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Evaluation of Soil Retention Capabilities Using RETC Application in Various Paddy Field Management Systems in Purwantoro District, Indonesia

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ABSTRACT

Prolonged dry seasons are one of the most influential impacts of global warming on the agricultural sector. Soil water retention is the ability of soil to hold water, which is presented in the form of pF curves (graphical representations of the relationship between soil water content and soil water potential). The soil's physical properties also influence the soil's water retention ability, which affects crop growth, crop yield, and land productivity. This study aims to measure soil water retention using the RETC program on various paddy field management systems: organic, semi-organic, and conventional. This research used a survey method in rice fields with different management systems and soil physical indicators approaches. The RETC program can be used to measure soil water retention in paddy fields accurately and efficiently. The results showed that the paddy field management system in Purwantoro Sub-district affects the soil's ability to retain water. The organic rice field management system has the highest available water content of 18%. The increase in soil water retention has a very significant positive correlation with soil organic matter content, where the organic matter content in the organic rice field management system is higher than the semi-organic and conventional management systems by 4.33%. Soil water retention capacity was determined by soil fraction content (0.522**), dust content (-0.438**), and effective depth (0.663**). The higher the clay content, the higher the available water content.

1. INTRODUCTION

The susceptibility of agricultural practitioners to drought is contingent upon the interplay of several potential consequences associated with climate change [1]. The residents of Purwantoro District, especially the farmers are experiencing the effects of climate change, particularly in relation to the agricultural sector, particularly rainfed land, which is very susceptible to prolonged periods of drought [2]. The losses incurred by farmers due to drought are dictated by the interplay between the impacts of climate change and the farmers' ability to adapt [3].

The impact of extreme climate change in the form of drought is the first cause of crop failure. This condition has implications for reducing production and the welfare of farmers [4]. Water availability determines the success of crop cultivation activities on dry land as a solvent for nutrients in the soil so that plants can absorb them to meet the needs of nutrients for plant growth [5]—water loss results in reduced water availability in the soil. The availability of water in the soil used by plants is measured in the soil pores in the root layer of plants [6]. Land with different management systems generally also has different soil water retention capacities. This condition is influenced by using fertilizers, such as conventional land use using inorganic and semi-organic fertilizers, which use organic and inorganic fertilizers.

In contrast, the organic land use system only uses organic fertilizers. Organic land use will have a high organic matter content in the soil. This condition is in line with Mulyono et al. [7], explained that organic carbon content, content weight, and clay texture are soil properties that have a correlation and potential for predicting soil water retention.

Soil water retention data can be predicted using RETC, a computer program calculates soil water retention and unsaturated hydraulic conductivity functions. RETC predicts the unsaturated hydraulic conductivity function from observed groundwater retention data using the mathematical models of Mualem [8] and Burdine [9]. The program also uses a non-linear least squares parameter optimization method to estimate unknown coefficients in the hydraulic model, according to Van Genuchten et al. [10]. RETC includes a detailed discussion of the various analytical expressions used to quantify the soil water retention function and hydraulic conductivity. RETC also allows the user to couple analytical functions simultaneously with observed water retention and hydraulic conductivity data, assuming that one observed conductivity value not necessarily at saturation is available. Some examples are presented to illustrate the various program options.

The physical features of the land determine soil water retention capability, while the agricultural strategy used influences paddy fields' physical properties. Observations of soil water retention are carried out using the RETC and the MVG methods, which require variable data on soil physical properties of textural conditions and soil bulk density. High levels of sand and clay fractions will increase the available water content; the higher the bulk density value, the lower the available water content [11]. The physical properties of soil in a field affect the ability of soil to retain water and the ability of soil water retention affects the resistance of land to drought [12]. Changes in rice field management systems impact soil physical properties and the ability of soil to retain water, having both adverse and beneficial impacts on the ecosystem. Previous research by Supriyadi et al. [13] has explained that chemical fertilizers always impact biological fertility and soil physical conditions. Therefore, it is crucial to analyze the physical conditions of rice fields.

Soil water retention is essential to know because the fulfillment of dryland water needs relies heavily on the ability of soil water retention. Assessing soil water retention with the RETC computer method is very practical and time-efficient, but still very little is done. In this study, the assessment of soil water retention uses a modified approach to analyzing soil physical properties by comparing soil water retention conditions in conventional, semi-organic and organic land uses. The purpose of this research is to determine the retention capacity of rice fields in the Purwantoro Subdistrict using a fast and accurate method, namely RETC, find the determinants of groundwater retention in rice fields to determine a better land management system, and become a recommendation in land irrigation during the dry season.

