JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
Volume 12, Number 5 (October 2025):8751-8767, doi:10.15243/jdmlm.2025.125.8751
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

Research Article

The hydrological functions of Ultisols: Study of biopores and oil palm waste application impact in oil palm plantations

Sunarti[1*], Endriani[2], Muhammad Raidan Azani[3]

[1] Agroecotechnology Department, Faculty of Agriculture, and Center of Excellence on Watershed Management and Hydropower, University of Jambi, Jl Raya Jambi-Ma. Bulian Km. 15 Mendalo, Muaro Jambi, Jambi, Indonesia
[2] Agroecotechnology Department, Faculty of Agriculture/University of Jambi, Jl Raya Jambi-Ma. Bulian Km. 15 Mendalo, Muaro Jambi, Jambi, Indonesia
[3] Department of Environment, Jambi City, Jl H Agus Salim No. 07, Kota Baru District, Jambi, Indonesia

[*]corresponding author: snarti@unja.ac.id

Article history:
Received 2 June 2025
Revised 15 August 2025
Accepted 18 August 2025

Keywords:
biopores
hydrological function
oil palm
oil palm waste
Ultisols

Abstract

Ultisol is one type of soil available for the development of oil palm plantations in Indonesia. Oil palm development is faced with negative perceptions due to the degradation of soil and regional hydrological functions. The purpose of this research was to evaluate the impact of the application of biopores filled with various types of oil palm waste on the hydrological function of Ultisols with oil palm plantations. This research used an experimental method designed by creating eight experimental plots consisting of seven plots with biopores filled with various types of oil palm waste and one plot without biopores. The research data included organic carbon content, bulk density, porosity, permeability, infiltration, and water retention of soil. Data were obtained through analysis of soil samples in the laboratory and field measurements. Data were analyzed descriptively and by regression analysis with a confidence level of 95% (α = 0.05). The research results showed that the application of biopores with various oil palm wastes was able to improve soil characteristics and hydrological functions of Ultisols in oil palm plantations. The application of biopores with a combination of *Mucuna bracteata*, empty oil palm fruit bunches, oil palm pruning leaves, and oil palm shell biochar showed the best effect on improving soil characteristics and hydrological functions. Improvement of soil characteristics was correlated with improvement of hydrological function in Ultisols. Therefore, biopores filled with oil palm waste can be recommended as an integrative soil and water conservation technology for controlling the hydrological functions of Ultisols in oil palm plantations.

To cite this article: Sunarti, Endriani, and Azani, M.R. 2025. The hydrological functions of Ultisols: Study of biopores and oil palm waste application impact in oil palm plantations. Journal of Degraded and Mining Lands Management 12(5):8751-8767, doi:10.15243/jdmlm.2025.125.8751.

Introduction

Ultisol is one type of soil that is targeted for oil palm plantation development in Indonesia, although the characteristics of Ultisol show several obstacles to being used as agricultural land, such as low organic carbon content, high density, low porosity, low water availability, and sensitivity to erosion. The use of Ultisols for oil palm plantation development is related to the limited availability of fertile land. Meanwhile, the area of Ultisols reaches 45.8 million ha or 25% of the land area of Indonesia (Prasetyo and Suriadikarta, 2006).

The rapid development of oil palm in Indonesia is faced with two contradictory facts. The first fact is that oil palm is an agricultural commodity with economic value. According to data from BPS Indonesia, in 2022, the area of oil palm plantations in Indonesia reached 14.99 million ha, an increase of 47.33% compared to 2003, which was only 7.89

million ha (Central Bureau of Statistics of Indonesia, 2004, 2024). The area of oil palm plantations in Indonesia produces 45.74 million tons of oil palm, which is an Indonesian export commodity. Based on data from the Ministry of Agriculture (2021), Indonesia's oil palm exports in 2020 were 25.95 million tons, worth US$17.36 billion. The second fact is that the development of oil palm plantations in Indonesia is also considered to cause degradation of hydrological functions and pollution due to the disposal of oil palm waste. Several researchers have noted that the expansion of oil palm plantations can alter the local hydrological cycle, affecting water availability and increasing the risk of drought and flooding (Heidari et al., 2020; Gómez et al., 2023). The research results by Ullyta et al. (2022) proved that soil infiltration in oil palm plantations is smaller, and conversely, surface flow is greater than infiltration and surface flow in soil with agroforestry systems. The presence of oil palm waste is also considered a global environmental degradation because the disposal of waste such as empty bunches can pollute water sources, and waste from oil palm processing has an impact on greenhouse gas emissions and air pollution (Meijaard et al., 2020; Teng et al., 2020). The assumption is that environmental degradation affects the acceptance of Indonesian oil palm products in the global market.

The hydrological function of the soil is crucial in supporting groundwater reserves and water availability on agricultural land and in a region. Even the hydrological function will affect the sustainability of agricultural crop production (Di Prima et al., 2020; Vereecken et al., 2022). Rossiter et al. (2024) also stated that the selection of land use types and cropping systems in the Eastern Ganges Plain requires consideration of soil hydrology. Conversely, land management and use actions will affect the soil hydrological function. The research results by Liu et al. (2024) revealed that changes in land use are drivers of changes in regional hydrological processes. The expansion of agricultural land intensifies plant evapotranspiration, thus potentially exacerbating water stress during the early stages of plant growth. This is also in accordance with the statement of Patiño-Gutiérrez et al. (2024) that the ability of grasslands in Paramo to store, regulate, and supply water is influenced by agricultural activities and changes in land use. Therefore, the soil hydrological function must be a consideration in the planning of agricultural land use, including the development of oil palm plantations.

Soil and water conservation technology has been widely recommended for the conservation of soil hydrological functions. However, biopores offer an integrated solution to the degradation of hydrological functions and pollution from oil palm plantation waste. Therefore, its application is also an alternative action to fulfill the requirements of the Indonesian Sustainable Palm Oil (ISPO) in the development of oil palm plantations, namely the principles of environmental management, natural resources, and biodiversity (Presidential Regulation of the Republic of Indonesia No. 44/2020). The application of the ISPO principles aims to eliminate the assumption that oil palm plantations are the primary cause of environmental degradation, thereby increasing the acceptance of Indonesian palm oil products in the global market.

Biopores are a soil and water conservation technology designed to provide water absorption paths into the soil and are integrated with the composting of organic materials. According to Ruslinda et al. (2022), biopores are more commonly applied in residential areas to control puddles or floods. The research results by Dammayatri et al. (2023) demonstrated that designing and optimizing green open spaces, and implementing biopores (18.27% of what is needed), can reduce puddles in Jakarta by 15.6%. However, because biopores are integrated with composting, it is estimated that biopores can also improve soil properties. Increasing water absorption into the soil and the water holding capacity of soil through biopores will increase water availability and groundwater reserves (Landl et al., 2019; Devianti et al., 2020; Hanuf et al., 2021; Umasugi et al., 2021; Ashabie and Masjud, 2022; Ruslinda et al., 2022). Even the research results of Devianti et al. (2020) show that biopores with *Mucuna bracteata* can significantly reduce surface runoff by 31.81% and erosion rates by 29.66%, compared to areas without biopores.

Biopores have been proven to reduce the impact of damage to soil hydrological function. However, an appropriate formulation is needed regarding the application of biopore integration and palm oil waste on soil in oil palm plantations. The results of existing studies have also failed to provide a comprehensive and specific understanding of their impact on soil properties and soil hydrological conditions in oil palm plantations. Therefore, exploration of studies focusing on biopore integration with several types of oil palm waste is expected to contribute to determining the most effective and practical formula for conserving the hydrological function of soil in oil palm plantations (Aprisal et al., 2019; Devianti et al., 2020, 2022; Hanuf et al., 2021; Gómez et al., 2023). The research aimed to explore the impact of biopore application with various types of oil palm waste on the hydrological function of Ultisols with oil palm plantations.

Materials and Methods

Location and time of study

The research was conducted on the Oil Palm Research and Teaching Farm plantation of the Faculty of Agriculture, University of Jambi, in Mendalo Indah Village, Jambi Luar Kota District, Muaro Jambi Regency. The research was conducted in 2023 for 3 months (August-October 2023). The surface of the oil palm plantation land at the experimental location was covered with shrub vegetation of medium density. Oil palm plants in all experimental plots were 4 years old. Oil palm plants have not been optimally maintained, as is generally the case with smallholder oil palm plantations. The soil at the research location is classified as Ultisols with a slope of 9%. The soil at the experimental location had a soil bulk density of 1.47 g cm^{-3} and a porosity of only 44.53%. The soil organic carbon content was very low, at 0.85%. The soil permeability was 3.78 cm h^{-1}. The infiltration rate and capacity were 2.08 cm h^{-1} and 11.40 cm h^{-1}, respectively. A constant infiltration rate of 1.56 cm h^{-1} was achieved in a relatively short time of 30 minutes. The initial soil water retention at several pressure (pF) conditions was 41.54% (pF 1.0), 30.72% (pF 2.0), 24.33% (pF 2.54), and 13.39% (pF 4.2). Based on soil water retention at field capacity (pF 2.54) and permanent wilting point (pF 4.2), the soil available water was 10.94%.

Materials

The materials required for this research included biopores, oil palm waste in the form of *Mucuna bracteata* green material, empty oil palm bunches, pruned oil palm leaves, oil palm shell biochar, EM4, and disturbed and undisturbed soil samples. Biopore filler materials in the form of oil palm leaves pruned were obtained from oil palm plantations at the research location. *Mucuna bracteata*, empty oil palm fruit bunches, and oil palm shell charcoal were obtained from oil palm plantations around the research location. *Mucuna bracteata*, empty fruit bunches, shell charcoal, and oil palm leaves pruned that will be inserted into the biopore infiltration holes were previously chopped using copper. Biopore filler materials have different characteristics, especially their decomposition speed, which is indicated by the C/N ratio. *Mucuna bracteata*, empty oil palm fruit bunches, oil palm shell charcoal, and oil palm leaves pruned each have C/N values of 8.60, 26.00, 19.23, and 67.00. The EM4 used in the research was a ready-to-use material purchased at an agricultural store. The disturbed and undisturbed soil samples were taken from the experimental location and used as material for analysis in the laboratory to obtain soil data before and after treatments.

Research design

The research employed an experimental method. The experiment was conducted by creating twenty-four observation plots with eight treatments. The observation plots were prepared with a size of 9 m x 9 m. The treatments tested were biopore + *Mucuna bracteata* (P1); biopore + empty oil palm bunch (P2); biopore + empty oil palm bunch + oil palm shell biochar (P3); biopore + oil palm shell biochar (P4); biopore + pruned oil palm leaves (P5); biopore + pruned oil palm leaves + oil palm shell biochar (P6); biopore + *Mucuna bracteata* + empty oil palm bunch + pruned oil palm leaves + oil palm shell biochar (P7); and without biopore (P8). The eight treatments were arranged in a randomized block design with three replications.

