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Research Article

Improvement of soil available water capacity using biopore infiltration hole with compost in a coffee plantation

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Abstract

Coffee plantation management has an important role in soil quality in order to increase coffee production. Biopore Infiltration Hole with Compost (BIHC) can increase soil available water capacity. In this study, the goal was to improve soil available water capacity in a coffee plantation with the implementation of the BIHC. This study was conducted at PTPN XII Bangelan, Malang, on March - August 2020. A randomized block design with seven treatments and four replications was used. The BIHC consisted of two-hole depths (30 cm and 60 cm) and two types of compost (goat manure and coffee pulp compost). The soil characteristics observed were water retention (pF) and organic C at soil depths of 0-20, 20-40, and 40-60 cm. The coffee tree observed were number of leaves and chlorophyll content. Data obtained were subjected to analysis of variance (ANOVA) by the F test and Duncan's Multiple Range Test (DMRT) at 5% probability, using SPSS program. Results of the study showed that BIHC was able to increase the content of soil C-organic and the available water capacity significantly compared with control treatment. The BIHC implementation could increase soil available water capacity up to 65% at a soil depth of 0-20 cm, up to 60% at a soil depth of 20-40 cm, and up to 51% at a soil depth of 40-60 cm more than the control treatment. The soil available water capacity suggested a significant positive correlation ($p \leq 0.05$) with the leaves number of coffee tree and chlorophyll content of leaves.

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Introduction

Globally, Indonesian coffee production together with Vietnam, Brazil, and Colombia, dominate the world market (Atmadji et al., 2019). South Sumatra, Lampung, Aceh, North Sumatra, and East Java are the five provinces that have the largest coffee plantation areas in Indonesia (BPS, 2019). However, North Sumatra (1,080 kg ha^{-1}), Jambi (968 kg ha^{-1}), Riau (951 kg ha^{-1}), South Sumatra (924 kg ha^{-1}), and West Java (808 kg ha^{-1}) were the provinces with the highest productivity of coffee plantation. These indicate that the coffee area should be accompanied by the good management of coffee cultivation. In order to increase coffee production, coffee land management should be considered in order to get optimal yield and high quality of coffee grains. Moreover, coffee cultivation should be balanced with sustainable soil management. The use of inorganic fertilizers has significantly increased coffee production (Satyanarayana et al., 2002), but if it is applied at a high rate for a long time, it can result in soil degradation, such as increasing soil acidity, unstable soil aggregates, and soil compaction (Nyalemegbe et al., 2009; Kanianska, 2016). Crop management in a coffee plantation is the main key in affecting soil characteristics and soil available water capacity (AWC). The coffee growth, nutrient cycling, and the photosynthesis of coffee leave strongly affected by AWC (Minasny and McBratney, 2017). Sustainable soil management should be able to enhance soil quality in a coffee plantation; usually, these involve the N-fixing legume shade trees, application of organic matter (compost and manure), soil and water conservation practices, and suitable intercropping systems (Mulumba and Lal, 2008; van Asten et al., 2011). Soil organic matter content usually is related to the soil available water capacity (AWC); it also improves soil quality that induced the growth and yield of coffee tree (Chemura, 2014).

The soil AWC indicates the available water content for plants, which is calculated between field capacity (FC) or upper limit and permanent wilting point (PWP) or lower limit. AWC is affected by climate conditions such as rainfall and evapotranspiration. Moreover, AWC also affected by soil physical characteristics such as soil porosity, soil texture, bulk density, and soil chemical characteristic is organic matter content (Rawls et al., 2003; Kodesova et al., 2011). Numerous research studies have identified the benefits of applying organic matter in enhance soil characteristics and soil quality. Furthermore, decreasing of soil organic matter content have resulted in the increase of soil bulk density, soil compaction, soil penetration resistance, and decrease in soil porosity (Robin et al., 2018), reduce soil aggregate stability (Zhou et al., 2013) and lower soil water availability (Olness and Archer, 2005; Dexter et al., 2008; Chaudhari et al., 2013; Ankenbauer and Loheide, 2017; Minasny and McBratney, 2017). Even though many studies have been undertaken to understand the effects of organic matter application on increasing soil water retention, there are still no available suitable techniques to apply organic matter in coffee plantations.

Biopore Infiltration Hole with Compost (BIHC) is one of the applied agrotechnologies in the form of a hole in the soil surface to a certain depth functioned to absorb surface runoff and as sites for organic matter placement (Permatasari, 2015). Some benefits of the BIHC implementation are absorption of surface runoff, reduction of erosion and nutrients losses (Devianti et al., 2019), increasing infiltration (Widiya and Krisnawati, 2017; Santosa, 2018), increasing soil water holding capacity (WHC) (Sibarani and Bambang, 2012; Landl et al., 2018), increasing soil porosity (Reck et al., 2018), and increasing the capacity of available soil water (Umasugi et al., 2021). The BIHC can harvest an amount of rainwater and is expected to minimize soil degradation. Compost and manure application have resulted in the increase of available soil nutrients, the improvement of soil physical characteristics and available soil moisture in relation to the improvement of crop growth and productivity (Landl et al., 2019).