2. METHODOLOGY

2.1 Study area

The research was conducted in Purwantoro District, Wonogiri Regency, Central Java, Indonesia. The geographical location of Purwantoro District is 7°50'50"-7°48'49.0" S and 111°01'47.6"-111°09'48.3" E with an altitude of 296 meters above sea level (m asl), rainfall (1,750 - 2,250 mm/year) with an area of 5,952.7837 ha, composed of 2 urban villages and 13 villages. The total population is 45,569 people, and agriculture is the most common field of livelihood. The research was conducted on land use in rice fields with organic, semi-organic, and conventional cultivation systems. There is one type of soil, Inceptisol, and on slopes of 0-8%, 8-15%, 15-25%, 25-40%. The analysis includes physical analysis, field observations, and RETC software analysis. The analysis was conducted at the Laboratory of Physics and Soil Conservation, Faculty of Agriculture, Universitas Sebelas Maret.

2.2 Soil sampling and plant sampling

This research used an exploratory, descriptive survey method through a field survey approach and laboratory analysis results. The survey was conducted using a purposive sampling method. A working map is a unit of land map unit (LMU) consisting of the results of overlaying thematic maps, namely the Indonesian land map (RBI) of Purwantoro District, Wonogiri Regency, a map of diversity sources including the type of rice field management (by Wonoagung Organic Farmers Association), rainfall map (Climatology Data Portal), and slope map (Indonesian Geospatial Agency). The difference in rice field management consists of organic, semi-organic, and conventional rice fields (Figure 1). Rainfall in the study area is 2250mm/year and 1750mm/year. The slope is 0-8%, 8-15%, 15-25%, 25-40%. The results of the map overlay will produce a sampling map with the number of land mapping units (LMU) totaling 12 LMU (Figure 2). The sampling will repeat 3 points for each LMU, and the number of sampling points is 36 Soil samples were taken at 36 sampling points using a biopore drill method at a depth of 1-20 cm (tillage layer) of about 1 kg and in the vegetative phase of the plant (maturation phase). Soil samples that have been taken are then analyzed in the laboratory.

