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Implication of organic farming practice in changes in physical-chemical properties of plough pan layer in paddy soils

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A b s t r a c t. The impacts of organic farming practices on the physical-chemical properties of the plough pan layer in paddy soils are still not well-documented. This study was conducted by making nine soil profiles from three farming systems, namely conventional, semi-organic, and organic fields. The results revealed that the formation of the plough pan layer resulted in an increase in soil penetration resistance, modulus of rupture, and bulk density, while soil porosity and soil permeability decreased. The clay in the layer was composed of kaolinite, nacrite, dickite, with dissolved Fe>Mn>Al. After 10 years of organic farming practice, there was an increase in humic acid, fulvic acid, CEC, Fe-humic, Mn-Humic, soil porosity, and topsoil thickness, while the thickness of plough pan, modulus of rupture, and soil penetration decreased. The Fe-humic and Mn-humic content increased by 4.74 and 2.73 times, respectively, compared to the conventional system. This indicates that humic compounds derived from organic fertilizers play a crucial role in the complexation and dissolution processes of mineral components, resulting in improved soil physical and chemical properties.

K e y w o r d s: conventional-organic system, modulus of rupture, soil organic matter, cation exchange capacity, and Fe-humic

1. INTRODUCTION

The intensive paddy rice cultivation system introduced by the Indonesian Government since the 1970s has led to the persistence of residual agrochemical compounds in the soil. This system often employs puddling, the most common method of lowland rice cultivation in Asian countries, which completely distorts the soil structure of the puddled layer and leads to the formation of a distinct plough pan (Eickhorst and Tippkötter, 2009; Hidayat *et al*., 2019; Al Viandari *et al*., 2022). Kögel-Knabner *et al*. (2010) found that the formation of these Anthrosols is induced by tilling the wet soil (puddling), and the flooding and drainage regime is associated with the development of a plough pan and specific redoximorphic features. When submerged, iron (Fe) and manganese (Mn) oxides are reduced to a more soluble form (Aung and Masuda, 2020; Li *et al*., 2021). These dissolved Fe^{2+} and Mn^{2+} ions then accumulate in the lower B horizon. During dry periods, they re-oxidize and form a crust called concretions, giving the pan a rusty appearance. Over time, this process creates a distinct plough pan

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in the paddy soil profile (Kurniati *et al*., 2016; Li *et al*., 2021; Wei *et al*., 2022). Mechanical compaction from farming equipment and trampling by humans and animals also contributes to plough pan formation (Moormann and van Breemen, 1978; Sander *et al*., 2008; Rahman and Amin, 2023).

Plough pans, characterized by fewer meso- and macropores, hinder rice root development (Trouse, 1979; Islam *et al*., 2021) and impede drainage, leading to waterlogging (Oberthur *et al*., 1997; Sander *et al*., 2008; Liu *et al*., 2003; Rahman and Amin, 2023). In well-structured soils, secondary pores, like those formed by decaying roots and between soil aggregates, control water flow through their size distribution and connectivity (Sander *et al*., 2008, Shi *et al*., 2021). Submerged conditions in paddy soils create a dynamic environment that alters nutrient availability (Kölbl *et al*., 2014; Conklin, 2005; Ponnamperuma, 1985; Grybos *et al*., 2009; Wissing *et al*., 2013; Rahman and Amin, 2023). This is evident in increased dissolved phosphorus, potassium, and silicon (Yoshida, 1981). Over time, these chemical and mineralogical changes lead to the formation of permanent soil profile features like Bir, Bmn, or Birmn horizons. These horizons are diagnostic indicators of iron and manganese reduction-oxidation processes, along with eluviation (movement of elements in solution downwards) and illuviation (deposition of elements lower in the profile) (Wissing *et al*., 2013).

As organic farming gains prominence as a sustainable alternative to conventional practices, it offers numerous benefits beyond crop yield. This system reduces residual chemical compounds, creating a safer environment for food production while addressing broader environmental concerns. Organic farming promotes health benefits through natural practices and contributes to reducing carbon, nitrogen, and water footprints. Furthermore, it enhances soil carbon sequestration, which can mitigate greenhouse gas emissions and improve food safety standards (Kautsar *et al*., 2019; Arunrat *et al*., 2021; Arunrat *et al*., 2022; Rahman *et al*., 2024). Recognizing that the plough pan layer (PPL) forms as a result of intensive agricultural practices, understanding how different farming systems impact this layer is crucial. Organic farming, in particular, has the potential to alter the plough pan layer's physical and chemical characteristics due to its reliance on organic inputs. Information about the effects of organic fertilizer application on the physical and chemical properties of the plough pan layer in paddy soils is still rarely studied.

This study aims to investigate the transformative effects of organic farming practices on the physical and chemical properties of the plough pan layer in paddy soils, comparing these effects with those observed in conventional and semi-organic systems.

2. MATERIALS AND METHODS

2.1. Collection of soil samples

The research area is located in Musuk, Jetis, and Sukorejo Village, Sragen District, Central Java Province, representing conventional, semi-organic, and organic farming systems, respectively (Fig. 1). Each region has 3 representative soil profiles as replications, resulting in a total of 9 soil pedons, each sized 1.5 x 2 m. The site and soil profile description procedures referred to the National Soil Survey Handbook from USDA (2016). The soil profile descriptions included the thickness of horizons, the pattern and clarity of horizon boundaries, nodule/concretion of Fe/Mn, plough pan layer, penetration, colour, rooting, rocky, pores, texture, consistency, and other relevant characteristics. Soil samples were collected from each horizon and analysed for physical and chemical properties.