Research implementation

The research activities consisted of biopore installation, soil sampling, and infiltration measurement. Biopores in each experimental plot were made with five pieces (Figure 1) with a depth of 100 cm. Biopores were filled with several types of oil palm waste that were adjusted to the treatment in each observation plot. The amount of waste put into the biopores was adjusted to the depth of the biopores. Soil sampling and infiltration measurement were taken before and after 3 months of biopore installation. Soil sampling in the observation plot consisted of both disturbed and undisturbed soil samples. Disturbed soil samples were used to determine soil organic carbon content, and undisturbed soil samples were used to determine soil bulk density, porosity, soil water retention, and soil permeability. Infiltration measurements were conducted at observation points determined at the same position in each experimental plot (around the biopore) with a double-ring infiltrometer.

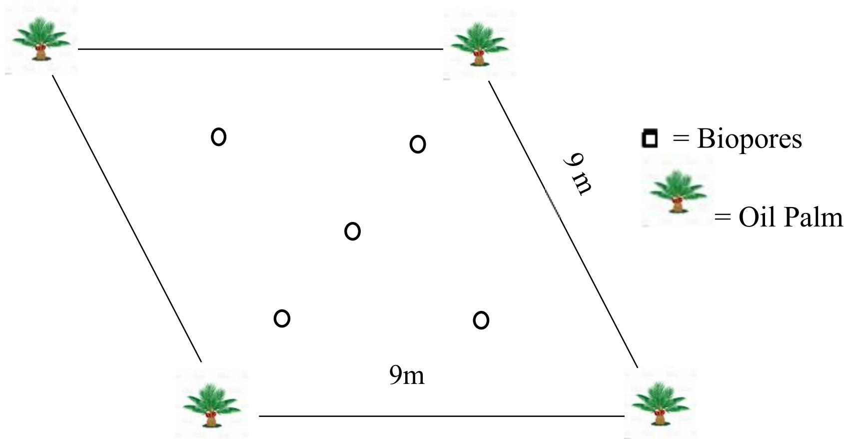


Figure 1. Observation plot design of biopores position.

Soil analysis methods

The soil data collected consisted of organic carbon, bulk density, total pore space, permeability, and soil water content at pF levels of 1.0, 2.0, 2.54, and 4.20 obtained through analysis of soil samples in the laboratory. Soil organic carbon was determined using the wet cindering method using potassium dichromate and titration with sulfuric acid (Walkley and Black, 1934; Meersmans et al., 2009). Soil bulk density and water retention were determined by the gravimetric method. Soil porosity was calculated based on soil bulk density and particle density (Flint and Flint, 2018). The soil available water was calculated based on the difference between soil water content at pF 2.54 and pF 4.20 (Spasić et al., 2023). Soil permeability was determined by the constant water table method according to the principle of Darcy's Law (Hillel, 2003; Lakshmi, 2004). Infiltration was measured in the field using a double-ring infiltrometer and will be analyzed using the Horton Model (Hillel, 2003; Lakshmi, 2004; Yang et al., 2020; Faridah et al., 2023; Khanaum and Borhan, 2023).

Data analysis

Data related to several soil properties and hydrological functions obtained through research were analyzed descriptively. Correlation between soil properties and correlation of several soil properties with hydrological functions were analyzed using regression analysis with a confidence level of 95%.

Results and Discussion

Selected soil properties under the influence of biopores and oil palm waste application

The research results illustrated that biopores filled with several types of palm oil waste caused an increase in soil organic carbon content, compared to the organic carbon content of soil without biopores (Table 1) and soil before treatments. In accordance with other research that also proved the effect of biopore treatment filled with organic materials can increase soil organic carbon content (Rahman et al., 2020; Hanuf et al., 2021; Nur Qadri and Gau, 2023). The increase in organic carbon content is caused by waste from crop residue that is put into the biopores, undergoing decomposition, thereby contributing carbon and organic matter to the soil. According to Fu et al. (2021), crop residue contains approximately 40% organic carbon, and when crop residues are incorporated into the soil, they can increase and reduce the loss of soil organic carbon content.

Table 1. Soil organic carbon, bulk density, and porosity due to the application of biopores and oil palm waste.

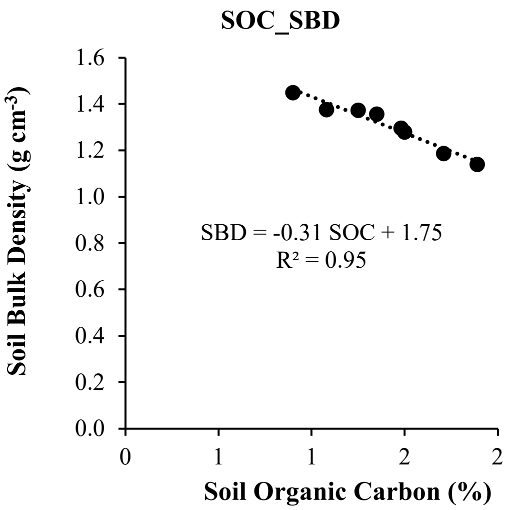
Plot Code	Soil Organic Carbon		Soil Bulk Density (g cm^{-3})	Porosity (%)
	Content (%)	Criteria*		
P1	1.50	Low	1.28	51.69
P2	1.08	Low	1.38	48.00
P3	1.35	Low	1.36	48.85
P4	1.71	Low	1.19	55.29
P5	1.25	Low	1.37	48.18
P6	1.48	Low	1.30	51.08
P7	1.89	Low	1.14	57.02
P8	0.90	very Low	1.45	45.36

Remark: * based on criteria of Soil Research Center (1980); biopore + *Mucuna bracteata* (P1); biopore + oil palm empty fruit bunch (P2); biopore + oil palm empty fruit bunch + oil palm shell biochar (P3); biopore + oil palm shell biochar (P4); biopore + pruned oil palm leaves (P5); biopore + pruned oil palm leaves + oil palm kernel shell biochar (P6); biopore + *Mucuna bracteata* + oil palm empty fruit bunch + pruned oil palm leaves + oil palm shell biochar (P7); and without biopore (P8)

The increase in soil organic carbon due to the use of biopores and various types of oil palm waste reached 20%. The organic carbon content in soil with biopores ranged from 20% to 110% compared to the soil without biopores (P8). The highest increase in soil organic carbon content occurred in plots with biopores that received a mixture of *Mucuna bracteata*, empty fruit bunches, pruned leaves, and palm shell biochar (P7), but the increase still fell within the low criteria (Table 1). The difference in the increase in soil organic carbon content variations in decomposition rates or C/N ratios among plots which were attributed to differences in the types of oil palm waste. According to Dang et al. (2025), the C/N ratio of crop residues affects the amount of organic carbon contribution to soil. This is in accordance with the results of previous research that also showed that the composition and combination of types of organic materials put into biopores will affect the amount of compost or organic material produced, causing differences in their contribution to soil organic carbon content (Santosa, 2018; Ruslinda et al., 2021; Ruslinda et al., 2022). Research by Getino-Álvarez et al. (2023) also explained that a good balance of mineralization and immobilization of soil organic matter occurs when the decomposition rate or C/N value is 20-30, as under forest stands.

The research results showed that the application of biopores filled with several types of oil palm waste also had a positive effect on reducing bulk density and increasing soil porosity (Table 1). This occurs due to the increased aggregation and activity of soil microorganisms resulting from the contribution of soil organic carbon from oil palm waste filling the biopores. According to Fu et al. (2021), incorporation of crop residues into the soil can increase the microorganisms' activities and produce organic acids, which can affect the aggregation, structure, bulk density, and porosity of the soil. The research results are in accordance with previous studies that also showed the use of organic materials, such as olive oil mill waste and biochar, caused improvements in soil bulk density and porosity levels, and formed structures and soil pores (Winarso et al., 2021). The use of biopores and various types of oil palm waste resulted in a decrease in soil bulk density of 5.52%-21-38% compared to soil in plots without biopores. On the other hand, the increase in soil porosity is 5.82%-25.71% (Table 1). The changes in both are also not optimal due to the suboptimal increase in soil organic carbon content, because soil organic carbon content is closely correlated with soil bulk density and soil porosity (Fukumasu et al., 2022; Robinson et al., 2022) and the research results also showed that the soil organic carbon with soil bulk density and porosity had a correlation coefficient of 0.95 each (Figure 2). This finding is in accordance with the research results that also prove that increasing the content of organic carbon or matter in the soil will affect the decrease in soil bulk density or soil density (Winarso et al., 2021; Dewi et al., 2022).

The condition of improving soil organic carbon content and soil density that is not optimal due to the use of biopores and various types of oil palm waste is also caused by observations carried out in a short period of time (8 weeks) or when the oil palm waste in the biopores begins to compost or decompose. This condition causes the organic material produced to not interact perfectly in the soil. However, based on research data, observations over a longer period of time are predicted to show the effect of implementing biopores and more optimal oil palm waste on improving soil organic carbon content, soil bulk density, and soil porosity.



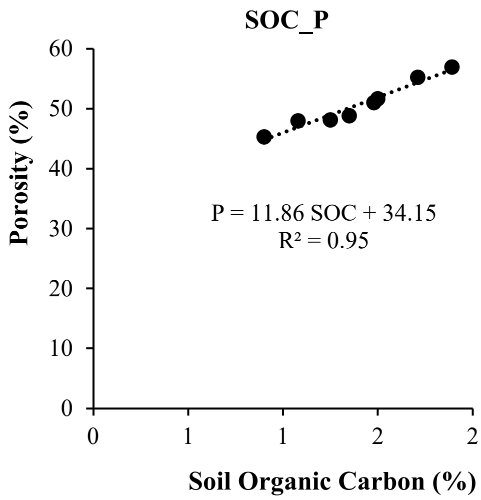


Figure 2. Correlation between organic carbon content and soil bulk density.

Previous research has shown that the positive effect of providing organic material to the soil will strengthen over time and even in the long term; continuous provision of organic material to the soil will also affect the organic material content in deeper soil layers. The impact of providing organic material shows dynamic changes in the soil. Providing organic material or fertilizer in the long term shows an increase in soil organic carbon content and the abundance of soil microorganisms so that it has a major effect on soil porosity and structure. Therefore, it is necessary to carry out observations over a longer and periodic period to see the dynamics of its influence (Johansen et al., 2023; Lange et al., 2023). The effect of biopore application and oil palm waste on soil organic carbon content, soil bulk density, and soil porosity will be related to soil hydrological conditions such as soil permeability, infiltration, and soil water retention.

The soil hydrological function under the influence of biopores and oil palm waste application

Soil permeability

The research results (Table 2) show that the application of biopores with various types of oil palm waste on the soil in oil palm plantations shows an effect on soil permeability. The soil permeability with biopores and oil palm waste has a permeability that is classified as quite fast to very fast. While the permeability of soil without biopores and oil palm waste, and the previous soil permeability, is classified as moderate. The highest increase in permeability (27.78 cm h^{-1}) occurred due to the use of biopores and a mixture (*Mucuna bracteata*, empty oil palm fruit bunches, oil palm leaf prunes, and oil palm shell biochar (P7). Meanwhile, the lowest increase occurred in soil with biopores and empty oil palm fruit bunches (P2). This is related to the increase in organic carbon content and porosity and a decrease in bulk density in soil with biopores and empty oil palm fruit bunches (P2), which is lower than soil with biopores filled with other oil palm waste (Table 1).

