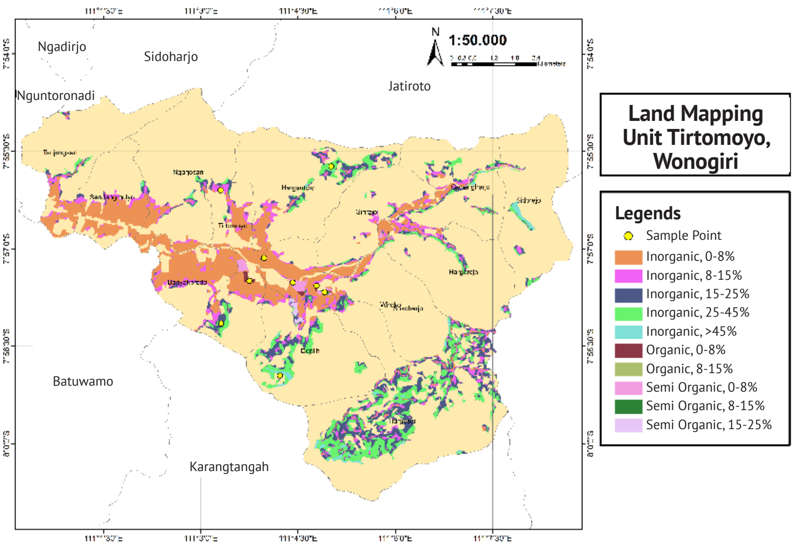

***Figure 3**. Field observation and sampling point of the study*

***Source:** secondary data*

Laboratory analysis. Soil samples taken from the field were then dried for laboratory analysis. Analysis of research parameters refers to the technical guidelines of the Soil Research Institute (2006). The parameters observed were texture (by pipette method), moisture content (by gravimetric method), porosity (by pycnometer method), permeability (by permeameter method), and organic carbon (according to the method suggested by A. Walkley and C.A. Black (1934).

Soil physical health status determination. Soil physical health analysis using the method suggested by B.N. Moebius-Clune *et al.* (2017) was modified according to concrete research conditions. This study used 6 indicators of soil physical health: soil texture, permeability, penetration resistance, effective depth, moisture content, and porosity. Indicators in each replicate at each LMU were entered into a scoring table (Table 2), calculated, and categorised according to soil health values (Table 3).

***Table 2**. Scores of the soil physical health indicator*

No.	Indicators	Very Low	Low	Medium	High	Very High
		Score 1	Score 2	Score 3	Score 4	Score 5
1.	Soil texture(1)	S, C, Si	SiC	SiL, SC	LS, SiCL, SCL	L, SL, CL
2.	Permeability (cm/h)(2)	<0.025-0.125	0.125-0.5	0.5-2.0 and >25	2.0-6.25 and 12.5-25	6.25-12.5
3.	Soil Penetration Resistance (kg/cm^2)(3)	>1.5	1.4-1.5	1.2-1.3	1-1.1	<1
4.	Soil Effective Depth (cm)(4)	<10	10-25	25-50	50-90	>90
5.	Moisture Content (%)(3)	31-41	1-3	4-10	11-18	19-30
6.	Total Porosity (%)(5)	<5	5-10	10-25	25-40	>40

***Note:** S=Sand, C=Clay, Si=Silt, SiC=Silty Clay, SC=Sandy Clay, LS=Loamy Sand, SiCL=Silty Clay Loam, SCL=Sandy Clay Loam, L=Loam, SL=Sandy Loam, CL=Clay Loam*

***Sources:** L. Puspitasari (2018); M. Aliero et al. (2018); L. Rachman (2019)*

Table 3. *Classification of soil physical health status*

Soil Physical Health Value	Status
0-20	Very Low
20-40	Low
40-60	Medium
60-80	High
80-100	Very High

Source: *B.N. Moebius-Clune et al. (2017)*

The score results were then included in the calculation of soil health status using the formula 1 according to B.N. Moebius-Clune *et al*. (2017) as follows:

$$\text{Soil Physical Health Value} = \frac{\text{Score Summary}}{\text{Maximum Score}} \times 100\,. \quad (1)$$