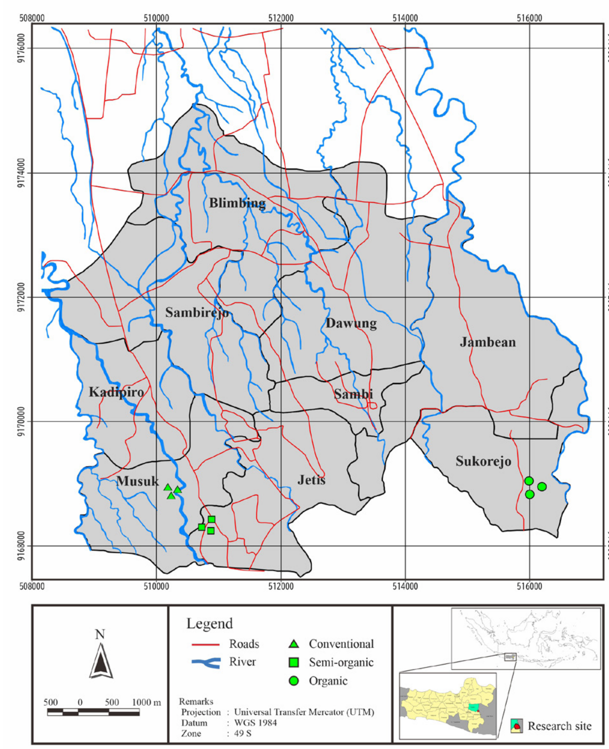

Fig. 1. Soil profile location at the studied areas.

2.2. Agricultural practices

Musuk Village, practicing conventional farming, has predominantly slopes of 2-15% with some areas having slopes greater than 15%. This village continues to practice conventional farming with a significant application of inorganic fertilizers, supplemented occasionally with organic fertilizers. The standard fertilizer application for each growing season includes 200 kg ha^{-1} of Urea or NPK as the base fertilizer and an additional 100 kg ha^{-1} of Urea as a supplementary fertilizer. Some farmers also add 300 kg ha^{-1} of SP-36 as a base fertilizer and 500-800 kg ha^{-1} of organic fertilizer in certain seasons. The use of organic fertilizer depends on its availability and the farmer's preference. The commonly used rice varieties are Mekongga and some Menthik. Productivity in Musuk varies from 6 to 7 t ha^{-1} depending on the season.

Jetis Village, used as a sample area for semi-organic farming, has gradually adopted organic farming practices after observing the success of organic agriculture in improving farmer welfare. The history of organic farming in Jetis varies from 2 to 6 years. The accessibility of agricultural land adjacent to village roads has facilitated the application of organic fertilizers. The commonly used rice varieties in Jetis include IR-64, Menthik, Menthik Wangi, and some Mekongga, with most farmers preferring IR-64 and Menthik. The standard base fertilizer application for each growing season includes a mix of organic matter at 4.8-9 t ha^{-1} $year^{-1}$, Urea at 100-140 kg ha^{-1}, NPK at 100-120 kg ha^{-1}, and SP-36 at 100-150 kg ha^{-1}. Supplementary fertilization involves applying NPK at 50-100 kg ha^{-1}. Additionally, some farmers apply green bamboo organic fertilizer when the rice plants are flowering. The use of organic fertilizers is relatively high due to easy access to large quantities of organic material and the privately owned land status, which encourages farmers to reduce chemical fertilizer use and transition to organic fertilizers gradually. The planting pattern in Jetis is similar to Musuk, with rice grown year-round, three times a year, supported by a semi-technical irrigation system. Productivity in Jetis varies from 6.5 to 8 t ha^{-1}, with an average productivity of 7.5 t ha^{-1}.

Sukorejo Village, as a model village for organic farming, has achieved significant progress in organic agriculture due to the drive to improve farmer welfare, government support, and effective marketing strategies. Situated at the foot of Mount Lawu, it benefits from high-quality irrigation that meets the criteria for organic farming. Most of the agricultural land in this village has been using organic fertilizers for approximately 10 years. In the early years of transitioning to organic farming, the amount of organic fertilizer applied was 8 tons per hectare per year, which continued for the first 3 years. From the 3rd to the 8th year, farmers reduced the application rate to 6 tons per hectare per year. Since the 8th year, the current application rate has been reduced further to 2-3 tons per hectare per year. The rice variety planted in the research location is uniform, specifically Menthik Wangi. The crop yields in Sukorejo are generally higher than in Musuk or Jetis, reaching 8-9 t ha^{-1}, and can even achieve up to 9.3 t ha^{-1} in favourable weather conditions. These high yields have been achieved since around 2008. Prior to 2008, rice productivity was approximately 7 t ha^{-1}, and during the initial years of organic farming, productivity sharply declined to around 5 t ha^{-1}.