Table 2. Soil permeability under the influence of biopores and oil palm waste application.

Plot Code	Permeability ($cm\ h^{-1}$)	Criteria*
P1	19.81	Fast
P2	8.48	Rather Fast
P3	11.81	Rather Fast
P4	22.01	Fast
P5	10.29	Rather Fast
P6	17.51	Fast
P7	27.78	Very Fast
P8	3.83	Moderate

Remark: *According to criteria of Uhland and Alfred (1951); biopore + *Mucuna bracteata* (P1); biopore + oil palm empty fruit bunch (P2); biopore + oil palm empty fruit bunch + oil palm shell biochar (P3); biopore + oil palm shell biochar (P4); biopore + pruned oil palm leaves (P5); biopore + pruned oil palm leaves + oil palm kernel shell biochar (P6); biopore + *Mucuna bracteata* + oil palm empty fruit bunch + pruned oil palm leaves + oil palm shell biochar (P7); and without biopore (P8)

The effect of soil organic carbon on permeability also depends on the type of organic material and land use (Li et al., 2021; Fitria and Soemarno, 2022). The soil carbon, organic, and bulk density influence soil permeability, although in some conditions, they will also be simultaneously influenced by soil texture due to the relationship to soil pores (Schroeder et al., 2022), and according to Singh et al. (2020), soil organic carbon and bulk density are sensitive parameters for soil permeability prediction.

The increase in soil permeability due to the application of biopores and oil palm waste in this research (Table 2) was lower than the soil permeability in the research of Fitria and Soemarno (2022), which used organic materials in the form of compost from organic waste and lime in coffee plantations. The difference in soil permeability shows a difference in response due to differences in the type of organic material. This is because the difference in C/N of compost is lower than that of fresh organic material, so that the compost reacts faster in the soil (H. Yang et al., 2021; Xie et al., 2022). Even the research results by Yan et al. (2021) also showed that the difference in C/N of pig farm biogas slurry given to the soil also caused differences in organic carbon content in the soil.

The research results (Figure 3) also prove that soil organic carbon content is correlated with soil permeability with a correlation coefficient of 0.97. Likewise, soil bulk density and soil porosity show a correlation with soil permeability, with correlation coefficients of 0.96 each. Soil with biopores and empty oil palm fruit bunches (P2) has a higher soil density and the lowest porosity compared to soil with biopores and other types of oil palm waste.

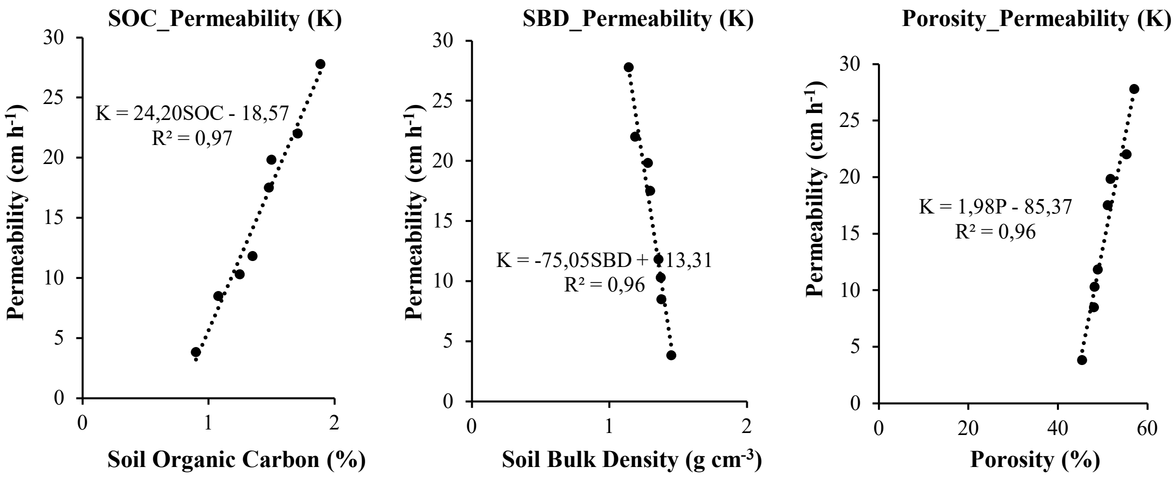


Figure 3. The correlation of soil permeability with soil organic carbon and soil bulk density.

Previous research has shown that soil organic carbon affects soil permeability along with soil water content, soil bulk density, and soil porosity (Yu et al., 2018; Forster et al., 2020; Alista and Soemarno, 2021; Lu et al., 2023). According to Usowicz and Lipiec (2021), soil organic carbon and soil porosity are positively correlated with soil permeability, while soil bulk density is negatively correlated with soil permeability.

Soil infiltration

The research results (Table 3) show that the application of biopores and various types of oil palm waste has an effect on increasing soil infiltration in oil palm plantations. In addition, the previous infiltration rate and capacity were only 2.08 $cm\ h^{-1}$ and 11.40 $cm\ h^{-1}$, respectively, and the constant infiltration time

(1.56 cm h^{-1}) was achieved at a faster time, namely 30 minutes. The effect of the application of biopores integrated with palm oil waste on infiltration is caused by changes in organic carbon content, bulk density, porosity, and soil permeability (Cal and Barik, 2020). The research results (Table 3) showed that various types of oil palm waste inserted into biopores show differences in effectiveness in influencing infiltration. The highest increase in infiltration occurred in soil with biopores filled with a mixture of *Mucuna bracteata*, empty fruit bunches, pruning leaves, and biochar of oil palm shell (P7). Figure 4 illustrates that the increase in infiltration rate due to the application of biopores filled with empty oil palm fruit bunches (P2) and biopores filled with empty oil palm fruit bunches and biochar of oil palm shell (P5) is lower than that of soil infiltration with biopores filled with other types of oil palm waste. Both also show no significant difference in the infiltration rate in soil without biopores (P8). In fact, based on the time to achieve a constant infiltration rate, P2 and P5 are also the same as the time to achieve a constant infiltration rate in soil without biopores (Table 3). The difference in the effectiveness of various types of oil palm waste on infiltration is also in accordance with the results of research by Santosa (2018), which proved that various types of fruit waste inserted into biopores showed different effectiveness in increasing soil infiltration.

Table 3. Soil infiltration on oil palm plantations due to the application of biopore and oil palm waste.

Plot Code	Constant Time (minute)	Infiltration Velocity, f (cm h^{-1})	Infiltration Capacity, F (cm h^{-1})
P1	55	4.36	38.40
P2	40	3.13	22.80
P3	50	4.22	34.80
P4	55	4.43	39.60
P5	40	3.30	25.20
P6	50	4.26	35.40
P7	65	4.52	42.60
P8	40	2.73	19.20

Remark: biopore + *Mucuna bracteata* (P1); biopore + oil palm empty fruit bunch (P2); biopore + oil palm empty fruit bunch + oil palm shell biochar (P3); biopore + oil palm shell biochar (P4); biopore + pruned oil palm leaves (P5); biopore + pruned oil palm leaves + oil palm kernel shell biochar (P6); biopore + *Mucuna bracteata* + oil palm empty fruit bunch + pruned oil palm leaves + oil palm shell biochar (P7); and without biopore (P8)

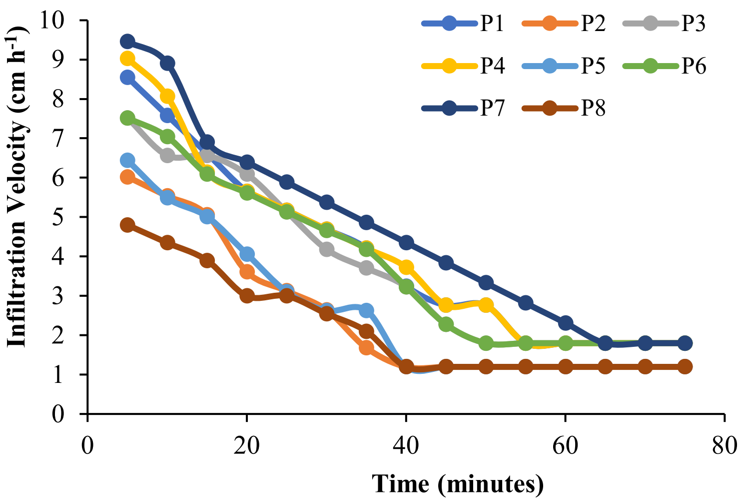


Figure 4. Infiltration velocity curve as affected by biopores and some oil palm waste applications.

Biopores filled with banana waste have the highest effectiveness in increasing soil infiltration, because the decomposition rate is faster than that of papaya and mango waste. The difference in infiltration is due to the different types of organic materials introduced into the biopores. Different types of organic materials incorporated into the soil will respond differently to soil properties, including infiltration (Bashir et al., 2021). Based on the infiltration data (Table 3) and the infiltration rate trend (Figure 4), it can be understood that the use of oil palm shell biochar as a biopore filler has a positive impact on increasing soil infiltration. Infiltration in soil with biopores filled with oil palm shell biochar shows a higher infiltration rate and capacity compared to soil with biopores without oil palm shell biochar. This is in accordance with the findings of several studies that reveal that biochar affects infiltration. Even biochar with a smaller size can increase the soil infiltration rate due to the abundant pore structure and increased specific surface area (Sharma et al., 2021; Jia et al., 2024; Sun et al., 2024). The recommendation to mix biochar with other organic materials is expected to be effective in increasing infiltration (Zou et al., 2022).

The research results also showed that soil infiltration in oil palm plantations is related to soil organic carbon content, bulk density, porosity, and water retention. Figure 5 shows a close correlation between soil organic carbon content and infiltration rate and capacity, with correlation coefficients of 0.84 and 0.91, respectively. Furthermore, soil bulk density and porosity are also correlated with infiltration rate and capacity, with correlation coefficients of 0.71 and 0.82, respectively. The correlation of soil organic carbon content, bulk density, and porosity with infiltration is also in accordance with the results of previous research, which have proven that increasing soil porosity will accelerate the process of water infiltration into the soil (Rahman et al., 2020; Sindagamanik et al., 2021; Umasugi et al., 2021; Prosanti et al., 2023; Qadri and Gau, 2023). Basset et al. (2023) also state that there is a significant correlation established between infiltration and soil structural properties such as soil bulk density, organic carbon, and porosity. This condition is a result of improving organic carbon, which can increase the activity of soil microorganisms, which affects soil pores (Fu et al., 2021). The infiltration depth also increases with decreasing soil bulk density (Al-Ogaidi et al., 2023). Improvements in soil properties resulting from the application of a technology will correlate with each other (Hu et al., 2024).