Rice yield productivity. Observations of rice plant productivity were carried out at harvest time using the tile technique and calculating the yield of harvested dry grain (*GKP*) at the research location. The tile method is a technique that aims to determine the productivity or crop yield per hectare of rice field (Agoes *et al.*, 2018). The tiling method is carried out by making sampling plots of 1×1 m area on the planted land and the resulting data is converted into t/ha units (Arinta & Lubis, 2018). *Ubinan* calculation was performed according to formula 2.

$$\text{Rice productivity} = \frac{10{,}000\ m^2}{\text{Ubinan total area}} \times \text{weight of dry grain}. \quad (2)$$

Statistical analysis. In this study, researchers used a determining factor approach. Determining factors are those considered to accurately determine the physical health of the soil based on the results of statistical tests. The statistical tests conducted in this study were one-way ANOVA, DMRT, and Pearson's correlation test. One-way ANOVA was used to determine the effect of rice field farming system (organic, semi-organic, and inorganic) on the soil physical health indexes and properties. Furthermore, the relationship between the physical health of the soil and the productivity of rice plants, as well as the determinants of soil physical health (relationships between indicators and the physical health status of the soil) were analysed using Pearson's correlation. Crop productivity sampling was conducted using the method suggested by the Indonesian Central Bureau of Statistics in 2020. Data from the ANOVA analysis and Pearson's correlation were then used as the basis for determining suitable and efficient recommendations for land management in an effort to maintain the health of rice fields' soil. The materials and methods used in this study have followed national guidelines in Indonesia. In addition, researchers referred to the standards requirements and provisions of Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Data and information of soil health status is essential in supporting the growth of plant. Soil physical health contributes to the decomposition of organic matter and the recycling of nutrients. A healthy soil with good physical properties is essential for maintaining a balanced and functioning ecosystem (Guo, 2021). The higher the value of the soil health, the healthier the soil physical condition. Soil physical properties such as texture, permeability, penetration resistance, effective depth, soil moisture content, and porosity influence soil physical health condition. The study results showed that rice fields in the area under study are classified into 2 categories – medium and high. Rice fields with medium category are found in LMU 1 and LMU 2. Other LMUs of the rice fields were classified into high category (Table 4).

Table 4. *Data results of soil physical health in each LMU*

LMU	Replication No.	Indicators Score						Accumulation Score	Status	Rice Productivity (ton/ha)
		T	PE	PR	ED	MC	PO			
			(cm/h)	(kg/cm)	(cm)	(%)	(%)			
1	1	1	2	3	3	4	5	60	Medium	6.75
	2	1	2	4	3	4	5	63.33	High	6.86
	3	5	2	4	3	4	5	76.67	High	7.59
2	1	1	2	3	3	4	5	60	Medium	6.80
	2	1	2	3	3	5	5	63.33	High	6.86
	3	5	2	3	3	5	5	76.67	High	7.44
3	1	5	2	3	3	4	5	73.33	High	7.28

Table 4. Continued

LMU	Replication No.	Indicators Score						Accumulation Score	Status	Rice Productivity (ton/ha)
		T	PE (cm/h)	PR (kg/cm)	ED (cm)	MC (%)	PO (%)			
	2	4	2	3	3	4	5	70	High	7.03
	3	5	2	3	3	5	4	73.33	High	7.34
4	1	5	2	2	3	4	4	66.67	High	6.88
	2	5	2	3	3	5	5	76.67	High	7.45
	3	5	2	2	3	4	5	70	High	7.10
5	1	4	2	2	3	5	4	66.67	High	6.89
	2	5	2	3	3	4	5	73.33	High	7.32
	3	4	2	2	3	4	5	66.67	High	6.98
6	1	4	2	4	4	4	5	76.67	High	7.56
	2	3	2	5	3	5	5	76.67	High	7.58
	3	3	2	4	4	5	5	76.67	High	7.65
7	1	1	2	5	4	4	5	70	High	7.14
	2	4	2	5	4	5	5	83.33	High	7.59
	3	4	2	4	4	4	5	76.67	High	7.61
8	1	1	2	5	3	4	5	66.67	High	6.98
	2	3	2	5	3	5	5	76.67	High	8.02
	3	1	2	4	3	4	5	63.33	High	6.95
9	1	4	2	4	3	4	5	73.33	High	7.96
	2	4	2	3	3	4	5	70	High	7.17
	3	4	2	3	3	5	5	73.33	High	7.88
10	1	4	2	4	3	4	5	73.33	High	7.38
	2	4	2	3	3	4	5	70	High	7.23
	3	4	2	5	3	4	5	76.67	High	8.23