The objective of this study was to improve the soil available water capacity in a coffee plantation using the BIHC treatments.

Materials and Methods

Study location

This study was conducted from March 2020 to August 2020 in the Robusta Coffee Plantation (*Coffea canephora* var. Robusta), Afdeling Besaran, Block III, PTPN XII, Bangelan, Malang Regency. PTPN XII Bangelan is located at $8^0$04’38” S and $112^0$28’58” E, 450-680 m above sea level, and land slope 0-40%, with the Alfisols and Inceptisols soil orders.

Soil and plant characteristics

Soil properties data such as soil organic carbon (SOC), soil texture, total porosity, bulk density, pore distribution and water retention (pF 1, pF 2, pF 2.5, and pF 4.2) were obtained from the analysis of soil samples in the laboratory. Soil samples were collected from three soil depths of 0-20 cm, 20-40 cm, and 40-60 cm. Plant analysis included the SPAD indexes of coffee leaves and number of leaves per coffee tree. The equation model for transforming the SPAD index (SPAD: Soil-Plant Analyses Development, Konica Minolta Sensing, Model number 72923021) into the chlorophyll content is defined by Netto et al. (2005):

$$Y= 44.5885+0.7188X+ 0.0933X^2 \quad ………. (1)$$

where,

X is the data from SPAD measurement,
Y is the content of total chlorophyll (μmol m^{-2})

Total chlorophyll was measured by randomly collecting five mature (fully developed) leaves from each coffee tree to be measured total chlorophyll using the SPAD.

Available soil water capacity

Available soil water capacity (AWC) was calculated from pF 2.5 (field capacity) and pF 4.2 (permanent wilting point). The calculation of the soil pore distribution are as follows (a) rapid drainage pore or aeration soil pore is the difference of water content at the total pore space, and at pF 2.0, (b) slow drainage pores are the difference in water content at pF 2.0 and pF 2.5, and (c) available water pores are the difference in soil water content between pF 2.5 and pF 4.2.

Experimental design and data analysis

The BIHC scheme is shown in Figure 1. The experiment was carried out in a randomized block design with seven treatment and four replicates. The BIHC treatments are: (1) P0 (control: Non BIHC treatment); (2) P1 (hole depth 30 cm + goat manure); (3) P2 (hole depth 30 cm + coffee pulp compost); (4) P3 (hole depth 60 cm + goat manure); (5) P4 (hole depth 60 cm + coffee pulp compost); 6) P5 (hole depth 30 cm and 60 cm + goat manure); and (7) P6 (hole depth 30 and 60 cm + coffee pulp compost). The experimental data were tested by the F test (analysis of variance), and when significant, means were compared by DMRT (Duncan’s Multiple Range Test) at 5% level of probability. The data were analyzed using the SPSS program.

Soil physical characteristics before application

The soil physical characteristics are shown in Table 1. The soil in the study location is dominated by clay fraction (42-47%) and silt fraction (37-42%) in each soil layer, with silty clay loam texture in topsoil and silty clay texture in the subsoil. The clayey texture of topsoil and subsoil result in the high ability to hold soil water, in which the AWC is 15.53% v/v and the field moisture capacity (FC) is 46.46% v/v. However, fast drainage soil pore is related to the easy losses of soil water. Soil ability to store and retain water is strongly related to soil texture and total porosity (Li et al., 2013) and water holding capacity (Sojka et al., 2009). High and low levels of soil water content at saturated condition (pF 0) is mostly affected by the content of clay fraction and content of soil organic matter (Rawls et al., 2003; Saxton and Rawls, 2006; Nita et al., 2014; Minasny and McBratney, 2017; Prout et al., 2020).

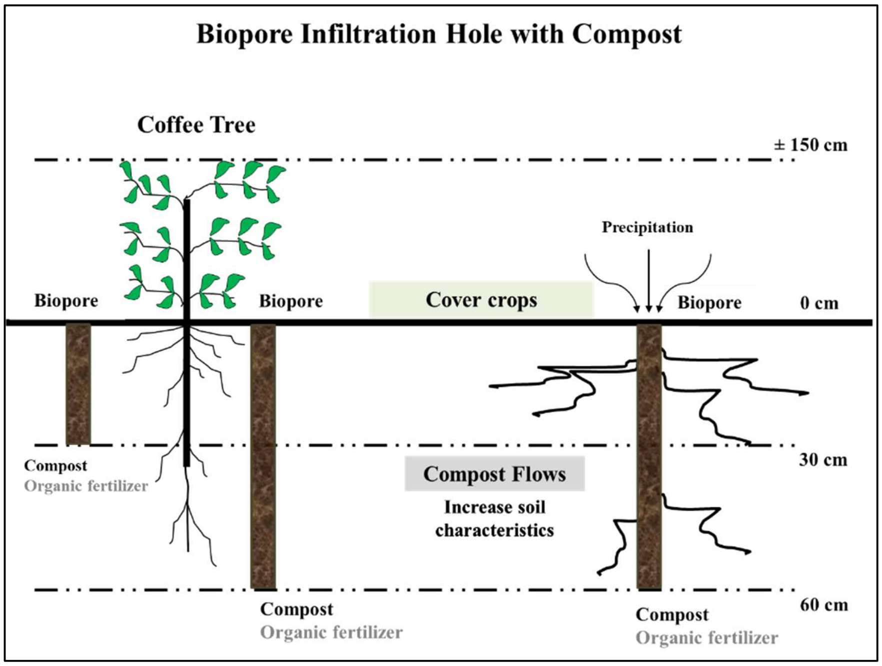

Figure 1. Biopore Infiltration Hole with Compost (BIHC) Scheme.