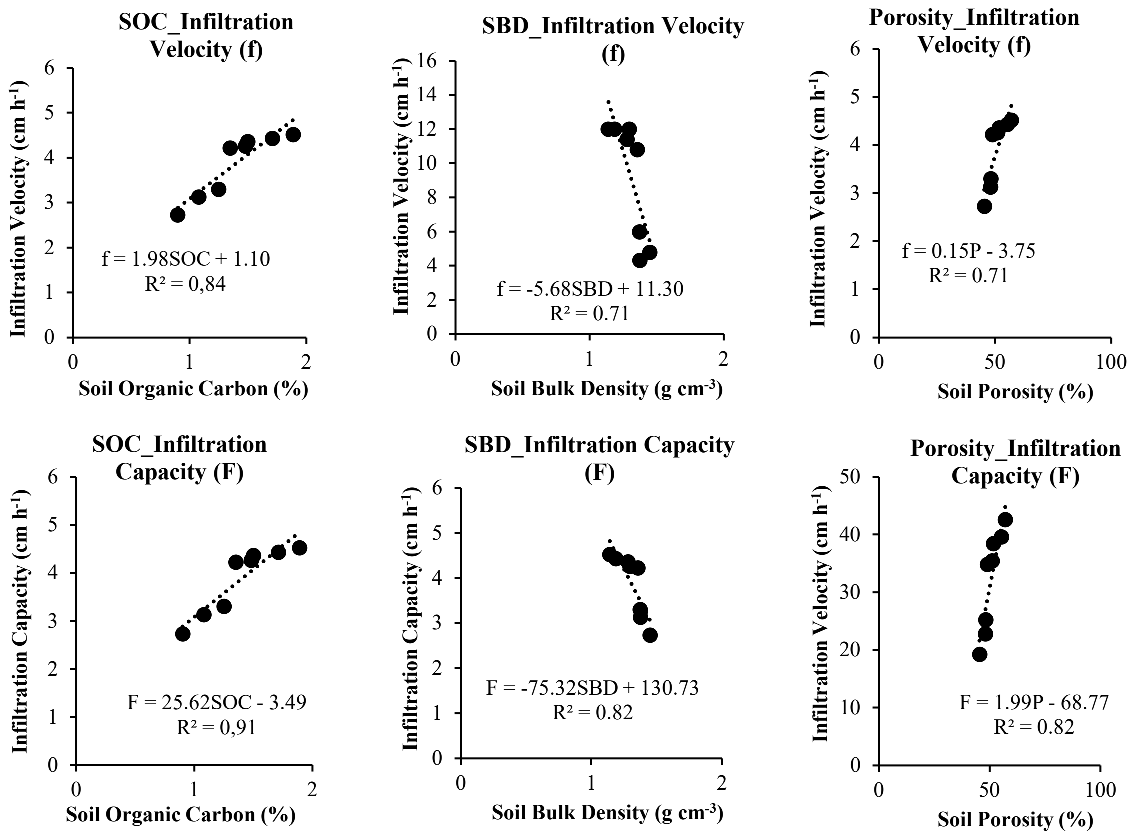


Figure 5. The correlation of soil organic carbon, bulk density, and porosity with infiltration.

Soil water retention

The research results (Figure 6) showed that the application of biopores and oil palm waste causes varying changes in soil water retention compared to the initial soil water retention. The changes vary based on the type of oil palm waste inserted into the biopores. The decrease in soil water retention in PWP conditions was highest in soil with biopores and a mixture of *Mucuna bracteata*, oil palm leaf pruned, and oil palm shell biochar (P7), and the increase in soil water retention in FC conditions was highest in soil with biopores and *Mucuna bracteata* (P1). The heterogeneity of soil water retention in PWP and FC due to differences in types of oil palm waste is also in accordance with the differences in the effects of compost, biochar, and biosolids on the soil. The use of compost and biochar has a better effect on improving soil organic matter content and soil physical properties than biosolids (Malone et al., 2023). The research results also showed that the decrease in soil water content in PWP and the increase in soil water content in FC were only 2.49%-28.13% and 5.29%-13.32%, respectively. This is also related to the less-than-optimal improvement of soil organic carbon content, bulk density, and porosity (Table 1), due to the fact that the results of waste decomposition in the biopores have not reacted optimally in the soil. Soil amendments require varying amounts of time to react in the soil optimally, and regular application over a long period will show optimal reaction (Johansen et al., 2023; Lange et al., 2023).

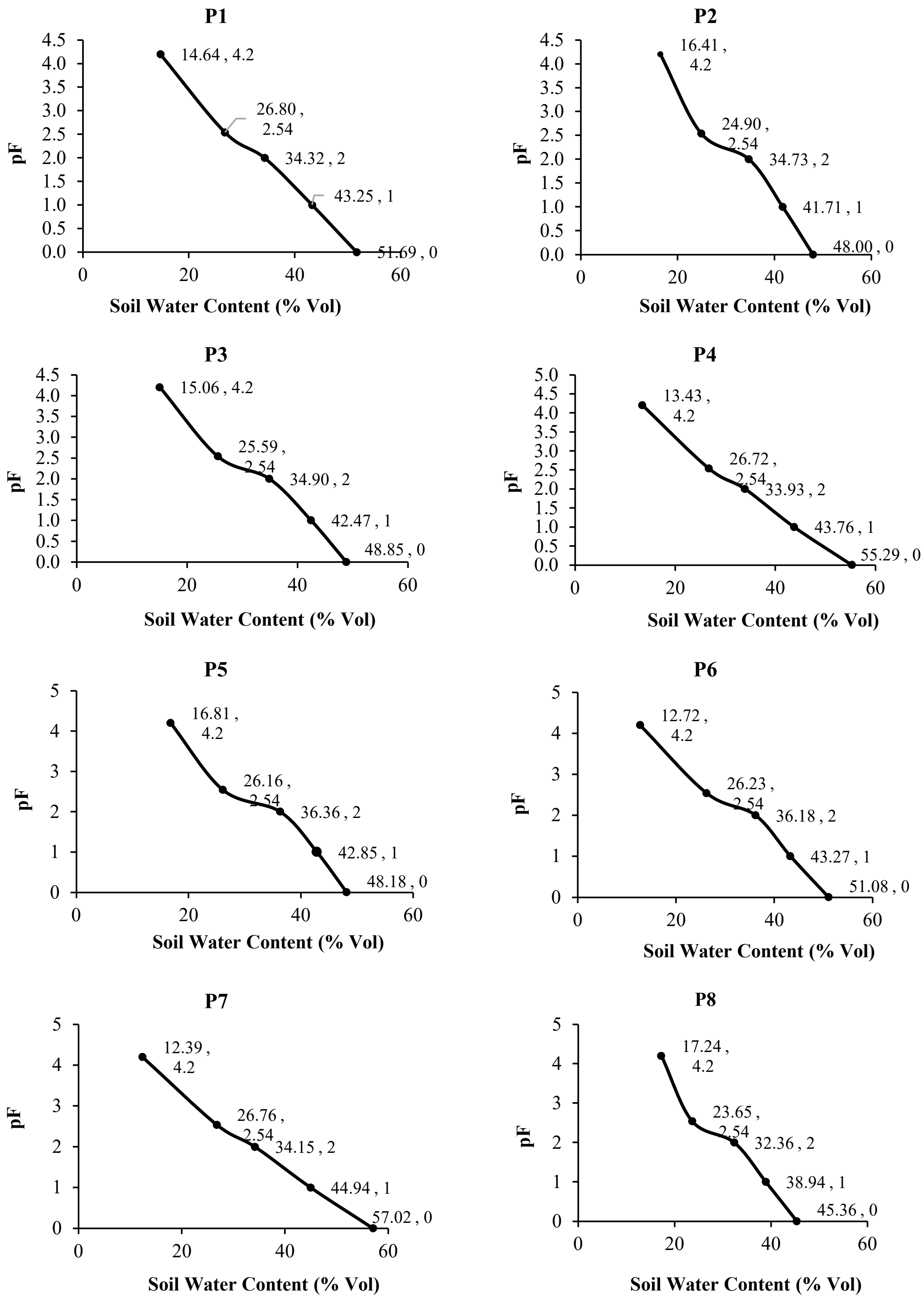


Figure 6. Soil water retention curve for each experiment plot.

The soil water retention curve (Figure 6) given by biopores and various types of oil palm waste shows a difference from that of soil without biopores and oil palm waste. The soil water retention curve with biopores and oil palm waste shows a gentler slope than the soil without biopores and oil palm waste (P8). This condition is caused by the lower density of soil with biopores and oil palm waste compared to soil without biopores and oil palm waste (Table 1). According to Chen (2020), research results explain that a higher soil density will cause the slope of the soil water retention curve to be steeper.

The result of research in Figure 7 illustrated that soil organic carbon content was closely correlated with changes in soil water retention under PWP and FC conditions, with correlation coefficients of 0.82 and 0.79, respectively. Several other research results showed that changes in soil water retention due to changes in soil organic carbon content vary in various soil conditions. Reducing disturbance or intervention to the soil combined with soil organic matter input will result in better soil water retention (Abdallah et al., 2021; Umasugi et al., 2021; Lemma et al., 2022; Jiang, 2023; Wang et al., 2023). Increasing soil organic carbon content can increase soil structure aggregation and porosity, thus affecting increased soil water retention (Panagea et al., 2021; Yang et al., 2023). Therefore, the research results (Figure 8) also proved that soil water retention in PWP and FC conditions was quite closely correlated with soil bulk density, with correlation coefficients of 0.78 and 0.68, respectively. An increase in soil bulk density causes an increase in soil water content in PWP conditions and decreases soil water content in TL conditions. In accordance with the results of other research that also show that there is a significant correlation between soil bulk density and soil water retention in PWP and FC conditions, it can even show that sand content can be used to predict water retention in FC and silt content to predict PWP (Qiao et al., 2019; Liu et al., 2024). The correlation coefficient, which is not too high, is also due to the presence of other physical properties of the soil that also affect soil water retention but have not been measured in this research, including soil pore size, pore size distribution, particle size, structure, and temperature. Therefore, more detailed research is still needed regarding the relationship between pore size, pore size distribution, and soil structure with soil water retention (Torres et al., 2021; Pham et al., 2023; Goldberg-Yehuda et al., 2024), especially to complement studies on oil palm plantations due to the application of biopores and oil palm waste.