2.3. Soil physical-chemical analyses

Particle size distribution was determined using pipette method, while bulk density (BD) and particle density (PD) were measured using core sampling and a pycnometer (gravimetry), respectively (USDA, 2014). Soil permeability was measured with a permeameter, whereas pore distribution was calculated based on soil pF values measured by Pressure Plate Apparatus. Water drainage pore was obtained by subtracting pF0 – pF2.54, fast drainage pores was pF0 – pF2, low drainage pores was pF2 – pF2.54, and water available was pF2.54 – pF4.2. Modulus of Rupture (MOR) was determined using the mini briquet method. Soil pH was measured in suspensions of H_2O (soil:solution ratio = 1:2.5) with a glass electrode after 2 h of mechanical shaking. Soil organic matter (SOM) was determined with the wet combustion method (Walkley and Black). Cations and cation exchange capacity were analysed using ammonium acetate 1 N pH 7.0 (Rowell, 1994; BPSI Tanah dan Pupuk, 2023), and electrical conductivity (EC) was measured using a ratio of soil and water of 1:2.5 (Van Reeuwijk, 1993; BPSI Tanah dan Pupuk, 2023). Analysis of humic and fulvic acid from organic matter was carried out with the base (NaOH)-acid (HCl) method. Available Fe, Al, and Mn were analysed with the Morgan-Wolf method. Plough pan layer samples were subjected to analyses of clay minerals (by X-RD), oxide fractions of Al, Fe, and Mn extracted with three selective dissolution methods (dithionite citrate bicarbonate/DCB, NH_4-oxalate pH 3, and pyrophosphate). The Al and Fe present in the solution were measured by atomic absorption spectrophotometry (AAS) (USDA, 2014).

2.4. Statistical analyses

Data on soil physical and chemical properties were analysed using one-way ANOVA with the SPSS Statistics V.26 program to determine significance at a P value of 0.05. Post-hoc comparisons among the three treatments were performed using Tukey's Honestly Significant Difference (HSD) test.

3. RESULTS

3.1. Morphology and physico-chemical properties of soil surface

Based on the soil profile description, the soil type in the three rice cultivation systems had the same category, namely Aquandic Humudepts (soil taxonomy). The soil morphological character indicated that the diagnostic horizon formed in the soil profile was Cambic (Bw), and the moisture regime was udic. However, at a depth of about 60 cm, the groundwater level emerged and inundated the subsurface layer; hence, at the sub-group level, it can be categorized as Aquandic Humudepts.

Based on the cross-section of the soil profile of the three rice cultivation systems, different thicknesses of topsoil layers were obtained, *i.e.* 20-25, 30-45, and 40-50 cm for the conventional, semi-organic, and organic systems, respectively (Fig. 2). This indicated that the addition of organic

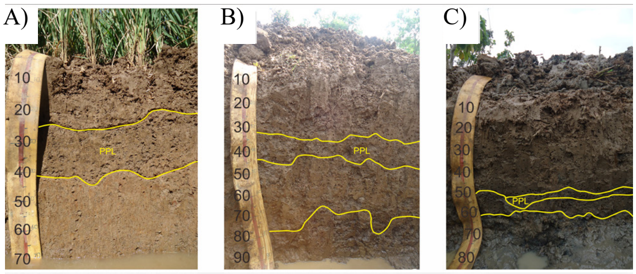

Fig. 2. Soil profiles of: A) conventional, B) semi-organic, C) organic farming system.

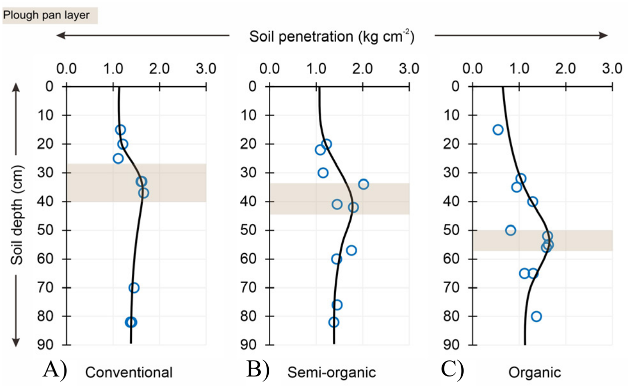

Fig. 3. Soil penetration values of: A) conventional, B) semi-organic, C) organic area.

matter may change the physical and chemical characteristics of the plough pan layer, thus reducing the thickness of the plough pan and increasing the thickness of the topsoil.

One of the important physical properties of soil related to organic farming practices is soil penetrability. At the surface layer, soil penetration in the organic field was significantly lower (< 1 kg cm^{-2}, $p<0.05$) compared to the conventional and semi-organic fields, which had values greater than 1 kg cm^{-2} (Fig. 3). On average, the highest soil penetration values were recorded in the conventional fields (1.16 ± 0.05 kg cm^{-2}), followed by the semi-organic system (1.15 ± 0.07 kg cm^{-2}) and the lowest values in organic systems (0.77 ± 0.20 kg cm^{-2}) (Table 1). Meanwhile, the bulk density in the surface layer did not show significant differences among farming systems (Table 1, Fig. 4). Another physical property that was significantly affected by organic cultivation was modulus of rupture (MOR). The highest MOR value of surface soil was found in the conventional fields (0.08 ± 0.03 bar), followed by the semi-organic variant (0.03 ± 0.01 bar), and approximately equal in the organic fields (0.03 ± 0.00 bar).

Generally, organic cultivation did not significantly affect some soil physical properties of the surface layer, such as BD, PD, porosity, permeability, water drainage pores, fast drainage pores, low drainage pores, water availability, and the percentage of particle sizes (silt, clay, and sand) (Table 1). Nevertheless, although not significantly different, the available water parameter was higher in the organically