Notes: *T – Texture; PE – Permeability; PR – Penetration Resistance; ED – Effective Depth; MC – Moisture Content; PO – Porosity*
Source: *compiled by the authors of this study*

The analysis results (Fig. 4) suggest that soil physical health significantly correlates with rice productivity (r=0.465; P-value=0.010; n=30). The higher the soil physical health value, the higher the yield productivity of the rice crop. Good soil health will increase crop productivity.

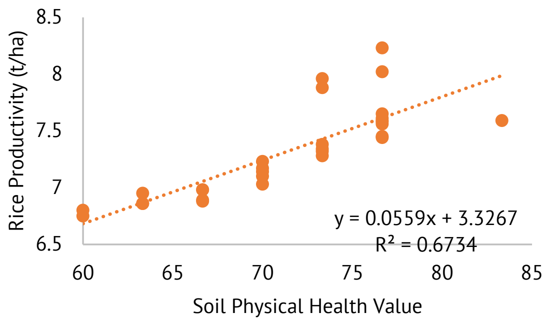

Figure 4. *Correlation of soil physical health index with rice yield productivity*
Source*: compiled by the authors of this study*

The analysis of variance showed that the rice field farming system significantly affects soil physical health status (F=4.569; P-value=0.02; n=30). Organic rice fields have the highest average soil health with 76.69, while inorganic and semi-organic rice fields have an average of 69.11 and 71.48 (Fig. 5).

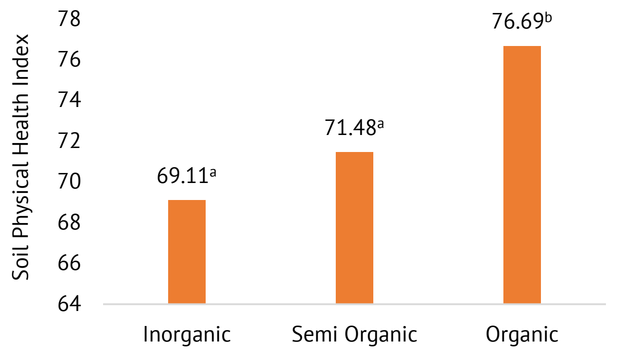

Figure 5*. Effect of rice field farming system on soil physical health*
Note: *different letters on the chart are significantly different values in the 5% level of DMRT*

The differences in average values of soil physical indicators are presented in Table 5. Another factor that can directly or indirectly affect soil and physical health indicators is the organic carbon content in the soil. Organic carbon is important in supporting sustainable agriculture since it can improve the physical properties of the soil. Based on the analysis of variance, the farming system significantly influenced organic carbon in the soil and several physical characteristics such as penetration resistance (F=12.765, P-value=0.000, n=30), effective depth (F=42.528, P-value=0.000, n=30), and porosity (F=18.071, P-value=0.000, n=30).

***Table 5**. Effect of rice field farming system on soil physical health properties*

Parameter	Rice field System		
	Organic	**Semi-organic**	**Inorganic**
Organic carbon	1.53a	1.32b	1.19c
Soil penetration resistance	0.88b	0.97b	1.28a
Soil effective depth	56.67a	39.44b	38.67b
Soil porosity	46.39a	44.36b	42.43c
Soil permeability	0.34a	0.34a	0.37a
Soil moisture content	19.59a	17.39a	18.79a

***Note:** numbers followed by the same letter are not significantly different at the 5% of Duncan's test*
***Source**: compiled by the authors of this study*

Correlation tests between soil physical health indicators and soil physical health values were conducted to establish the determinants of soil physical health (Table 6). The correlation test results showed that indicators of penetration resistance, porosity, and texture determine soil physical health. Soil physical health was significantly correlated with penetration resistance (r=-0.424; P-value=0.019; n=30), porosity (r=0.473; P-value=0.046; n=30), and soil texture (r=0.627; P-value=0.000; n=30).