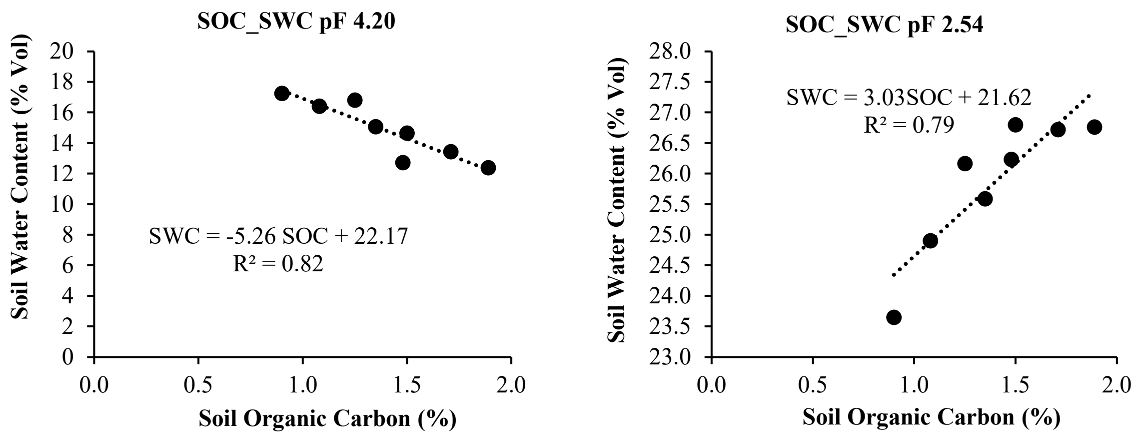


Figure 7. Correlation of organic carbon with soil water retention.

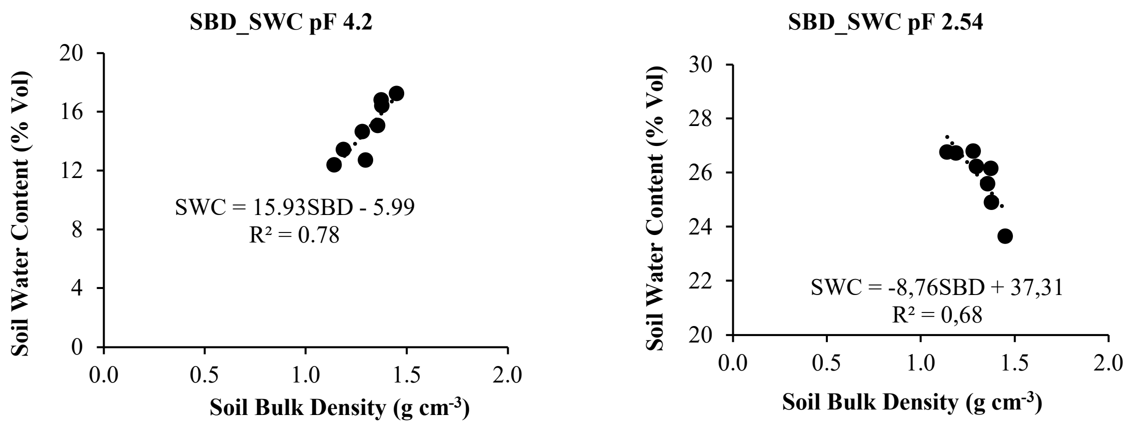


Figure 8. Correlation of soil bulk density with soil water retention.

Changes in soil water retention in PWP and FC conditions of soil in oil palm plantations that implement biopores and oil palm waste have an impact on changes in the content of soil available water. The research results (Table 4) illustrated that the soil available water content has changed due to the implementation of biopores and oil palm waste. This finding is the same as the research by Hanuf et al. (2021), which has proven that the application of biopores and compost in coffee plantations can increase the soil available water content by up to 65%, 60%, and 51% at depths of 0-20 cm, 21-40 cm, and 41-60 cm, respectively. The changes in soil water retention are caused by the dynamics of soil organic carbon in soil due to the application of various technologies, including the provision of soil amendment (Panagea et al., 2021; Ramírez et al., 2023; Goldberg-Yehuda et al., 2024).

Table 4. Soil available water (SAW) in oil palm plantation as affected by the application of biopores and some oil palm wastes.

Plot Code	Soil Available Water (% Vol)	Criteria*
P1	12.16	Moderate
P2	8.49	Low
P3	10.53	Moderate
P4	13.29	Moderate
P5	9.35	Low
P6	13.51	Moderate
P7	14.37	Moderate
P8	6.41	Low

Remark: based on criteria of Soil Research Center (1980); biopore + *Mucuna bracteata* (P1); biopore + oil palm empty fruit bunch (P2); biopore + oil palm empty fruit bunch + oil palm shell biochar (P3); biopore + oil palm shell biochar (P4); biopore + pruned oil palm leaves (P5); biopore + pruned oil palm leaves + oil palm kernel shell biochar (P6); Biopore + *Mucuna bracteata* + oil palm empty fruit bunch + pruned oil palm leaves + oil palm shell biochar (P7); and without biopore (P8)

The impact of biopore and oil palm waste application on increasing soil available water content (Table 2) shows variation based on the type of waste filled into the biopore as well as soil water retention in PWP and FC (Figure 2). This condition arises due to the difference in decomposition rates of each type of organic material, resulting in varying contributions to the organic carbon content and differing reactions in the soil (Dang et al., 2025). The research results also showed that empty oil palm fruit bunches and oil palm leaf prunings had C/N ratios of 26.00 and 67.00, respectively, which were higher than those of *Mucuna bracteata* (8.60) and oil palm shell biochar (19.23). Therefore, empty oil palm fruit bunches and oil palm leaf prunings will be slower to contribute organic carbon to the soil if not combined with other materials that have low C/N. The research results are also aligned with the findings of other research, which show that differences in the types of litter inserted into biopores cause differences in their effects on soil water retention or storage and soil available water levels (Santosa, 2018; Umasugi et al., 2021).

The increase in soil available water content due to the application of biopores and oil palm waste ranged from 32.45% to 124.18% with moderate criteria, except for P2 and P5, which were still classified as low criteria. In addition, the soil available water resulting from the application of P2, P5, and P8 is lower than the initial soil available water. Click or tap here to enter text. It shows that the soil organic matter plays a dynamic role and each type of organic material will have a different level of effectiveness in the maintenance and improvement, and each soil property, including soil water retention and soil available water (Bashir et al., 2021; Chari and Taylor, 2022). The application of biopores and oil palm waste to the soil in oil palm plantations has not had a significant impact on changes in the soil's available water content. This is also related to the less-than-optimal improvement in soil organic carbon content, bulk density, and porosity due to the application of biopores and oil palm waste as discussed above. In accordance with the research results that showed that the soil available water content is closely correlated with the soil organic carbon content, bulk density, and porosity, with correlation coefficients of 0.92, 0.84, and 0.84, respectively (Figure 9).

This phenomenon is also in accordance with the results of previous researches, which prove that an insignificant increase in organic carbon content in the soil has only a small impact on soil water retention (Minasny and McBratney, 2018; Sunarti and Lizawati, 2024). Previous research results also prove that although soil available water content is influenced by soil organic carbon content, bulk density, and drainage pores simultaneously, there are still other soil properties that are also predicted to affect soil available water, such as soil colloid types and soil cation absorption (Libohova et al., 2018; Aliyyah et al., 2022; Sunarti and Lizawati, 2024). The optimization of soil water retention through the application of biopores and oil palm waste still requires periodic observation over a longer period to gain an understanding of the dynamics of soil organic carbon contributions and their reactions within the soil. This is also related to the importance of the influence of soil organic carbon on soil permeability and infiltration, which concerns the process of water absorption into the soil, becoming a source of water retained in the soil (Goldberg-Yehuda et al., 2024).

The research results presented in Figure 10 also showed that soil permeability is correlated with soil water retention, with a coefficient of 0.82 for the correlation of soil water content at pF 4.2, 0.76 for the correlation of soil water content at pF 2.54 with permeability, and 0.91 for the correlation of soil available water content with permeability. Likewise, the rate and capacity of soil infiltration also show a correlation with soil water retention at PWP, FC, and soil available water (Figure 11). This is in accordance with the opinion of Goldberg-Yehuda et al. (2024), which states that soil permeability and infiltration concern the process of water absorption into the soil to become a source of water retained in the soil.

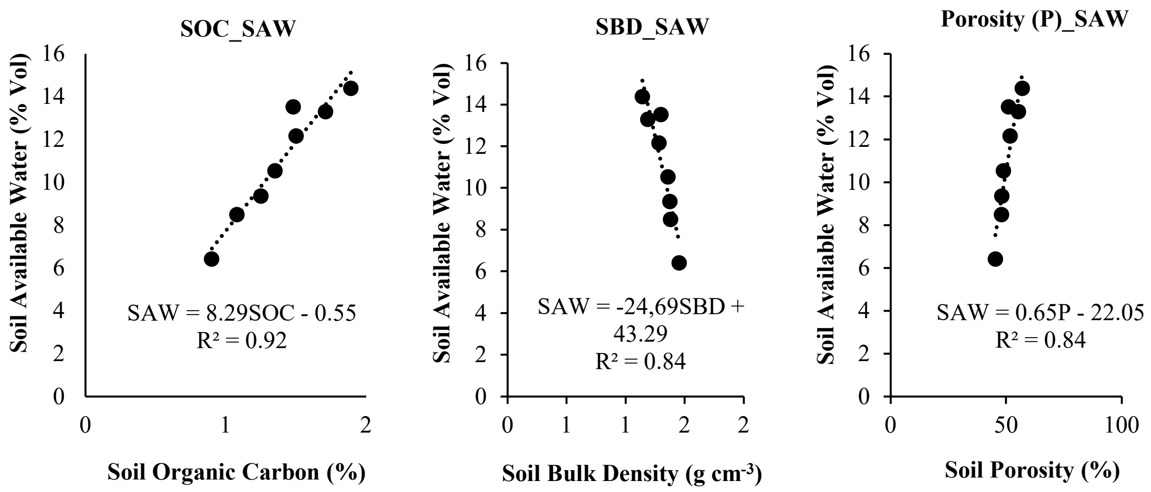


Figure 9. Correlation of soil organic carbon, bulk density, and porosity with soil available water.

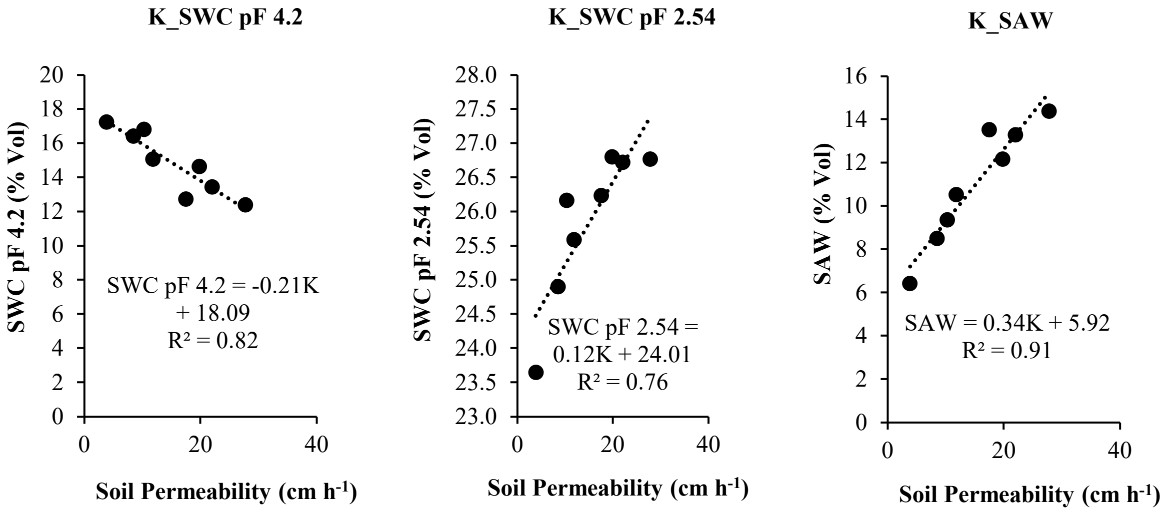


Figure 10. Correlation of soil permeability with soil available water.