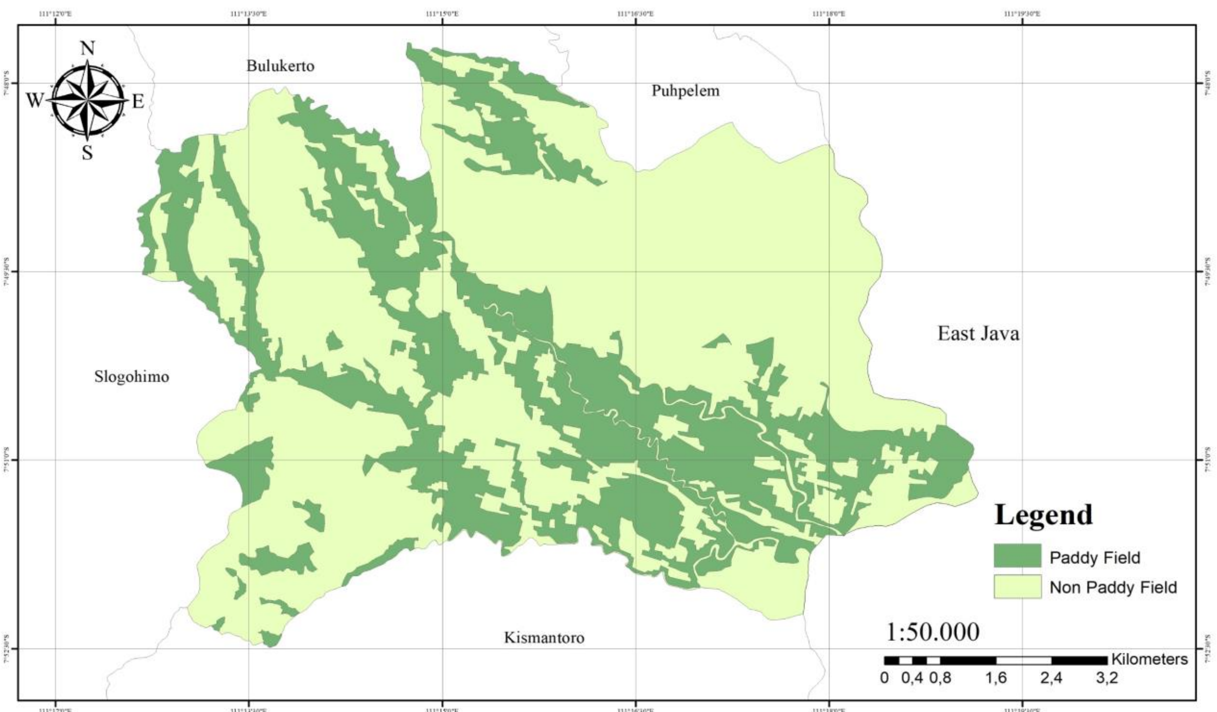

Figure 1. Distribution of rice fields in study area

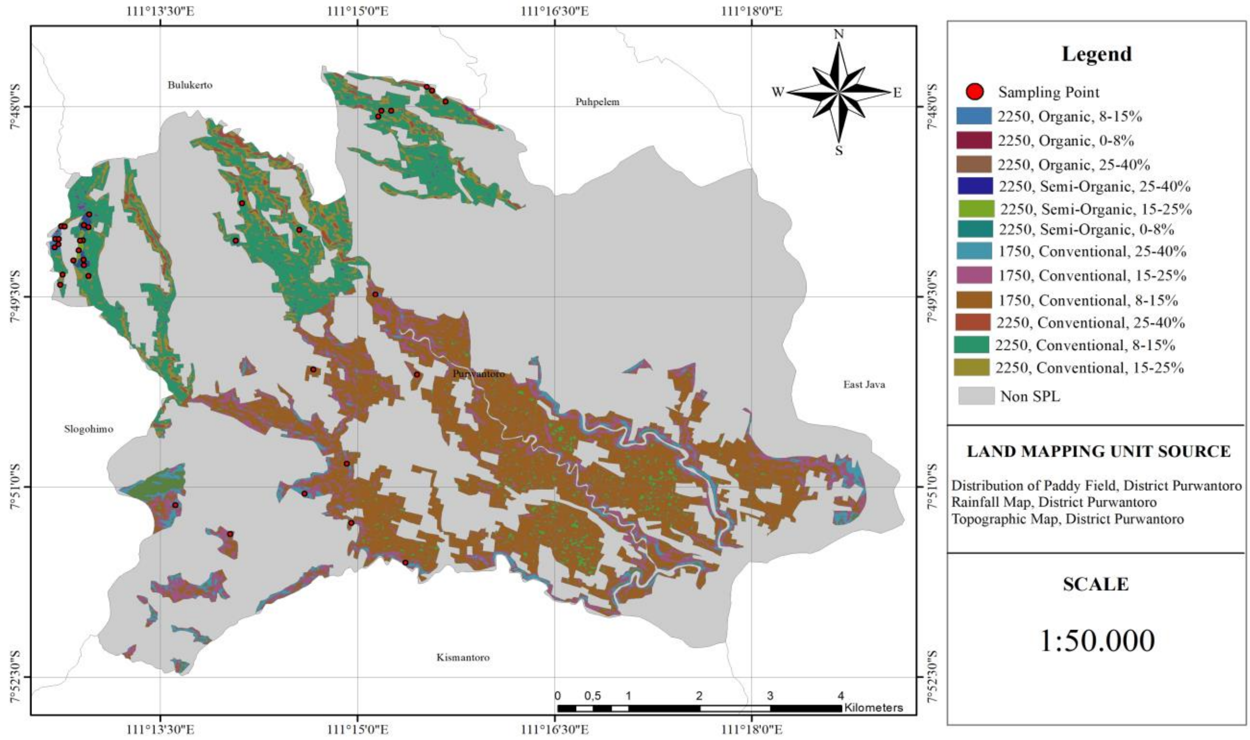

Figure 2. Land maping unit of study area

The parameters studied include soil bulk density by gravimetric method, texture by pipette method, specific gravity by pycnometer method, soil C-organic by Walkey and Black method, wind dry moisture content by gravimetric method, effective depth by drill observation (20), soil water retention by RETC computer program analysis where Ct: BV (g/cm^3); BD: bulk density (g/cm^3); %C: soil organic content (%); DP: soil depth (cm); curve retention (%), soil texture fraction (%).