Table 1. Soil physical properties of surface layer

Parameter	Farming systems		
	Conventional	Semi-organic	Organic
Penetrability (kg cm^{-2})	1.16 ± 0.05 a	1.15 ± 0.07 a	0.77 ± 0.20 b
BD (g cm^{-3})	1.28 ± 0.14 a	1.38 ± 0.20 a	1.20 ± 0.19 a
PD (g cm^{-3})	2.27 ± 0.08 a	2.14 ± 0.08 a	2.14 ± 0.05 a
Porosity (n,%)	43.6 ± 8.09 a	35.37 ± 11.41 a	43.73 ± 9.96 a
Permeability (cm h^{-1})	1.14 ± 0.80 a	2.00 ± 1.26 a	0.08 ± 0.06 a
WDP	50.14 ± 3.59 a	44.77 ± 5.6 a	49.21 ± 5.72 a
FDP	43.91 ± 2.20 a	39.83 ± 2.95 a	45.26 ± 7.13 a
LDP	6.23 ± 1.41 a	4.94 ± 3.02 a	3.95 ± 3.90 a
WA	12.55 ± 1.46 a	14.91 ± 1.02 a	15.04 ± 1.71 a
Silt (%)	30.36 ± 7.33 a	40.94 ± 3.50 a	36.48 ± 10.26 a
Clay (%)	36.75 ± 2.76 a	46.81 ± 11.16 a	40.00 ± 3.56 a
Sand (%)	32.9 ± 9.03 a	12.26 ± 10.39 a	23.52 ± 8.14 a
MOR (bar)	0.08 ± 0.03 a	0.03 ± 0.01 b	0.03 ± 0.00 b

Values are given as mean ± standard deviation. The same letter in the same row indicates no significant difference based on the Tukey HSD test at the 5% significance level. BD – bulk density, PD – particle density, WDP – water drainage pores, FDP – fast drainage pores, LDP – low drainage pores, WA – water availability, MOR – modulus of rupture.

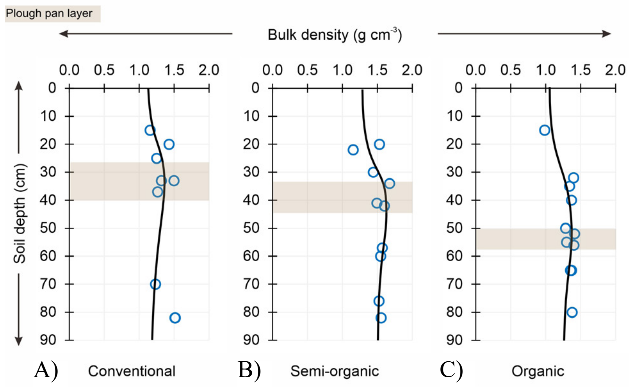

Fig. 4. Soil bulk density of: A) conventional, B) semi-organic, C) organic area.

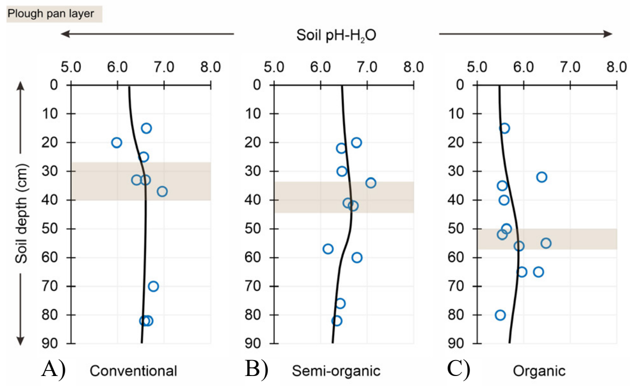

Fig. 5. Soil pH of: A) conventional, B) semi-organic, C) organic area.

cultivated fields (15.04 ± 1.71%), compared to the conventional fields (12.55 ± 1.46%) and the semi-organic fields (14.91 ± 1.02%).

Soil chemical properties that were significantly ($p < 0.05$) influenced by the organic farming practices included pH-H_2O, organic matter, C-organic, and available Fe (Table 2). The soil pH-H_2O in the conventional and semi-organic fields were observed at a range from 6.39 to 6.56, which is categorized as slightly acidic (Table 2, Fig. 5). Meanwhile, in the organic areas, the soil pH was lower (5.59), likely due to the addition of large amounts of organic material. The C-organic content increased from 1.81% in the conventional fields to 3.19% in the semi-organic system and further to 3.20% in the organic fields (Table 2, Fig. 6). Available Fe content was also higher in the organic fields (21.26 ± 0.66%), compared to the conventional (13.45 ± 3.22%) and semi-organic fields (15.53 ± 3.75%). In turn, other properties, such as electrical conductivity (EC), humic acid, fulvic

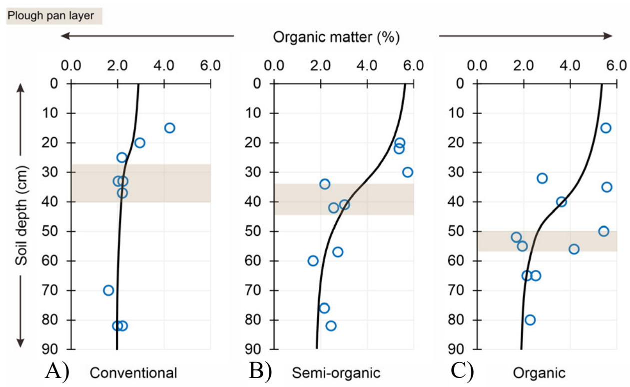

Fig. 6. Soil organic matter of: A) conventional, B) semi-organic, C) organic area.