***Table 6.** Correlation between soil physical health indicators and soil physical health (as determinant factors)*

	Soil Texture	**Permeability**	**Soil Penetration Resistance**	**Soil Effective Depth**	**Moisture Content**	**Porosity**	**Organic Carbon**	**Soil Physical Health**
Soil Texture	1							
Permeability	0.261	1						
Soil Penetration Resistance	0.330	0.205	1					
Soil Effective Depth	-0.055	-0.330	-0.330	1				
Moisture Content	-0.078	-0.083	-0.083	0.044	1			
Porosity	0.032	-0.147	-0.471**	0.589**	-0.266	1		
Organic Carbon	0.387*	-0.052	-0.380*	0.507**	0.240	0.046	1	
Soil Physical Health	0.627**	0.047	-0.424*	0.336	0.181	0.473**		1

***Source:** compiled by the authors of this study based on data analysis*

Efforts to improve soil physical health are focused on improving the conditions of determinant factors, including penetration resistance, porosity, and texture. Based on the study results presented in Table 4, soil physical properties are distributed in various values. Soil texture in each replication at each LMU provides a variety of values. Soil texture with the lowest value was found at LMUs 1, 2, 7, and 8, namely clay with a value of 1. Soil texture with the highest value was found at LMUs 1, 2, 3, 4, and 5, namely sandy loam and loamy sand with a value of 5. The effects of farming systems on soil texture in fields are complex and depend on factors such as the presence of plants, soil texture, and the addition of organic matter (Bacq-Labreuil *et al.*, 2018). These factors interact to influence the diversity of pore sizes, porosity, and pore connectivity, ultimately affecting water availability, nutrient uptake, and overall soil health.

Soil permeability in all LMUs under study had the same values, categorised as 2. Permeability in paddy fields in Tirtomoyo District ranges within 0.26-0.44 cm/h (Table 4). Soil permeability with a value range within 0.0125-0.5 cm/h is included in the slow category. Permeability is related to soil texture. Soil permeability is classified as very slow, and in some LMUs, the soil is classified as clay. This is in line with the findings of F. Louati *et al.* (2018), which explain that soil permeability is at a very slow level with a high proportion of clay. Soil penetration resistance values tend to vary from 0.5 to 1.5 kg/cm. Soil penetration resistance with a score of 2 was found at LMUs 4 and 5. Penetration resistance with the highest score of 5 was found at LMUs 6, 7, 8, and 10 (Table 4). Soil penetration resistance indicates whether or not the soil is easy for plant roots to penetrate. The easier it is to penetrate the soil, the smaller the penetration resistance value.

The highest effective soil depth was found in LMUs 6 and 7 at 60 cm with a score of 4, while effective soil depth with a score of 3 was found in all LMUs except LMU 7 (Table 4). Soil moisture content in the Tirtomoyo District ranges within 12.04-26.01%. Soil moisture content with a score of 4 was found in all LMUs, while soil moisture content with a score of 5 was found in LMUs 2, 3, 4, 5, 6, 7, 8, and 9 (Table 4). Soil moisture content is better in soil with high organic matter than soil with low organic matter. Organic matter in the soil enables better infiltration and retention. It acts as a sponge, holding water and making it available to plants. This results in higher soil moisture content (Tokova *et al.*, 2020). Soil porosity in Tirtomoyo District ranges within 40.97-47.27%. Soil porosity with a score of 4 was found at LMUs 3, 4, and 5, while the rest of LMUs porosity had the highest score of 5 (Table 4).

Rice productivity in the area under study had various values, ranging within 6.75-8.23 t. The highest rice productivity was at LMU 10 with 8.23 t, while the lowest was at LMU 1 with 6.75 t (Table 4). Rice field system affects rice productivity. Using organic fertilisers positively affects rice productivity since it improves soil properties. According to M. Salam *et al.* (2021), using organic fertilisers can increase rice plant production by 16.67%. The study results showed that organic farming and semi-organic farming of rice fields have higher productivity than inorganic fields. Organic rice fields have a productivity of 7.52 t/ha and semi-organic – 7.53 t/ha, higher than inorganic rice fields with 7.1 t/ha. According to P. Gao *et al.* (2023), combining organic and inorganic fertilisers is better for maintaining and increasing crop yields. Semi-organic rice fields have high productivity because it gets inputs from organic and inorganic fertilisers, and therefore rice plants' macro and micronutrient needs can be satisfied.