2.3 The RETC modelling

The utilization of computer models for the estimation of unsaturated groundwater movement or flow has gained significant popularity in recent times due to the limitations associated with hydraulic conductivity estimation [14]. Computer models have gained significant popularity as tools for predicting the movement of unsaturated groundwater due to their inherent advantages over conventional approaches [15]. These advantages primarily lie in their ability to address the restrictions involved in estimating hydraulic conductivity. These models have the potential to offer more complete and precise evaluations of groundwater flow dynamics, hence facilitating improved decision-making in relation to diverse water-related matters [16].

The process of groundwater saturation by numerical models is both time-consuming and costly. The study utilizes the functions in RETC, to predict pF value. This study seeks to evaluate the efficacy of pF using soil samples collected from research area in Purwantoro District. Additionally, it attempts to assess the performance of the pF model by comparing it to a fitting curve.

The formulas used in this study of RETC analysis namely Van Genuceh's and Brook-Corey's.

$$\emptyset = \emptyset_r + \frac{\emptyset_s - \emptyset_r}{[1 + (\alpha h)^n]^m}$$

where, the subscripts r and s denote residual and saturated water contents, respectively, α is an empirical parameter whose inverse is frequently referred to as the air entry, value n and m are dimensionless empirical shape factors. When using the application, it is necessary to input physical soil observation parameters such as texture and bulk density.

2.4 Statical analysis

The Analysis of Variance (ANOVA) test was conducted to determine the effect of the paddy field management system on soil water retention. If it shows a significant value, continue with Duncan's Multiple Range Test (DMRT) test to determine the difference in soil water retention value in each paddy field management system. In addition, we examined limiting factors using Pearson's correlation test in this study. Limiting factors are determined as parameters significantly correlating with available water content (soil water retention). These limiting factors will later be used as a reference basis for preparing land management recommendations for farmers and stakeholders.

3. RESULTS

3.1 Soil water retention

The pF condition indicates the pressure or suction of a particular soil and describes the condition of its water content. The organic rice field research results have a high water content at pF 1 and pF 2.54, while pF 4.2 is at the bottom (Figure 3).

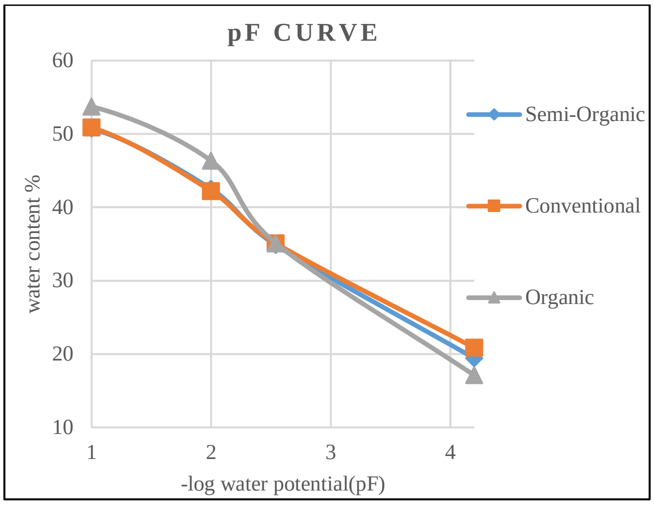

Figure 3. pF curve of various paddy field

Table 1. Soil water retention of rice field in Purwantoro

LMU	Water Available	Water Content				Pores	
		pF 1	pF 2	pF 2.54	pF 4.2	Macro	Micro
		% Volume					
A	18.00	54.50	47.70	36.00	18.00	6.80	11.70
B	18.40	52.80	46.00	34.20	15.80	6.80	11.80
C	17.60	53.90	45.30	35.10	17.50	8.60	10.20
D	15.60	50.90	42.80	34.70	19.10	8.10	8.10
E	15.70	50.90	42.50	34.90	19.20	8.40	7.60
F	15.00	50.40	42.20	35.00	20.00	8.20	7.20
G	15.00	50.90	42.70	36.00	21.00	8.20	6.70
H	10.70	51.70	40.00	32.80	22.10	11.70	7.20
I	15.20	53.00	44.70	37.00	21.80	8.30	7.70
J	15.70	52.60	44.90	38.20	22.50	7.70	6.70
K	14.60	48.00	40.00	32.40	17.80	8.00	7.60
L	14.30	49.00	41.00	34.20	19.90	8.00	6.80