Table 2. Soil chemical properties of surface soil layer

Parameter	Farming systems		
	Conventional	Semi-organic	Organic
pH (H_2O)	6.39 ± 0.35 a	6.56 ± 0.18 a	5.59 ± 0.05 b
EC (ms cm^{-1})	0.37 ± 0.01 a	0.31 ± 0.04 a	0.37 ± 0.06 a
Organic matter (%)	3.13 ± 1.04 b	5.50 ± 0.21 a	5.51 ± 0.07 a
C-organic (%)	1.81 ± 0.60 b	3.19 ± 0.12 a	3.20 ± 0.38 a
HA (%)	0.81 ± 0.31 a	1.01 ± 0.31 a	1.02 ± 0.15 a
FA (%)	0.45 ± 0.09 a	0.46 ± 0.10 a	0.45 ± 0.10 a
HA/FA	1.92 ± 1.12 a	2.19 ± 0.26 a	2.36 ± 0.74 a
CEC (cmol(-) kg^{-1})	24.39 ± 0.41 a	24.67 ± 0.98 a	25.92 ± 1.99 a
Available Fe (%)	13.45 ± 3.22 b	15.53 ± 3.75 ab	21.26 ± 0.66 a
Available Al (%)	5.03 ± 1.65 a	3.51 ± 1.28 a	3.61 ± 0.57 a
Available Mn (%)	5.08 ± 1.07 a	5.95 ± 0.86 a	5.11 ± 0.25 a

HA – humc acid, FA –fulvic acid. Other explanations as in Table 1.

acid, the humic/fulvic acid ratio, cation exchange capacity (CEC), available Al, and available Mn, were not significantly affected by organic cultivation.

3.2. Physico-chemical properties of plough pan layer (PPL)

The different rice cultivation systems significantly ($p < 0.05$) affected soil penetrability of PPL (Table 3, Fig. 3). The formation of the plough pan layer resulted in crusting in the subsurface soil. Soil penetrability values obtained in the conventional, semi-organic, and organic fields were 1.63, 1.86, and 1.61 kg cm^{-2}, respectively. These values were higher than those in the surface soil. Soil bulk density (BD) was also significantly influenced by the rice cultivation system, with BD values of 1.62 g cm^{-3} for the semi-organic fields, 1.36 g cm^{-3} for the conventional fields, and 1.37 g cm^{-3} for the organic fields. The soil BD from the semi-organic area was higher than from the conventional fields, which may be correlated with the higher content of the clay fraction.

The differences in the rice cultivation systems had no significant effect on the physical properties of PPL, such as particle density, porosity, permeability, water drainage pores, fast drainage pores, low drainage pores, water availability, particles size fractions, and modulus of rupture (MOR). Although the MOR values varied among the conventional (0.12 bar), semi-organic (0.15 bar), and organic fields (0.08 bar), these differences were not statistically significant. This lack of significance may be due to the high clay content in these fields.

The differences in the rice cultivation practices also had no significant effect on the chemical properties of PPL, such as pH-H_2O, electrical conductivity, C-organic, humic acid, fulvic acid, HA/FA ratio, cation exchange capacity, available Al, and available Mn (Table 4, Figs 7 and 9). However, the available Fe in PPL was significantly influenced by the different cultivation systems ($p<0.05$). The highest available Fe content was determined in the organic systems (20.81%), which was significantly higher than in the conventional systems (14.45%) but not significantly different from that in the semi-organic systems (17.12%).

Oxide compounds deposited in the plough layer were characterized using selective dissolution methods to determine the fraction of crystalline (free), amorphous, and humic complexes. Iron (Fe) extracted by DCB, oxalate ± pH 3, and pyrophosphate solution is commonly denoted as Fe-d, Fe-o, and Fe-p, respectively, as well as for other metals such as Al and Mn. The content of Fe-d, Fe-o, and Fe-p in the PPL soil from the organic rice fields was higher than that of the conventional or semi-organic fields (Table 5). The DCB-extracted Al (Al-d) was not detected in PPL from all the studied fields, whereas Al-o was just observed in the conventional system with a concentration of 1.21%. Al-p was detected in the PPL soil from the conventional and organic fields (0.10%), whereas the soil sample from the semi-organic field did not show detectable levels. The content of Mn-d and Mn-o in the PPL soil from the locations followed the order: conventional > semi-organic > organic field, while the Mn-p forms were higher in organic

Table 3. Soil physical properties of plough pan layer

Parameter	Farming system		
	Conventional	Semi-organic	Organic
Penetrability (kg cm^{-2})	1.63 ± 0.03 b	1.86 ± 0.14 a	1.61 ± 0.02 b
BD (g cm^{-3})	1.36 ± 0.12 b	1.62 ± 0.05 a	1.37 ± 0.06 b
PD (g cm^{-3})	2.29 ± 0.07 a	2.27 ± 0.08 a	2.26 ± 0.03 a
Porosity (n, %)	40.58 ± 7.09 a	28.79 ± 3.92 a	39.17 ± 2.74 a
Permeability (cm h^{-1})	0.25 ± 0.29 a	0.07 ± 0.11 a	0.01 ± 0.01 a
WDP	47.89 ± 4.41 a	46.54 ± 3.82 a	50.08 ± 5.21 a
FDP	41.96 ± 2.4 a	40.45 ± 3.34 a	44.59 ± 4.93 a
LDP	5.93 ± 2.14 a	6.09 ± 0.49 a	5.50 ± 1.49 a
WA	13.41 ± 1.75 a	13.02 ± 1.42 a	13.43 ± 2.09 a
Silt (%)	34.19 ± 10.69 a	39.89 ± 5.15 a	28.88 ± 8.80 a
Clay (%)	37.47 ± 2.31 a	50.86 ± 11.88 a	51.49 ± 2.63 a
Sand (%)	28.34 ± 12.62 a	9.25 ± 7.99 a	19.63 ± 6.25 a
MOR (bar)	0.12 ± 0.05 a	0.15 ± 0.05 a	0.08 ± 0.01 a

Explanations as in Table 1.