An analogous study was conducted by I. Chahal *et al.* (2021), where soil health indicators were positively correlated with crop productivity. Proper soil structure and aeration are essential for root development and nutrient uptake, ultimately contributing to higher yields. Additionally, well-structured soil helps in water infiltration and retention, reducing the risk of waterlogging or drought stress (Goswami *et al.*, 2020). On the other hand, compacted or poorly drained soil can hinder root growth, nutrient availability, and water movement, leading to lower rice yields. Therefore, maintaining favourable soil physical conditions through residue incorporation and reduced tillage can enhance rice productivity. Index values in organic farming are the highest. Soil physics indicators in organic farming have better conditions than in semi-organic and inorganic farming. Soil physical health properties are essential for improving soil health to achieve maximum productivity. Increased values of soil properties in organic rice fields are due to the provision of organic matter in higher fertilisers than in semi-organic and inorganic rice fields.

Farming systems in the area under study significantly differ in soil physical health values and properties such as organic carbon content, penetration resistance, effective depth, and porosity (Table 5). Organic rice fields had the highest organic carbon content, with an average of 1.53%, while inorganic rice fields had the lowest average organic carbon content with 1.19%. Semi-organic rice fields have a moderate organic carbon content of 1.32% (Table 5). Organic farmers promote the growth of diverse plant species and encourage the accumulation of organic matter in the soil. This organic matter, such as plant residues and animal manure, the decomposition process is influenced by the presence of soil fauna. The activity of soil fauna in organic farming systems can enhance the decomposition process, releasing nutrients essential for plant growth (Frouz, 2018). This is in line with the earlier study conducted by Supriyadi *et al.* (2020), which found that different treatments on organic and inorganic rice fields affect the organic carbon content. According to J. Gerke (2022), providing organic matter in the soil positively affects the organic carbon content. Organic rice fields have the highest organic carbon content compared to semi-organic and inorganic rice fields due to the application of higher organic fertilisers during management.

The rice field farming system has a significant effect on soil penetration resistance. Inorganic farming had the highest average penetration resistance of 1.28 kg/cm^2, while semi-organic fields had a lower average of 0.97 kg/cm^2. Organic fields had the lowest average of penetration resistance at about 0.88 kg/cm^2 (Table 5). According to J. Zemke *et al.* (2020), soil penetration resistance is a critical property that supports plant root growth and is influenced by the soil's organic matter content. In line with research conducted by J. Filho *et al.* (2022), soil organic matter content affects soil penetration resistance. especially when the soil is in a dry condition.

Organic rice fields have the highest average effective depth of 56.67 cm, significantly different from inorganic and semi-organic rice fields with an average effective depth of 38.67 cm and 39.44 cm, respectively (Table 5). This is because rice plants' roots in organic fields are stronger than in semi-, and inorganic fields. The root system of rice crops on organic farming can reach deeper areas due to longer and stronger roots. This condition has a positive impact on plant growth and productivity, as it allows for the absorption of nutrients. High availability of nutrients in organic-rich allowing for better root penetration and exploration of the soil profile. According to A. Jayasekara *et al.* (2022), organic matter input in rice fields can increase the depth of plant roots. That proves organic rice fields have a greater effective soil depth than inorganic and semi-organic rice fields. Deeper effective soil depth is explained by higher organic matter in organic rice fields. Providing organic materials in solid and liquid organic fertilisers can increase the effective depth of the soil. According to I. Wedhana *et al.* (2018), soil with a shallow effective depth will inhibit the development of plant roots. The deeper effective depth of the soil will positively affect the movement of rice plant roots. Soil that is easily penetrated will provide best growing space for plants. The combination of fertiliser application increased soil organic carbon (SOC), leading to improved soil aggregate and decreased soil bulk density.