Figure 3 shows that at pF 1, organic rice fields have the highest value of 53.73%, conventional rice fields have a value of 50.86% and semi-organic rice fields with a value of 50.73%. Water content at pF 2 shows that organic land has the highest water content value of 46.33%, conventional land at 42.50%, and semi-conventional land at 42.21% (Table 1). The water content at pF 2.54 value of water content on organic and conventional land is 35.1% and the lowest on semi-organic land is 34.9%. The value of pF 4.2 is lowest in organic fields, with a value of 17%, in semi-organic fields, with a value of 19.43% and the highest in conventional fields, with a value of 20.85%. Higher porosity allows the soil to store more water, thus reducing the risk of reaching the permanent wilting point. It also proves that organic rice fields' water-holding capacity is more significant than semi-organic and conventional rice fields.

Figure 4 shows the drainage pore diagram of each rice field management. Organic land has the highest value, with 11.23% for micropores and 7.4% for macropores (Figure 4). The semi-organic farming system has a value of 8.23% for macropores and 7.63% for micropores. Conventional farming Systems have the lowest value for pore drainage, which is 7.12% for micropores and 8.65% for macropores. The real difference in available water content between organic land with semi-organic and conventional land is that organic land has a high value of 18%, semi-organic with a value of 15.43% and conventional land with a value of 14.25%.

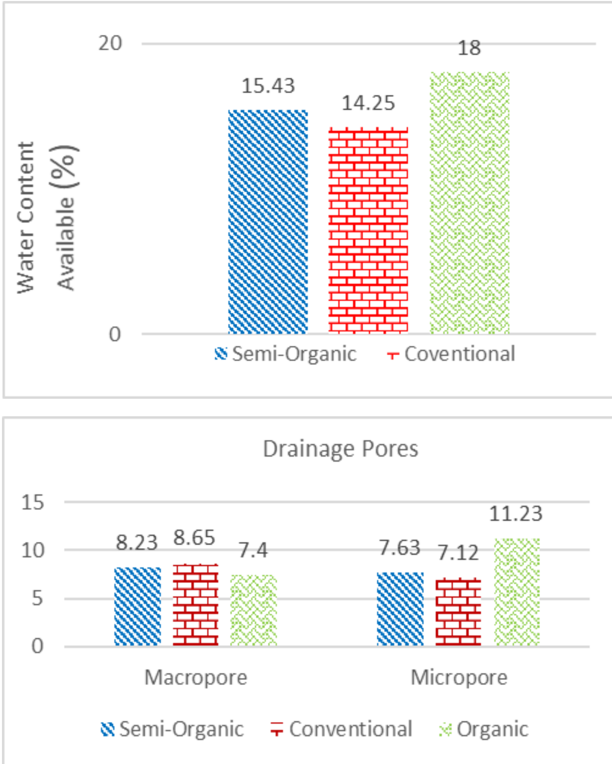

Figure 4. The average of water available, micropores, & macropores under different farming systems

3.2 The distribution of soil physical under various paddy field management

According to the observation results presented in (Table 2), the soil texture in the Purwantoro sub-district has a Clay classification where the soil texture fraction is dominated by clay, which ranges from 52-81%, while the silt fraction has a data range of 12-33% and the least is the sand fraction with a data range of 5-13%. Bulk density ranges from 1.19-1.29 gr/cm^3 and the data range for particle density is 2.61-2.66 gr/cm^3. Porosity ranges from 51.66-54.40%, effective depth ranges from 31-40 cm, moisture content of Purwantoro rice fields ranges from 6-7%, and organic matter content ranges from 4-1%.