The use or addition of oil palm shell biochar also has a positive effect on soil water retention as it affects soil organic carbon content, bulk density, porosity, and infiltration. The result of research by Maulana et al. (2025) showed that the use of 20 t ha^{-1} empty oil palm fruit bunch biochar can increase the organic matter of the soil by 31.74%. The result of research by Endriani et al. (2024) also proved that the use of 20 t ha^{-1} empty oil palm fruit bunch combined with compost and natural phosphate can improve organic matter content, bulk density, porosity, and water availability of soil. In accordance with the results of other research, that have also revealed that the provision of various types of biochar on various soil textures can increase soil water retention due to a decrease in macro pores, an increase in micro pores, and improvements in other soil physical properties. However, the use of biochar on soils with different textures causes diversity in biochar mechanisms in influencing soil water retention. The effect of biochar on soil water content in field capacity and available water in coarse-textured soils is greater than that of medium and fine-textured soils. Biochar can even be used for water conservation in light-textured soils (Alghamdi et al., 2020; Sharma et al., 2021; Wei et al., 2023; Daraei et al., 2024; Huang et al., 2024; Jia et al., 2024; Sun et al., 2024).

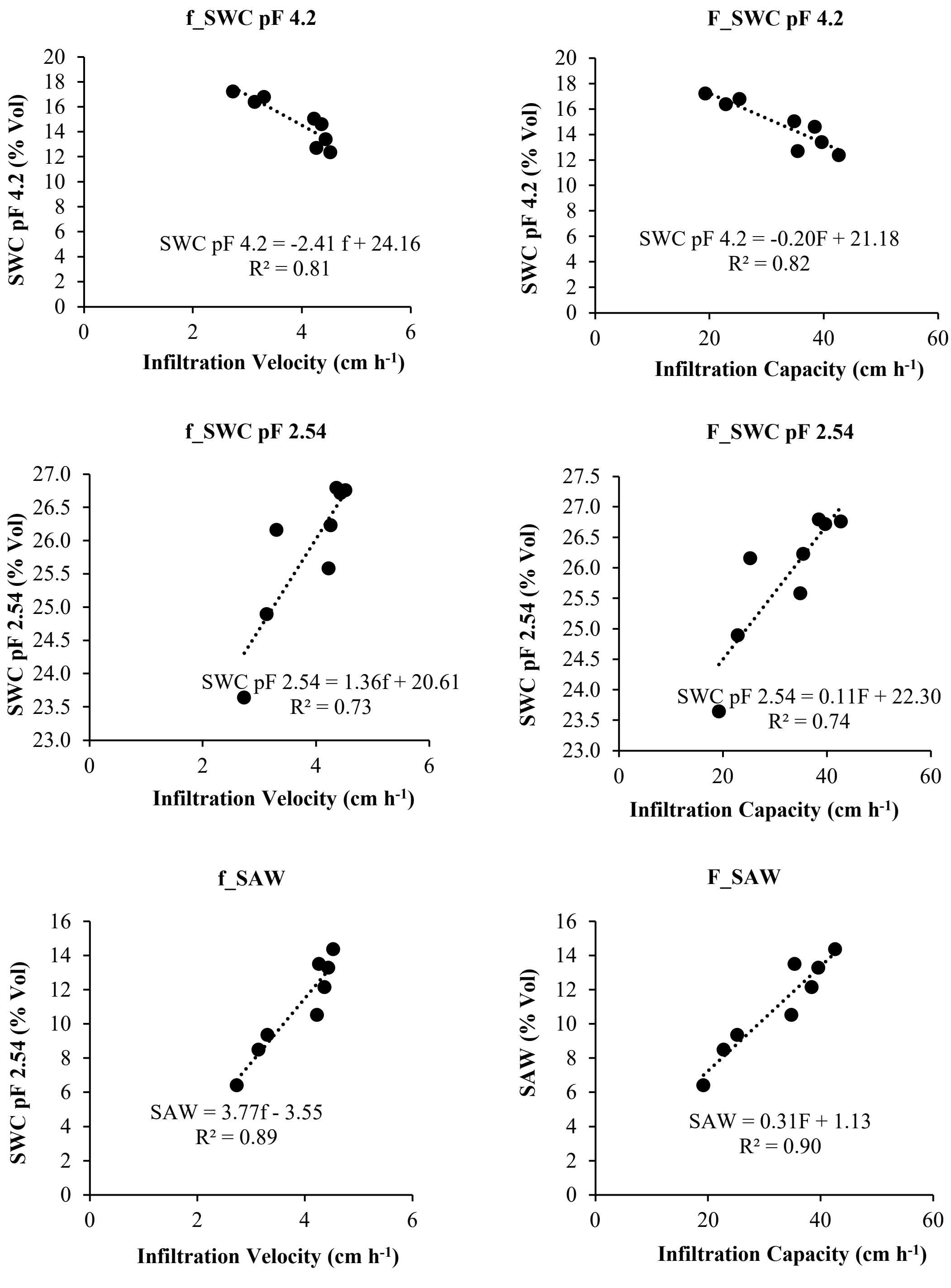


Figure 11. The correlation of soil water content and soil infiltration.

Conclusion

The integration of biopores with oil palm wastes has a positive impact on improving the organic carbon content, bulk density, porosity, permeability, infiltration, and water retention of Ultisols. The integration of biopores with a mixture of *Mucuna bracteata*, empty fruit bunches, pruned leaves, and oil palm shell biochar is the best alternative to enhance the soil characteristics and hydrological functions of Ultisols in oil palm plantations. Based on the research results, biopores and a mixture of several types of oil palm waste are an integrative soil and water conservation technology that can be applied to support the development of sustainable oil palm plantations.

Acknowledgments

The authors thank the Rector of Jambi University and Dean of the Faculty of Agriculture who have facilitated research funds through the 2023 Faculty of Agriculture Non-Tax Revenue Budget (PNBP), number: SP-DIPA-

023.17.2.677565/2023 dated November 30, 2022 with the Faculty of Agriculture Applied Research Scheme with Contract Agreement Letter No. 311/UN21.11/PT.01.05/SPK/2023 dated April 17, 2023. The authors also thank the Head of the Research and Teaching Farm, Faculty of Agriculture, Jambi University, and Doni Saputra who have assisted in implementing research in the field.

References

Abdallah, A.M., Jat, H.S., Choudhary, M., Abdelaty, E.F., Sharma, P.C. and Jat, M.L. 2021. Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A review. *Agronomy* 11(9), doi:10.3390/agronomy11091681.

Alghamdi, A.G., Alkhasha, A. and Ibrahim, H.M. 2020. Effect of biochar particle size on water retention and availability in a sandy loam soil. *Journal of Saudi Chemical Society* 24(12):1042-1050, doi:10.1016/j.jscs.2020.11.003.

Alista, F.A. and Soemarno, S. 2021. Analysis of soil surface and subsurface permeability in Robusta coffee land. *Jurnal Tanah dan Sumberdaya Lahan* 8(2):493-504, doi:10.21776/ub.jtsl.2021.008.2.20 (*in Indonesian*).

Aliyyah, H.L., Pulungan, N.A.H.J. and Sartohadi, J. 2022. Soil water availability for crops on landslide deposits in Bompon Sub-Watershed, Magelang. *IOP Conference Series: Earth and Environmental Science* 974(1), doi:10.1088/1755-1315/974/1/012042.

Al-Ogaidi, A.A.M., Mahmood, M.T., Mohammed, A.K. and Yasin, H. I. 2023. Effect of soil bulk density on water infiltration in layered soil. *Tikrit Journal of Engineering Sciences* 30(3), doi:10.25130/tjes.30.3.16.

Aprisal, Taifur, W.D., Dwipa, I. and Putra, T.H.A. 2019. The impact of palm oil mill wastewater on the soil properties of paddy fields. International *Journal on Advanced Science, Engineering and Information Technology* 9(6), doi:10.18517/ijaseit.9.6.9749.

Ashabie, A.S. and Masjud, Y.I. 2022. The study of Biopore Infiltration Holes (BIH) implementation to reduce waterlogging in President University campus area. *IOP Conference Series: Earth and Environmental Science* 1111(1), doi:10.1088/1755-1315/1111/1/012060.

Bashir, O., Ali, T., Baba, Z.A., Rather, G.H., Bangroo, S.A., Mukhtar, S.D., Naik, N., Mohiuddin, R., Bharati, V. and Bhat, R.A. 2021. Soil organic matter and its impact on soil properties and nutrient status. In: *Microbiota and Biofertilizers*, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs, doi:10.1007/978-3-030-61010-4_7.

Basset, C., Najm, M.A., Ghezzehei, T., Hao, X. and Daccache, A. 2023. How does soil structure affect water infiltration? A meta-data systematic review. *Soil and Tillage Research* 226:105577, doi:10.1016/j.still.2022.105577.

Çal, S. and Barik, K. 2020. Hydraulic conductivity values of soils in different soil processing conditions. *Alınteri Zirai Bilimler Dergisi* 35(1):132-138, doi:10.28955/alinterizbd.740904.

Central Bureau of Statistics of Indonesia. 2004. Statistical Yearbook of Indonesia 2004 (*in Indonesian*).

Central Bureau of Statistics of Indonesia. 2024. Statistical Yearbook of Indonesia 2024 (*in Indonesian*).

Chari, N.R. and Taylor, B.N. 2022. Soil organic matter formation and loss are mediated by root exudates in a temperate forest. *Nature Geoscience* 15(12), doi:10.1038/s41561-022-01079-x.

Chen, Y. 2020. Soil-water retention curves derived as a function of soil dry density. *GeoHazards* 1(1), doi:10.3390/geohazards1010002.

Dammayatri, R., Susantoro, T.M. and Wikantika, K. 2023. Green open space and barren land mapping for flood mitigation in Jakarta, the Capital of Indonesia. *Indonesian Journal of Geography* 55(2), doi:10.22146/ijg.76452.

Dang, L.V., Lyu, H., Matsuura, S., Wagai, R., Yasuno, H., Tanaka, H. and Sugihara, S. 2025. Plant residue quality regulates mineral-associated organic matter formation rate and pathway in converted upland soil. *Environmental Research* 283:122158, doi:10.1016/j.envres.2025.122158.

Daraei, E., Bayat, H. and Gregory, A.S. 2024. Impact of natural biochar on soil water retention capacity and quinoa plant growth in different soil textures. *Soil and Tillage Research* 244:106281, doi:10.1016/j.still.2024.106281.