Organic rice fields have the highest soil porosity value, averaging 46.39%. Inorganic rice fields have the lowest soil porosity value, with an average of 42.43%, while semi-organic rice fields have an average of 44.36% (Table 5). The three rice field farming systems have significantly different soil porosity values when compared to each other. The difference in porosity value is caused by applying organic fertiliser on organic and semi-organic paddy fields. According to D. Holthusen *et al.* (2018), soil porosity is influenced by differences in farming system. The study results proved that the rice field farming systems have significantly different soil porosity values when compared to each other. Organic rice fields have higher total porosity than semi-organic and inorganic rice fields. According to H. Fang *et al.* (2021), the provision of organic matter can affect soil porosity through several aspects, such as increasing soil aggregate stability, reducing soil compaction, and improving soil structural conditions. The difference in porosity value is caused by the provision of organic materials in solid and liquid fertilisers, which are higher in organic rice fields. Using organic fertilisers can increase the total porosity in the soil because decomposed organic matter in the soil will produce aggregates that are beneficial to soil porosity.

Determinant factors of soil physical health include soil texture, penetration, and porosity (Table 7). The higher the penetration resistance value, the lower the soil's physical health status. Low penetration resistance indicates that it is easier for roots to penetrate the soil to obtain nutrients, and therefore it can improve the physical health status of the soil. High values of soil penetration resistance are commonly found in soil with compact condition. A low compaction indicates better water holding capacity and lesser soil erosion potential. However, many factors determine soil physical health, such as particle size distribution, pore volume, hydrophobicity, and pore connectivity (He *et al.*, 2021). Therefore, it is essential to consider other indicators and factors when evaluating soil health, rather than relying solely on soil bulk density. Soil compaction relates to soil porosity. Low value of soil compaction indicates a high soil porosity. The higher the porosity value, the higher the soil physical health. This condition causes good soil porosity conditions to correlate with improved soil physical health status. Soil texture was significantly correlated with soil physical health status (Table 7). According to B.N. Moebius-Clune *et al.* (2017), texture is essential for various processes in the soil. Soil texture affects other soil health indicators. Soils with higher clay content generally have a higher ability to retain nutrients and accumulate soil organic matter. Good soil texture conditions will affect other physical indicators and improve soil physical health status.

The factors are enhanced by increasing the organic carbon content in the soil. The efforts to improve soil physical health will be focused on increasing the organic carbon content in the soil. That is because organic carbon content is significantly correlated with the determinants of soil physical health, namely soil penetration resistance and soil porosity. According to K. Kakar *et al.* (2020), applying organic fertilisers to the soil can improve soil physical properties. That will increase the ability of the soil to hold water and nutrients needed for crop production. According to B. Lei *et al.* (2022), providing organic matter as manure will improve soil health and organic carbon content. Improved soil physical health will indirectly increase the productivity of rice plants. The organic carbon content in rice fields can be increased by applying organic fertiliser from livestock manure or crop residues. An increase in organic carbon content in the soil causes an increase in total soil porosity. The organic carbon content in paddy fields can be increased by applying organic fertilisers from animal manure and crop residues. Organic matter in the form of composted straw and animal manure applied to the soil can increase the organic carbon content in the soil (Yuniarti *et al.*, 2019). Using compost and manure can boost the organic carbon content in the soil. The more organic fertiliser is added to the soil, the more organic carbon content is released.

Another effort to increase organic carbon content in the soil can be made by applying biochar. According to A. Mohammadi *et al.* (2020), biochar application can be used to improve the condition of soil properties. Biochar is organic material burned at temperatures between 300°C and 700°C with low oxygen concentration. Biochar can improve soil physical health through several mechanisms. Biochar has a high porosity and large surface area, which can improve soil water retention and reduce water evaporation. This enhances soil moisture availability for plant growth. Additionally, biochar can improve soil structure and aggregation, leading to better soil aeration and drainage. This can enhance plant root penetration and nutrient uptake. Introducing biochar such as rice husks can increase the organic carbon content in the soil. Increasing the dose of biochar positively correlates with the organic carbon content

(Ebido *et al.*, 2021). Therefore, it is best to use biochar at the beginning and post-harvest of tillage. Previous research has shown that biochar can significantly improve the physical health of the soil by increasing organic carbon content, soil water retention, soil structure and aggregates, and plant root penetration and nutrient uptake.