Table 4. Soil chemical properties of plough pan layer

Parameter	Farming system		
	Conventional	Semi-organic	Organic
pH (H_2O)	6.66 ± 0.28 a	6.65 ± 0.46 a	5.97 ± 0.47 a
EC (ms cm^{-1})	0.32 ± 0.05 a	0.25 ± 0.07 a	0.27 ± 0.09 a
Organic matter (%)	2.15 ± 0.11 a	2.49 ± 0.29 a	2.60 ± 1.37 a
C-organic (%)	1.25 ± 0.06 a	1.45 ± 0.17 a	1.51 ± 0.79 a
HA (%)	0.61 ± 0.31 a	0.9 ± 0.29 a	0.97 ± 0.10 a
FA (%)	0.27 ± 0.09 a	0.41 ± 0.10 a	0.25 ± 0.18 a
HA/FA	2.24 ± 1.02 a	2.3 ± 1.03 a	5.09 ± 2.55 a
CEC (cmol(-) kg^{-1})	23.57 ± 0.55 a	21.68 ± 2.87 a	23.57 ± 0.42 a
Available Fe (%)	14.45 ± 3.13 b	17.12 ± 1.22 ab	20.81 ± 0.65 a
Available Al (%)	5.83 ± 1.53 a	4.18 ± 1.61 a	3.35 ± 0.47 a
Available Mn (%)	5.60 ± 0.98 ab	6.55 ± 0.16 a	4.92 ± 0.21 b

HA – humc acid, FA – fulvic acid. Other explanations as in Table 1.

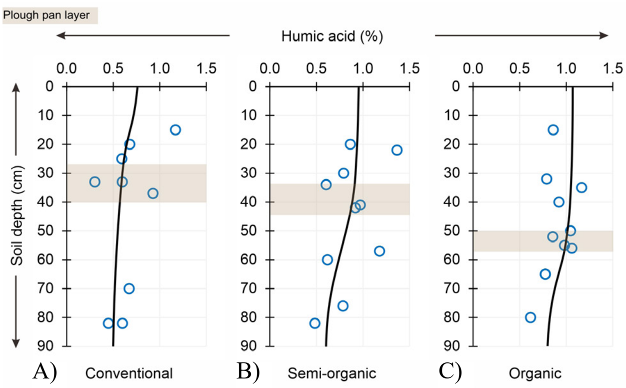

Fig. 7. Humid acid content in the soil from: A) conventional, B) semi-organic, C) organic area.

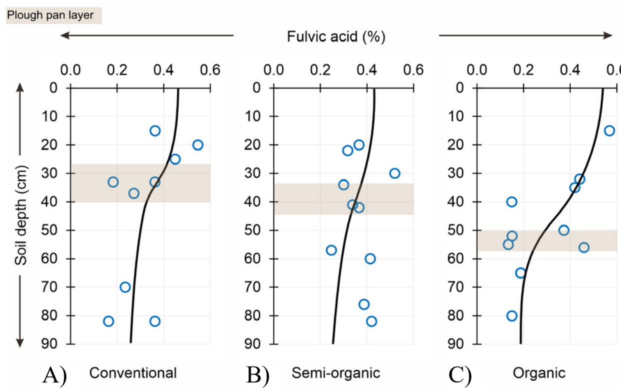

Fig. 8. Fulvic acid content in the soil from: A) conventional, B) semi-organic, C) organic area.

Table 5. Percentage of Al, Mn and Fe in plough pan layer extracted by selective dissolution method

Element	DCB	Oxalate ± pH 3	Pyrophosphate
		(%)	
		Conventional	
Al	nd	1.21	0.10
Mn	0.66	0.57	0.20
Fe	0.16	6.48	1.73
		Semi-organic	
Al	nd	nd	nd
Mn	0.21	0.47	0.14
Fe	0.09	2.73	1.51
		Organic	
Al	nd	nd	0.10
Mn	nd	0.31	0.54
Fe	1.18	7.79	8.19

> conventional ≈ semi-organic fields. This indicates that most forms of Mn hydrous oxide have been complexed into Mn-oxide-humate.

The X-ray diffractogram of the PPL clay samples from the conventional, semi-organic, and organic systems showed the same peaks obtained (Fig. 9). This indicates that the differences in the rice cultivation systems did not affect the clay mineral types. The clay minerals were categorized as the 1:1 type clay group because treatment with ethylene glycol resulted in the same peak. Three main peaks were identified at 7.28×10^{-10} m, 4.50×10^{-10} m, and 3.58×10^{-10} m, corresponding to the presence of kaolinite, nacrite, and dickite, respectively. These clay minerals are often accompanied by hematite, goethite, and sometimes gibbsite (Churchman and Lowe, 2012; Melo *et al*., 2020).