Table 2. Physical analysis of paddy fields in the study area

Farming System	Texture (%)			T	BD	PD	P	ED	ML	OM
	Sand	Silt	Clay							
Organic	5.31^{a}	12.91^{a}	81.78^{a}	Clay	1.19^{a}	2.61^{a}	54.50^{b}	40.42^{a}	7.43^{a}	4.33^{a}
Semi-Organic	10.82^{a}	21.95^{a}	67.23^{ab}	Clay	1.29^{b}	2.66^{a}	51.66^{a}	36.75^{a}	7.15^{a}	2.57^{b}
Conventional	13.23^{a}	33.99^{a}	52.78^{b}	Clay	1.28^{b}	2.64^{a}	51.90^{a}	31.69^{b}	6.57^{b}	1.49^{c}

Description: T=Textures, ED=Efective Depth, ML=Moisture Level, OM=Organic Matters, BD=Bulk Density, PD=Particel Density, P= Porosity

The ANOVA shows that organic, semi-organic, and conventional clay's average clay content was 81.78%, 67.23%, and 52.78%, respectively. The significant difference in clay content in organic fields indicates that land management affects soil texture (Table 2) and also shows that organic and semi-organic fields have a significant difference in effective depth, which is 40.42 cm for organic fields and 36.75 cm for semi-organic fields and conventional fields have the lowest depth with a value of 31.62 cm. Semi-organic rice fields own the highest bulk density value with a value of 1.29 gr/cm^3, a value that is not much different is also found in conventional rice fields with a figure of 1.28 gr/cm^3, organic rice fields have the smallest bulk density value of other cultural systems, namely 1.19gr/cm^3.

3.3 Limiting factor of soil water retention

Limiting factors are important to know to provide recommendations for improvement in efforts to increase groundwater retention capacity in the Purwantoro Sub-district. Limiting factors were obtained through correlation tests between available water content and various parameters (Table 3).

Table 3. Limiting factors of soil water retention

Parameters	Water Content Available
Clay Fraction	0,522**
Dust Fraction	-0,438**
Sand Fraction	-0,137
Wind Dry Loam	0,198
Specific gravity	-0,185
Effective Depth	0,663**
Soil Porosity	0,314*
Soil Bulk Density	-0,457**
Soil Organic Matter	0,603**

Description: ns = not correlated; * = significantly correlated; ** = highly significantly correlated

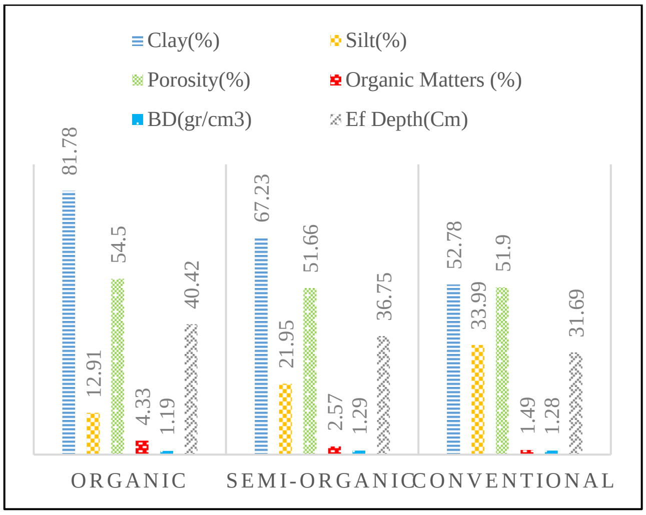

Figure 5. Limiting factor of soil water retention

Limiting factors in this study consist of 6 parameters, namely clay fraction (r = 0.522**), dust fraction (r = -0.438**), bulk density (r = -0.457**), porosity (r = 0.314*), effective depth (r = 663**) and organic matter (r = 0.603**). Figure 5 shows that organic rice fields have the highest clay fraction, organic matter, and effective porosity depth, while organic rice fields' bulk density and dust fraction content are the lowest.

4. DISCUSSION

4.1 Soil water retention

All land management systems have almost the same value for pF 2.54, as seen in Figure 3, with consecutive values of organic, semi-organic and conventional, which are 35.1%, 34.86%, and 35.1%. It indicates that the land management system does not affect the water content at pF 2.54. The research results by Ayu et al. [17] in Sumbawa showed that rainfall significantly affected the field capacity. This opinion aligns with the study's results, which showed no significant difference because the rainfall in the Purwantoro sub-district was not diverse and only consisted of 2 rainfalls.

Semi-organic and conventional land management systems have almost the same value in pF 1 and 2. In contrast, the organic farming system has a higher value for pF 1 and 2, indicating that the water content in wet and dry conditions on organic land is higher than on semi-organic and conventional land, according to Latuamury and Hut [18], the water content in wet and dry conditions of soil is influenced by organic matter which increases the water storage capacity of soil [19]. It reduces the evaporation of water from the soil.