CONCLUSIONS

Rice fields managed by flooding affect the physical characteristics of rice fields and have an impact on the soil's ability to support plant growth. Low soil physical health conditions will inhibit plants' absorption of water and soil nutrients. Based on the findings of this study, the physical health status of organic, semi-organic, and inorganic rice fields is classified as medium and high (index range within 60.00-83.33). Organic rice fields have the highest physical soil health compared to semi-organic and inorganic rice fields, with respective values for organic rice fields 76.69b, semi-organic rice fields 71.48a, and inorganic rice fields 69.11a. The findings of the study on rice fields suggest that the indicators of soil penetration resistance (r=0.424), soil porosity (r=0.473), and soil texture (r=0.627) greatly determine the soil physical health. Soil health is positively correlated with soil porosity and soil texture that has a high clay content. However, conversely, the lower the soil penetration, the higher the soil physical health. The physical health of the soil is significantly related to determining rice production results r=465). This means that the physical health of the soil determines rice yield production in the area under study. The higher the soil physical health index, the greater the yield. Recommended farming system efforts to overcome the determinants of physical soil health found include expanding the coverage of rice fields with an organic system, or by providing organic fertiliser and biochar during tillage in preparation for planting. Future research in soil physical health, with a focus on sustainable agriculture and environmental protection, has the potential to enhance soil resilience to climate change impacts, such as extreme temperatures, prolonged droughts, and increased flooding. Developing practical tools to assess soil physical health can aid in understanding the complex interactions between physical properties, soil health levels, and optimising crop production through water availability for plant growth.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Фізичний стан ґрунту за різних систем землеробства на рисових полях та його вплив на продуктивність рису (*Oryza sativa* L.)

Ґанджар Гердіансях
Викладач
Університет Себелас Марет
57126, вул. Ір. Сутамі, 36, м. Суракарта, Індонезія
https://orcid.org/0000-0001-5841-4642
Муджійо Муджійо
Професор педології та обстеження ґрунтів
Університет Себелас Марет
57126, вул. Ір. Сутамі, 36, м. Суракарта, Індонезія
https://orcid.org/0000-0002-6161-7771
Актавія Гераваті
Викладач
Університет Себелас Марет
57126, вул. Ір. Сутамі, 36, м. Суракарта, Індонезія
https://orcid.org/0000-0001-5278-8811
Ханіндьо Брамастомо
Бакалавр
Університет Себелас Марет
57126, вул. Ір. Сутамі, 36, м. Суракарта, Індонезія
https://orcid.org/0009-0009-3828-0531

Анотація. На фізичний стан ґрунту впливають декілька факторів, у тому числі системи землеробства, що безпосередньо впливає на ріст рослин і продуктивність ґрунту. Вивчення фізичного стану ґрунту в різних системах землеробства допоможе управляти процесами використання ґрунту та води. Метою цього дослідження є визначення впливу системи управління рисовими полями на фізичний стан ґрунту, виявлення детермінант фізичного стану ґрунту та розробка відповідних заходів для покращення фізичного стану ґрунту. У цьому дослідженні були використані описовий, дослідницький та опитувальний підходи із застосуванням методів цілеспрямованого відбору зразків ґрунту. Результати показали, що фізичний стан ґрунту на рисових полях у підрайоні Тіртомойо був класифікований як помірно здоровий і здоровий. Відмінності в системі управління рисовими полями впливають на фізичний стан ґрунту. Органічно керовані рисові поля мають найвищий показник фізичного здоров'я ґрунту – 76,69. Напіворганічні та неорганічні рисові поля мають нижчі показники здоров'я – 71,48 та 69,11. Стійкість ґрунту до проникнення, пористість і текстура ґрунту є визначальними факторами, оскільки вони можуть покращити індикаторні умови і фізичний стан ґрунту. Можна докласти зусиль для покращення фізичного стану ґрунту шляхом внесення органічних добрив та біомаси на рисові поля. Знаючи взаємозв'язок між показниками фізичного стану ґрунту та врожайністю рису, можна сподіватися, що фермери та інші зацікавлені сторони зможуть підвищити врожайність культури за рахунок покращення фізичного стану ґрунту

Ключові слова: визначальні фактори; система землеробства; органічний вуглець; врожайність рису; проникнення в ґрунт; пористість ґрунту