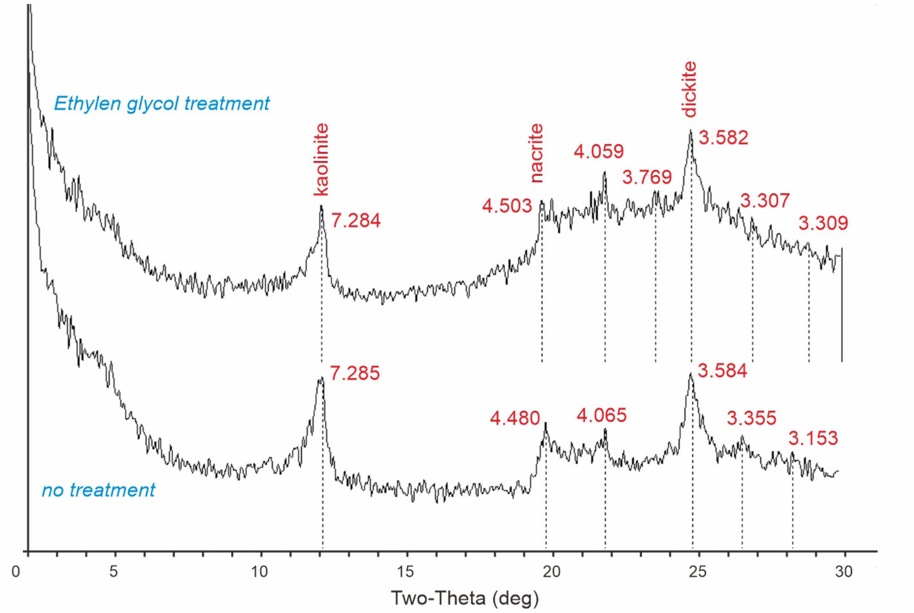

Fig. 9. X-ray difractograph of clay fraction from plough pan layer.

4. DISCUSSION

The practice of organic farming had notable implications for changes in soil morphology. Figure 2 shows that the plough pan layer was thinning and shifting downward. The organic cultivation over 12 years increased the thickness of ploughed soil. The topsoil thickness was observed to be greater in the organic fields compared to the semi-organic and conventional fields. The provision of organic material in a large amount and on a continuous basis had a beneficial impact, as it expanded the reach of roots for nutrient uptake from the rhizosphere. Another benefit of the organic material application was the improvements in several physical and chemical properties of the soil.

Soil penetrability is one of the important physical attributes related to the ease with which plant roots can penetrate the soil. The plough pan is the hardest layer to be penetrated by roots; therefore, penetrometer measurements of the plough pan layer will show higher values than those of other layers. Two measurements commonly used as a reference to confirm the presence of a plough pan layer are penetrometer readings and bulk density (Podder *et al*., 2012).

The main cause of the high soil penetration in semi-organic farming is the prolonged use of a hand tractor for land preparation. Jetis village, which represents the semi-organic system, has used the tractor since the mid-1990s, meaning that the tractors have been in use for more than 20 years. In the conventional farming, hand tractors have been used for about 10 years, and even less than 8 years at the bottom of the terrace. In turn, the intensive use of hand tractors in the organic farming began about 5 years ago. This indicates that the use of tractors is the main cause of high soil penetration, and the large amounts of organic matter have not been able to mitigate the effect of tractor use, as seen in the semi-organic farming. In addition, the surface soil of the organic field in Sukorejo had lower penetration values than the others. This was due to the relatively early use of tractors and the substantial addition of organic matter. Thus, this indicates that organic material plays a crucial role in improving soil structure, increasing the ease with which soil can be processed and penetrated by plant roots.

Changes in the plough pan layer related to the management of organic farming can be explained by the observed physical and chemical parameters. These changes are very evident in the penetrometer analysis, which shows declining resistance in the organic than conventional system. Similarly, the bulk density tended to be lower in the organic farming than in the conventional farming. This indicates that the organic matter added every season in large amounts over a long term is able to reduce soil penetration resistance and bulk density. On the other hand, what needs attention is that the addition of organic matter and the use of hand tractors on the paddy field during tillage have a great influence on plough pan layer characteristics. Tractor usage in a long term has an impact increasing penetration and bulk density despite the organic matter applied in the field in large amounts, as in the semi-organic field in Jetis Village.

The conventional soil profile generally shows the highest particle density compared to the other soil profiles. The soil surface layer in the conventional, organic, and semi-organic systems has an average density of 2.27, 2.14, and 2.14 g cm^{-3}, respectively. In the plough pan layer, all treatments showed no significant differences, and its value ranged from 2.26 to 2.29 g cm^{-3}.

Soil organic matter is a fundamental component of the entire agro-ecosystem that plays a role of a vital link between physical, chemical, and biological soil properties (Pramanik and Kim, 2014). Increasing SOM not only improves cation exchange capacity (CEC), humic acid, and fulvic acid but also enhances soil organic carbon (SOC), which can lead to improved crop yields (Arunrat *et al*., 2020; Seufert *et al*., 2012; Syamsiyah *et al*., 2023). The increase in total carbon is more noticeable in flooded soils, such as paddy soils, than in upland soils.

The addition of organic matter as part of organic farming increased the soil organic matter content. This was observed in the organic and semi-organic paddy soil; the upper layer of the soil had an average organic matter content about 5.50 and 5.51%, respectively (Table 2). The soil organic matter content from the organic and semi-organic systems was not significantly different, as farmers had been adding 2-3 t ha^{-1} $year^{-1}$ of organic matter for the past three years. Meanwhile, the semi-organic soil had large quantities of organic materials added, *i.e.* about 5-9 t ha^{-1} $year^{-1}$. Similar findings in previous studies highlight that sustained organic matter application is essential for enhancing soil health and SOM levels (Arunrat *et al*., 2020; Kautsar *et al*., 2019).

Soil organic matter contributed to increasing the negative charge of the soil, because the humic compounds contained many functional groups, such as carboxylates and phenolics. The cation exchange capacity (CEC) values, from high to low value, were as follows: organic > semi-organic > conventional. The high CEC in the organic farming system was due to the periodic and long-term addition of large amounts of organic matter. The average CEC value in the top layer of the organic soil was 25.92 cmol (-) kg^{-1}, which was not significantly different compared to the semi-organic soil with about 24.67 cmol (-) kg^{-1}. However, the CEC value in the organic farming was significantly different from that in the conventional farming, which had a value of 24.39 cmol (-) kg^{-1}. The high CEC in the conventional farming was due to the addition of organic matter in several seasons and the silty loam texture of soil, which has a high CEC.