The analysis results show that pF 4.2 has the lowest value in the organic farming system with a value of 17.1%, followed by the semi-organic farming system with a value of 19.4% and the highest is in the conventional farming system with a value of 20.85%. The results of Surya et al. [20] research stated that every 1% of organic matter provision affects the increase in soil porosity by 21.87%. Higher porosity allows the soil to store more water [21], thereby reducing the risk of reaching the permanent wilting point, thus also proving that the water-holding capacity of organic land is greater than that of semi-organic and conventional land [22].

Significant differences in soil water retention conditions are found in slow drainage conditions in organic fields (Figure 3). According to Masria et al. [23], soil density can affect porosity and pore connections in the soil. Dense soils tend to have smaller pores and fewer fast drainage pores, while loose soils have more significant and slow drainage pores. It aligns with the research results of Nita et al. [24], where the distribution of soil pores directly influences water content at pF 2.54 and pF 4.2. The more soil porosity increases, the lower the weight of the soil content, so that the space available for water will be larger.

The results of DMRT analysis for available water content can be seen in Figure 3, showing significant differences in available water content between organic land with semi-organic and conventional land. Organic land has a high value of 18%, semi-organic land has a value of 15.43% and conventional land has a value of 14.25%. The real difference in organic land is due to organic fertilizers and tillage treatments that use organic systems. It aligns with research conducted on clay soil by Intara et al. [25], which showed that applying organic matter can increase the soil's ability to bind water and increase available water content in some soil textures. This is because organic matter acts as a soil water binder.

Using organic materials such as manure can increase the ability of soil to retain water. Research by Mallareddy et al. [26] and Chen et al. [27] proved that the function of manure is to improve soil structure, supply nutrients, increase the ability of soil to retain water and nutrients and increase binding between particles. In addition, manure can improve soil biological properties by accelerating the multiplication of microorganisms in the soil. Therefore, adding manure can improve the physical properties of the soil so that plants can optimize their nutrient intake for growth and improve the quality of rice plants [28].

Retaining soil water is of utmost significance in cultivating rice fields [29]. Rice paddies, commonly called paddy fields, have distinct water management strategies owing to the distinctive characteristics of rice plants and their growth prerequisites. In the context of paddy field cultivation, soil water retention is of utmost importance due to its direct influence on water availability, nutrient absorption, and the overall well-being of plants [30]. The effective management of water, which encompasses the maintenance of optimal soil [31] and water retention, plays a crucial role in optimizing rice yields while simultaneously conserving resources and mitigating environmental consequences.

4.2 Condition physical properties of the soil

The significant difference in clay content in the organic field indicates that land management affects soil texture. The results presented in Table 3 prove an increase in clay in organic and semi-organic land due to applying organic matter. The results of research by Arunrat et al. [32] regarding the availability of C-organic in organic land that has been carried out for more than 5 years show that paddy fields treated with organic fertilizers have higher organic C than non-organic paddy fields, which is an average of 2.10-2.70%. C-organic is essential in soil clay content is supported by the opinion of Silalahi et al. [33] that increasing soil organic carbon content can increase the activity of microorganisms in the soil, which can assist in the decomposition of minerals and assist in the formation of carbon chains in the soil [34]. The analysis results also revealed that organic, semi-organic and conventional rice fields have a dust fraction content that is not significantly different. According to Schlüter et al. [35], organic matter can help improve the soil's ability to retain water. Lack of organic matter can cause the soil to become drier, resulting in soil particles becoming more dispersed and forming a dust fraction. The value of sand content in paddy fields has the lowest value among other soil fractions due to toyawahan, which can reduce the content of the sand fraction, as Sudaryanto [36] explained. Compaction can damage macro aggregates into smaller aggregates, even scattering the soil into single particles, making soil particles smoother (disintegration).

The organic farming system has the smallest bulk density value of the other cultivation systems, which is 1.19gr/cm^3, as research by Saputra et al. [37] states that the provision of organic matter into the soil can increase the amount of soil pore space and form a crumbly soil structure so that it will reduce the weight of soil content. The bulk density values of semi-organic and conventional soils slightly exceed the critical value of clayey soil for healthy agricultural soils, which is less than 1.2 g/cm^3 for clayey soils [38]. The results of specific gravity were not significantly different due to the relatively uniform paddy soil and mineral content in the Purwantoro Subdistrict. Surya et al. [20] stated in his research that the specific gravity value of soil is not easily changed because the particular gravity of soil will have a fundamental difference if there is a considerable variation in the composition of soil mineral material.