Devianti, Irwansyah, Yunus, Y., Arianti, N.D., Thamren, D.S. and Sitorus, A. 2022. Influence of biopores infiltration holes on the level of erosion in oil palm plantation areas. *International Journal of Design and Nature and Ecodynamics* 17(2), doi:10.18280/ijdne.170204.

Devianti, Jayanti, D.S. and Sarika, D.T. 2020. Analysis of surface runoff at oil palm plantation areas from the uses of Bio-Pore Infiltration Holes (BIH). *International Journal of Scientific & Technology Research* 9(1):3915-3918.

Dewi, R.K., Fukuda, M., Takashima, N., Yagioka, A. and Komatsuzaki, M. 2022. Soil carbon sequestration and soil quality change between no-tillage and conventional tillage soil management after 3 and 11 years of organic farming. *Soil Science and Plant Nutrition* 68(1), doi:10.1080/00380768.2021.1997552.

Di Prima, S., Castellini, M., Rodrigo-Comino, J. and Cerdà, A. 2020. Soil hydrology for a sustainable land management: Theory and practice. *Water (Switzerland)* 12(4), doi:10.3390/W12041109.

Endriani, Sunarti, Farni, Y., Listyarini, D. and Fuadi, N.A. 2024. The effectiveness of biochar, compost, and natural phosphate in improving soil quality in oil palm plantations. *Akta Agrosia* 27(2):71-80, doi:10.31186/aa.27.2.71-80.

Faridah, S.N., Achmad, M., Jamaluddin, T.A. and Jusmira, J. 2023. Infiltration model of Mediterranean soil with clay texture. *Jurnal Teknik Pertanian Lampung* 12(1), doi:10.23960/jtep-l.v12i1.162-173.

Fitria, L. and Soemarno, S. 2022. Effects of lime and compost on chemical characteristics and soil hydraulic conductivity of Alfisols at ATP Jatikerto coffee plantation. *Caraka Tani: Journal of Sustainable Agriculture* 37(1):48, doi:10.20961/carakatani.v37i1.54010.

Flint, L.E. and Flint, A.L. 2018. Porosity. In: *Methods of Soil Analysis, Part 4: Physical Methods*, doi:10.2136/sssabookser5.4.c11.

Forster, M., Ugarte, C., Lamandé, M. and Faucon, M.P. 2020. Relationships between root traits and soil physical properties after field traffic from the perspective of soil compaction mitigation. *Agronomy* 10(11), doi:10.3390/agronomy10111697.

Fu, B., Chen, L., Huang, H., Qu, P. and Wei, Z. 2021. Impacts of crop residues on soil health: a review. *Environmental Pollutants and Bioavailability* 33(1):164-173, doi:10.1080/26395940.2021.1948354.

Fukumasu, J., Jarvis, N., Koestel, J., Kätterer, T. and Larsbo, M. 2022. Relations between soil organic carbon content and the pore size distribution for an arable topsoil with large variations in soil properties. *European Journal of Soil Science* 73(1), doi:10.1111/ejss.13212.

Getino-Álvarez, M., San-Martin, R., Pretzsch, H., Pach, M., Bravo, F. and Turrión, M.B. 2023. Assessing soil C stock and C to N ratio of soil organic matter under mixed pine-beech forests at different scales. *European Journal of Forest Research* 142(5), doi:10.1007/s10342-023-01578-5.

Goldberg-Yehuda, N., Nachshon, U., Assouline, S. and Mau, Y. 2024. The effect of mechanical compaction on the soil water retention curve: Insights from a rapid image analysis of micro-CT scanning. *Catena* 242:108068, doi:10.1016/j.catena.2024.108068.

Gómez, A.M., Parra, A., Pavelsky, T.M., Wise, E., Villegas, J.C. and Meijide, A. 2023. Ecohydrological impacts of oil palm expansion: a systematic review. *Environmental Research Letters* 18(3), doi:10.1088/1748-9326/acbc38.

Hanuf, A.A., Prijono, S. and Soemarno. 2021. Improvement of soil available water capacity using biopore infiltration hole with compost in a coffee plantation. *Journal of Degraded and Mining Land Management* 8(3):2791-2799, doi:10.15243/jdmlm.2021.083.2791.

Heidari, A., Mayer, A., Watkins, D. and Castillo, M.M. 2020. Hydrologic impacts and trade-offs associated with developing oil palm for bioenergy in Tabasco, Mexico. *Journal of Hydrology: Regional Studies* 31, doi:10.1016/j.ejrh.2020.100722.

Hillel, D. 2003. *Introduction to Environmental Soil Physics*. Elsevier Inc., ISBN:978-0-12-348655-4, doi:10.1016/B978-0-12-348655-4.X5000-X.

Hu, J., Zhu, S., Yang, K., Ren, Y., Zhang, Z., Tang, M., Han, F. and Zhen, Q. 2024. Effects of different reclaimed mine land use patterns on the soil properties and water infiltration of opencast coal mines in the northern Loess Plateau, China. *Catena* 243:108193, doi:10.1016/j.catena.2024.108193.

Huang, C., Chen, Y., Jin, L. and Yang, B. 2024. Properties of biochars derived from different straw at 500 ℃ pyrolytic temperature: Implications for their use to improving acidic soil water retention. *Agricultural Water Management* 301:1-10, doi:10.1016/j.agwat.2024.108953.

Jia, A., Song, X., Li, S., Liu, Z., Liu, X., Han, Z., Gao, H., Gao, Q., Zha, Y., Liu, Y., Wu, X. and Wang, G. 2024. Biochar enhances soil hydrological function by improving the pore structure of saline soil. *Agricultural Water Management* 306:1-12, doi:10.1016/j.agwat.2024.109170.

Jiang, M. 2023. Impacts of rice cropping system changes on paddy methane emissions in Southern China. *Land* 12(2), doi:10.3390/land12020270.

Johansen, J.L., Dam, M., Kudjordjie, E.N., Santos, S.S., Palmqvist, A., Magid, J. and Vestergård, M. 2023. Effects of long-term fertilization with contemporary Danish human urine, composted household waste and sewage sludge on soil nematode abundance and community structure. *Science of The Total Environment* 860, doi:10.1016/j.scitotenv.2022.160485.

Khanaum, M.M. and Borhan, Md.S. 2023. Evaluating model effectiveness for soil infiltration attribute: Comparison of Green-Ampt, Horton and Modified Green-Ampt infiltration models. *Journal of Geoscience and Environment Protection* 11(02), doi:10.4236/gep.2023.112005.

Lakshmi, V. 2004. An introduction to the environmental physics of soil, water and watersheds. *Eos, Transactions American Geophysical Union* 85(46), doi:10.1029/2004eo460006.

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H. and Vanderborght, J. 2019. Modeling the impact of biopores on root growth and root water uptake. *Vadose Zone Journal* 18(1), doi:10.2136/vzj2018.11.0196.

Lange, M., Eisenhauer, N., Chen, H. and Gleixner, G. 2023. Increased soil carbon storage through plant diversity strengthens with time and extends into the subsoil. *Global Change Biology* 29(9), doi:10.1111/gcb.16641.

Lemma, A.B., Tsehai, K.K. and Wereka, B.B. 2022. Response of selected physical properties of Fluvisols to tillage implements and frequencies at Haramaya, Eastern Ethiopia. *Eurasian Journal of Soil Science* 11(3), doi:10.18393/ejss.1078352.

Li, H., Yao, Y., Zhang, X., Zhu, H. and Wei, X. 2021. Changes in soil physical and hydraulic properties following the conversion of forest to cropland in the black soil region of Northeast China. *Catena* 198:104986, doi:10.1016/j.catena.2020.104986.

Libohova, Z., Seybold, C., Wysocki, D., Wills, S., Schoeneberger, P., Williams, C., Lindbo, D., Stott, D. and Owens, P.R. 2018. Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. *Journal of Soil and Water Conservation* 73(4), doi:10.2489/jswc.73.4.411.

Liu, C., Xu, C., Zhang, Z., Xiong, S., Zhang, W., Zhang, B., Chen, H., Xu, Y. and Wang, S. 2024. Modeling hydrological consequences of 21st-Century climate and land use/land cover changes in a mid-high latitude watershed. *Geoscience Frontiers* 15(5), doi:10.1016/j.gsf.2024.101819.

Liu, L., Lu, Y., Horton, R. and Ren, T. 2024. Determination of soil water retention curves from thermal conductivity curves, texture, bulk density, and field capacity. *Soil and Tillage Research* 237, doi:10.1016/j.still.2023.105957.

Lu, S.-F., Han, Z.-J., Xu, L., Lan, T.-G., Wei, X. and Zhao, T.-Y. 2023. On measuring methods and influencing factors of air permeability of soils: An overview and a preliminary database. *Geoderma* 435:116509, doi:10.1016/j.geoderma.2023.116509.

Malone, Z., Berhe, A.A. and Ryals, R. 2023. Impacts of organic matter amendments on urban soil carbon and soil quality: A meta-analysis. *Journal of Cleaner Production* 419:1-13, doi:10.1016/j.jclepro.2023.138148.

Maulana, A., Harianti, M., Athiyya, S., Prasetyo, T.B., Monikasari, M., Darfis, I., Rezki, D. and Herviyanti, H. 2025. Biochar quality during slow pyrolysis from oil palm empty fruit bunches and its application as soil ameliorant. *Caraka Tani: Journal of Sustainable Agriculture* 40(1):84, doi:10.20961/carakatani.v40i1.93859.

Meersmans, J., Van Wesemael, B. and Van Molle, M. 2009. Determining soil organic carbon for agricultural soils: A comparison between the Walkley & Black and the dry combustion methods (north Belgium). *Soil Use and Management* 25(4), doi:10.1111/j.1475-2743.2009.00242.x.

Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Macfarlane, N., Hoffmann, R., Persio, M., Descals, A., Szantoi, Z. and Sheil, D. 2020. The environmental impacts of palm oil in context. *Nature Plants* 6(12), doi:10.1038/s41477-020-00813-w.

Minasny, B. and McBratney, A.B. 2018. Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science* 69(1), doi:10.1111/ejss.12475.

Ministry of Agriculture. 2021. National Superior Plantation Statistics 2020-2022 (*in Indonesian*).

Panagea, I.S., Berti, A., Čermak, P., Diels, J., Elsen, A., Kusá, H., Piccoli, I., Poesen, J., Stoate, C., Tits, M., Toth, Z. and Wyseure, G. 2021. Soil water retention as affected by management induced changes of soil organic carbon: Analysis of long-term experiments in Europe. *Land* 10(12), doi:10.3390/land10121362.

Patiño-Gutiérrez, S.E., Domínguez-Rivera, I.C., Daza-Torrez, M.C., Ochoa-Tocachi, B.F. and Oviedo-Ocaña, E.R. 2024. Effects of rainfall seasonality and land use change on soil hydrophysical properties of high-Andean dry páramo grasslands. *Catena* 238, doi:10.1016/j.catena.2024.107866.