The high content of humic acid in the surface layer of the soil was attributed to the addition of organic fertilizer and the accumulation of crop residues. In addition, humic acid is a high molecular weight organic acid (3.7-50 kDa), which results in low mobility (Shinozuka *et al*., 2004; Lu *et al*., 2020; Alomar, *et al*., 2023; Liu *et al*., 2023). This organic acid dissolves only in alkaline conditions, whereas this soil has a pH range of 6-7.

Humic acid is the most abundant substance and, together with fulvic acid, can be found in all soils and water (Hayes, 1984; Hayes and Swift, 2020; Alomar, *et al*., 2023; Zhu *et al*., 2023). The characteristic fraction of topsoil is very useful in the interpretation of the dynamics of organic matter in the soil (Ma *et al*., 2011; Anthony *et al*., 2022).

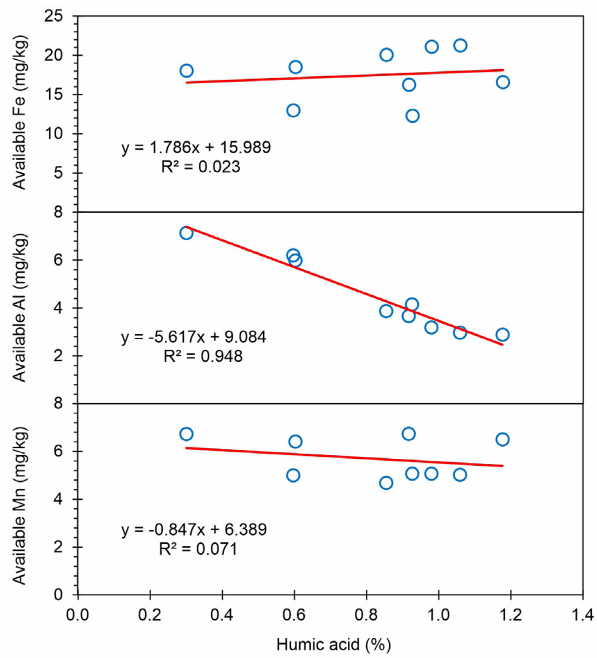

Fig. 10. Relationship of humic acid content and available Fe, Al, and Mn in plough pan layer.

Humic acid, as an organic macromolecule, has various functional groups, namely aromatic, aliphatic, phenolic, and quinolic compounds. The existence of these functional groups is influenced by the level of humification in organic matter (Velasco *et al*., 2004; Hayes and Swift, 2020). These functional groups play a role in complexing or chelating heavy metals that are present in the soil. Figure 10 shows a very significant negative correlation (r = -0.974) between the levels of humic acid and dissolved Al in the soil. This value was higher than the correlation of humic acid with the levels of Fe (r = 0.150) and dissolved Mn (r = -0.266). This showed that higher levels of humic acid led to more Al being complexed into Al-humic, thus decreasing its solubility.

Research conducted by Zech *et al*. (1997) showed that the process of humification of plant residues is characterized by an increase in C-carboxyl, C-alkyl, and C aromatics (especially the phenolic group) and a decrease in O-alkyl C. Therefore, with more humified organic substrates, it is easier to bind colloidal charged soil and form a better aggregate structure. This improves the physical properties, chemical properties, and biochemistry of the soil, ultimately increasing soil fertility (Bayer *et al*., 2000; Chen *et al*., 2020; Du *et al*., 2020; Ampong *et al*., 2022; Saygin *et al*., 2023).

The application of organic matter affected the Fe-oxide fraction in the soil, particularly associated with bound iron, and caused a significant difference. The amount of Fe bound to humic compounds was estimated from the Fe-p content. Humic compounds are mostly sourced from organic fertilizers that are added to the soil. The organic paddy fields showed higher levels of Fe-humic (8.19 ppm) than the semi-organic (1.51 ppm) and conventional (1.73 ppm) systems (Table 1). According to Juo *et al*. (1974), the Fe-o/Fe-d ratio can be used to determine the rate of aging or crystallization of free iron oxide, which is the main pedogenic process. The average value of active Fe in the lower surface horizon indicates the dominance of Fe oxide crystals. The transformation of amorphous Fe to Fe oxide shows an advanced stage of weathering. This active Fe fraction is very important and related to the P fertilization strategy, because this active Fe form can adsorb orthophosphate (HPO_4^{2-}) into a inner-sphere complex form that is not available to plants.

5. CONCLUSIONS

The cultivation system on paddy soil with puddling and plough devices results in the formation of the plough pan layer which has different physical, chemical, and mineralogical characteristics with a surface soil layer. Increasing such soil physical properties as the soil penetration, modulus of rupture, and bulk density and decreasing soil porosity and soil permeability caused the rhizosphere area not to be conducive to plant root growth. Clay accumulated in the plough pan layer was composed of kaolinite, nacrite, dickite, and the content of dissolved Fe>Mn>Al. The organic farming practice improved the soil properties, *i.e*. it increased the content of humic acid, fulvic acid, CEC, Fe-humic, Mn-Humic, soil porosity, and the thickness of the topsoil but decreased the thickness of the plough pan, modulus of rupture, and soil penetration. The Fe/Mn-humic content increased by 4.74 and 2.73 times, respectively, compared to the conventional system. This indicates that humic substances released by organic matter play an important role in the dissolution and complexation of mineral components in the plough pan layer, so that the volume of the rhizosphere area increased and the soil physical and chemical became better as such.

Conflicts of interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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