Figure 5 shows that organic and semi-organic, conventional land shows a real difference in effective depth. The provision of organic fertilizers can increase the effective depth. Pranata [39] stated that organic matter has several functions for the soil, including maintaining the air in the soil so that it is not easily compressed.

4.3 Limiting factors of soil water retention

Determinant factors are important to know in order to provide recommendations for improvement in efforts to increase soil water retention in the Purwantoro Subdistrict. Based on Table 3, the clay fraction significantly correlates with available water in the soil; the higher the clay fraction is contained, the more water will be available for plants. According to Islam et al. [40], organic matter can help increase water availability in clay soil. Organic matter acts as a binder and can improve soil structure, create larger pores and increase water infiltration and retention. Organic matter can also increase the aggregation of clay particles, thereby improving soil porosity and increasing water availability for plant roots.

The dust fraction in Table 3 shows that the dust fraction has a significant correlation with the amount of available water in the soil. Based on the value of the dust fraction, it means that the dust fraction is negatively correlated, and the higher the dust fraction content in the soil, the less water content there will be. According to Li et al. [41], a high dust fraction in the soil can reduce soil porosity, thereby reducing the ability of the soil to retain water. A high dust fraction can fill the soil pores, making them denser so water cannot enter them. Soils with a high dust fraction tend to have a lower water-holding capacity, while soils with a higher clay fraction have a higher water-holding capacity. Similarly, the relationship between moisture content in wind-dried soil and soil water content availability is as follows: the higher the moisture content value, the higher the soil water content (indicated in Table 3 by a positive correlation direction R = 0.198) because as the soil particles absorb more water, the soil moisture content increases.

However, additional factors such as characteristics of soil structure, organic matter, and soil tillage also influence soil's ability to hold water. Effective depth showed a significantly positive correlation in the test results, meaning that the deeper the effective depth of the soil, the better the ability of the land to store water. Soils with shallow effective depths can inhibit plant root development and affect the soil's ability to retain water. According to research by Tian et al. [42], soil with a deep effective depth will have a better ability to retain water because it has a larger and more pore space. In addition, plants with shallow effective rooting depths can experience water shortages, which affect plant growth, so effective depth is one-factor determining soil's ability to retain water.

Soil bulk density is a soil physics variable that significantly correlates with available water in the soil. The results of the correlation test show that the lower the soil BV value, the higher the soil water availability value. Water in the soil fills the existing soil pores. The more pores in the soil, the more water will be available; otherwise, the more pores in the soil will cause the soil's weight to be light [43]. The higher the value of soil content weight, the smaller the total soil pore space, so that the proportion of pore space for water is also less, while the smaller the value of soil content weight, the higher the value of soil pore space, so that the *water capacity* in the soil will also increase [44].

Soil organic matter content significantly correlates with available water in the soil [45]. The correlation test results show the correlation value of organic matter content with available water. The greater the organic matter content, the more water is available in the soil. Organic matter can improve soil texture and become a water barrier because organic matter can bind water. The research results by Syaranamual et al. [46] show that organic matter plays an important role in the soil, helping retain water and maintaining water availability. The soil water content on organic land is greater than on semi-organic and conventional land. It is due to the small bulk density, high soil depth, high organic matter content, and high clay fraction [47, 48].

5. CONCLUSION

Soil water retention ability on organic land use is better than semi-organic and conventional. Organic land use has 18% accessible water (high), semi-organic 15.43% (high), and conventional 14.25% (medium). Soil physical properties that determine soil water retention ability include clay texture content, effective depth, organic matter content, macroporess, microporess, bulk density, and dust fraction content in the soil. Improving soil water retention focuses on adding organic matter to the soil. Organic matter significantly affects the correlation test on the availability of water in the soil. Specific-site characteristics of organic rice fields with the highest soil organic matter response to organic amendments could guide their application and result in the highest gains in agricultural output. The use of organic fertilizer and amendments to the soil could be attributed to increased soil water storage efficiency.

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