Pham, T.A., Hashemi, A., Sutman, M. and Medero, G.M. 2023. Effect of temperature on the soil–water retention characteristics in unsaturated soils: Analytical and experimental approaches. *Soils and Foundations* 63(3), doi:10.1016/j.sandf.2023.101301.

Prasetyo, B.H. and Suriadikarta, D.A. 2006. Characteristics, potential, and technology of Ultisol management for dryland agriculture development in Indonesia. *Jurnal Litbang Pertanian* 25(2):39-46 (*in Indonesian*)

Presidential Regulation of the Republic of Indonesia No. 44. 2020. The Indonesian Sustainable Palm Oil Plantation Certification System (*in Indonesian*)

Prosanti, D.A., Prasetya, B. and Soemarno, S. 2023. The application of composted biopore infiltration holes in coffee plantations increases the number of mycorrhizal arbuscular spores and root colonies. *Jurnal Tanah dan Sumberdaya Lahan* 10(2):341-351, doi:10.21776/ub.jtsl.2023.010.2.18 (*in Indonesian*).

Qadri, S.N. and Gau, A.D.T. 2023. Effectiveness of providing organic material through biopore infiltration holes in cocoa plants. *Perbal: Jurnal Pertanian Berkelanjutan* 11(3), doi:10.30605/perbal.v11i3.3016 (*in Indonesian*).

Qiao, J., Zhu, Y., Jia, X., Huang, L. and Shao, M. 2019. Pedotransfer functions for estimating the field capacity and permanent wilting point in the critical zone of the Loess Plateau, China. *Journal of Soils and Sediments* 19(1), doi:10.1007/s11368-018-2036-x.

Rahman, R., Mahreda, E.S., Basir, B. and Badaruddin, B. 2020. The role of organic waste in biopore infiltration holes on soil chemical properties in post-mining lands. *EnviroScienteae* 16(3), doi:10.20527/es.v16i3.9756 (*in Indonesian*)

Ramírez, P.B., Machado, S., Singh, S., Plunkett, R. and Calderón, F.J. 2023. Addressing the effects of soil organic carbon on water retention in US Pacific Northwest wheat–soil systems. *Frontiers in Soil Science* 3, doi:10.3389/fsoil.2023.1233886.

Robinson, D.A., Thomas, A., Reinsch, S., Lebron, I., Feeney, C.J., Maskell, L.C., Wood, C.M., Seaton, F.M., Emmett, B.A. and Cosby, B.J. 2022. Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. *Scientific Reports* 12(1), doi:10.1038/s41598-022-11099-7.

Rossiter, D.G., Arenas-Calle, L., Urfels, A., Nayak, H., Sherpa, S. and McDonald, A. 2024. Characterizing soil hydrology in the Indo-Gangetic plain of Bihar, India: Methods and preliminary results. *Geoderma Regional* 37, doi:10.1016/j.geodrs.2024.e00784.

Ruslinda, Y., Aziz, R., Sari, N., Arum, L.S., Lestari, R.A. and Gunawan, H. 2021. The effect of raw material composition on composting results with the biopore infiltration hole (BIH) method. *ARPN Journal of Engineering and Applied Sciences* 16(10):1030-1035.

Ruslinda, Y., Haqqoni, M.A., Lestari, R.A. and Gunawan, K. 2022. Performance analysis of Biopore Infiltration Hole (BIH) composting based on soil texture and water infiltration rate. ARPN *Journal of Engineering and Applied Sciences* 17(17):1594-1601.

Santosa, S. 2018. Effect of fruit waste in biopore infiltration hole toward the effectiveness of water infiltration rate on Baraya campus land of Hasanuddin University. *Journal of Physics: Conference Series* 979(1), doi:10.1088/1742-6596/979/1/012037.

Schroeder, R., Fleige, H., Hoffmann, C., Vogel, H.J. and Horn, R. 2022. Mechanical soil database—Part I: Impact of bulk density and organic matter on precompression stress and consequences for saturated hydraulic conductivity. *Frontiers in Environmental Science* 10, doi:10.3389/fenvs.2022.793625.

Sharma, P., Abrol, V., Sharma, V., Chaddha, S., Rao, Ch.S., Ganie, A.Q., Hefft, D.I., El-Sheikh, M.A. and Mansoor, S. 2021. Effectiveness of biochar and compost on improving soil hydro-physical properties, crop yield and monetary returns in Inceptisol subtropics. *Saudi Journal of Biological Sciences* 28(12):7539-7549, doi:10.1016/j.sjbs.2021.09.043.

Sindagamanik, F.D., Antaria, S., Karim, N.T., Hamdi, F. and Asriany. 2021. The effect of pori hole distance variation on infiltration capacity in sandy clay soil sample drainage channels. *Civil Engineering and Architecture* 9(3), doi:10.13189/cea.2021.090325.

Singh, V.K., Kumar, D., Kashyap, P.S., Singh, P.K., Kumar, A. and Singh, S.K. 2020. Modelling of soil permeability using different data-driven algorithms based on physical properties of soil. *Journal of Hydrology* 580:124223, doi:10.1016/j.jhydrol.2019.124223.

Soil Research Center. 1980. Terms of Reference (TOR) Type A Soil Mapping, Transmigration Agricultural Research Project (P3MT) (*in Indonesian*)

Spasić, M., Vacek, O., Vejvodová, K., Tejnecký, V., Polák, F., Borůvka, L. and Drábek, O. 2023. Determination of physical properties of undisturbed soil samples according to V. Novák. *MethodsX* 10, doi:10.1016/j.mex.2023.102133.

Sun, Y., Wang, X., Wu, Q., Zong, T., Xin, X., Xie, J. and Yang, J. 2024. Use of rice straw nano-biochar to slow down water infiltration and reduce nitrogen leaching in a clayey soil. *Science of The Total Environment* 948:174956, doi:10.1016/j.scitotenv.2024.174956.

Sunarti and Lizawati. 2024. The application of organic mulch and chicken manure for improving soil water availability and yield of turmeric (*Curcuma domestica* Val) in an Inceptisol of Jambi, Indonesia. *Journal of Degraded and Mining Lands Management* 12(1):6905-6915, doi:10.15243/jdmlm.2024.121.6905.

Teng, S., Khong, K.W. and Ha, N.C. 2020. Palm oil and its environmental impacts: A big data analytics study. *Journal of Cleaner Production* 274, doi:10.1016/j.jclepro.2020.122901.

Torres, L.C., Keller, T., Paiva de Lima, R., Antônio Tormena, C., Veras de Lima, H. and Giarola, N.F.B. 2021. Impacts of soil type and crop species on permanent wilting of plants. *Geoderma* 384, doi:10.1016/j.geoderma.2020.114798.

Uhland, R.E. and Alfred, M. 1951. Soil permeability determinations for use in soil and water conservation. *Soil Science* 72(1):85, doi:10.1097/00010694-195107000-00020.

Ullyta, A., Tarigan, S.D. and Wahjunie, E.D. 2022. Infiltration and surface flow in agroforestry and oil palm. *Jurnal Ilmu Pertanian Indonesia* 27(3):359-366, doi:10.18343/jipi.27.3.359 (*in Indonesian*).

Umasugi, B., Prijono, S., Soemarno, and Ariffin. 2021. Improvement of soil moisture storage in clove plantation land using biopore technology and organic material litters. *Journal of Degraded and Mining Lands Management* 8(2):2601-2610, doi:10.15243/jdmlm.2021.082.2601.

Usowicz, B. and Lipiec, J. 2021. Spatial variability of saturated hydraulic conductivity and its links with other soil properties at the regional scale. *Scientific Reports* 11(1), doi:10.1038/s41598-021-86862-3.

Vereecken, H., Amelung, W., Bauke, S.L., Bogena, H., Brüggemann, N., Montzka, C., Vanderborght, J., Bechtold, M., Blöschl, G., Carminati, A., Javaux, M., Konings, A.G., Kusche, J., Neuweiler, I., Or, D., Steele-Dunne, S., Verhoef, A., Young, M. and Zhang, Y. 2022. Soil hydrology in the Earth system. *Nature Reviews Earth and Environment* 3(9), doi:10.1038/s43017-022-00324-6.

Walkley, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and proposed modification of the chromic acid titration method. *Soil Science* 37(1):29-38, doi:10.1097/00010694-193401000-00003.

Wang, X., Wang, L. and Wang, T. 2023. Effect of replacing mineral fertilizer with manure on soil water retention capacity in a semi-arid region. *Agronomy* 13(9), doi:10.3390/agronomy13092272.

Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T. and Wang, Z. 2023. Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. *Geoderma* 437:1-11, doi:10.1016/j.geoderma.2023.116591.

Winarso, S., Subchan, W., Haryanti, A., Setiawati, T.C. and Ramadhona, S. 2021. Increasing the abundance of microorganisms in a regosol soil using biopelet fertilizer composed from biochar, chicken manure, and shrimp waste to increase soil fertility. *Journal of Degraded and Mining Lands Management* 8(4):2881-2890, doi:10.15243/jdmlm.2021.084.2881.

Xie, Y., Zhou, L., Dai, J., Chen, J., Yang, X., Wang, X., Wang, Z. and Feng, L. 2022. Effects of the C/N ratio on the microbial community and lignocellulose degradation, during branch waste composting. *Bioprocess and Biosystems Engineering* 45(7), doi:10.1007/s00449-022-02732-w.

Yan, L., Liu, C., Zhang, Y., Liu, S. and Zhang, Y. 2021. Effects of C/N ratio variation in swine biogas slurry on soil dissolved organic matter: Content and fluorescence characteristics. *Ecotoxicology and Environmental Safety* 209, doi:10.1016/j.ecoenv.2020.111804.

Yang, H., Zhang, H., Qiu, H., Anning, D.K., Li, M., Wang, Y. and Zhang, C. 2021. Effects of C/N ratio on lignocellulose degradation and enzyme activities in aerobic composting. *Horticulturae* 7(11):482, doi:10.3390/horticulturae7110482.

Yang, M., Zhang, Y. and Pan, X. 2020. Improving the Horton infiltration equation by considering soil moisture variation. *Journal of Hydrology* 586, doi:10.1016/j.jhydrol.2020.124864.

Yang, Y., Zhong, M., Bian, X., You, Y. and Li, F. 2023. Preparation of carbon-based material with high water absorption capacity and its effect on the water retention characteristics of sandy soil. *Biochar* 5(1), doi:10.1007/s42773-023-00260-8.

Yu, B., Xie, C., Cai, S., Chen, Y., Lv, Y., Mo, Z., Liu, T. and Yang, Z. 2018. Effects of tree root density on soil total porosity and non-capillary porosity using a ground-penetrating Tree Radar Unit in Shanghai, China. *Sustainability (Switzerland)* 10(12), doi:10.3390/su10124640.

Zou, Y., Zhang, S., Shi, Z., Zhou, H., Zheng, H., Hu, J., Mei, J., Bai, L. and Jia, J. 2022. Effects of mixed-based biochar on water infiltration and evaporation in aeolian sand soil. *Journal of Arid Land* 14(4), doi:10.1007/s40333-022-0060-6.