Table 1. Soil characteristics

Soil Characteristics	Soil Depth (cm)		
	0-20	20-40	40-60
Soil Bulk Density (g cm^{-3})	1.41	1.38	1.34
Soil Particle Density (g cm^{-3})	2.47	2.46	2.45
Total Soil Porosity (%)	42.69	43.67	44.84
Sand fraction (%)	16	16	15
Silt fraction (%)	37	41	42
Clay fraction (%)	47	43	42
Textural Class of Soil	Silty clay loam	Silty clay	Silty clay
Saturated Soil Hydraulic Conductivity (cm hour^{-1})	7.21	6.03	5.51
Soil Organic Carbon (%)	1.56	1.08	0.99
Soil moisture content at;			
pF 0 (%v/v)	75.89	79.61	79.80
pF 1 (%v/v)	59.19	62.20	61.68
pF 2 (%v/v)	46.46	49.35	49.90
pF 2.5 (%v/v)	40.49	43.71	44.98
pF 4.2 (%v/v)	24.95	28.29	29.64
Available Water Capacity (%v/v)	15.53	15.41	15.33
Fast Drainage Pore (%v/v)	29.43	30.26	30.01
Slow Drainage Pore (%v/v)	5.97	5.64	4.82

High levels of clay and silt fractions lead to high soil bulk density. An increase in soil bulk density causes a porosity decrease due to an increase in clay content (Tracy et al., 2013). This means soil bulk density and total soil porosity showed a negative and significant correlation (Chaudhari et al., 2013). Based on the results of soil physical characteristics presented in Table 1, each characteristic of soil in the study location suggests the different values in each soil layer. As the soil the deep, there are the low soil bulk density and the low SOC content, where the bulk density in 0-20 cm soil depth is 1.41 g cm^{-3}, in 20-40 cm soil depth is 1.38 g cm^{-3}, and in 40-60 cm soil depth is 1.34 g cm^{-3}. The SOC content is classified as "low level" at the soil layer of 0-20 cm and 20-40 cm, while at the soil depth of 40-60 cm, it is classified as "very low level". The low SOC content affects other physical characteristics of the soil. This causes the bulk density of topsoil is higher and the total porosity is lower than the subsoil. This means that the deeper soil layer, the higher the soil's ability to hold AWC. Other studies show that hedgerow trees can increase soil moisture compared to control, and soil moisture storage increased in deeper soil depth (Livesley et al., 2004; Zadeh and Sepaskhah, 2016; Prijono et al., 2016; Metzger et al., 2017; Muñoz-Villers et al., 2020)

Results and Discussion

Effect of BIHC on available water capacity

AWC increased in each layer of the soil both in control and BIHC treatments. Table 2 shows that the AWC of all BIHC treatments is significant by the control treatment ($p \leq 0.05$); however, amongst the BIHC treatments did not show a significant difference. The decomposition of organic matter causes a buildup of decomposed organic matter so that the SOC content increases. The increase of soil organic matter content is followed by the increase of the soil AWC.

Table 2. The effectiveness of BIHC on available water capacity.

Code	Treatment	AWC in each soil depth (% v/v)		
		0-20 cm	20-40 cm	40-60 cm
P0	Control	14.19 a	14.97 a	16.31 a
P1	Hole depth 30 cm + goat manure	21.05 b	23.43 ab	23.54 b
P2	Hole depth 30 cm + coffee pulp compost	21.54 b	23.88 b	24.10 b
P3	Hole depth 60 cm + goat manure	22.13 b	22.34 ab	22.76 b
P4	Hole depth 60 cm + coffee pulp compost	22.02 b	23.02 ab	24.17 b
P5	Hole depth 30 + 60 cm + goat manure	21.87 b	23.20 ab	23.27 b
P6	Hole depth 30 + 60 cm + coffee pulp compost	23.40 b	23.70 b	24.65 b

Remarks: Numbers followed by the same letters in the same column are not significantly different at the 5% DMRT level.

Increased activity of soil organisms is due to additional organic matter, which causes the development and creates the new formation of soil pores, especially around active roots, which naturally increase soil infiltration and increase available pore water for plants.

Coffee pulp compost and goat manure addition to BIHC can increase AWC, but it cannot be decided which compost is effective in increasing AWC. This is because the results showed that BIHC treatments did not show a significant difference. The insignificant effect between BIHC treatments was thought to be caused by the type of compost that did not affect the increase in soil AWC. This is indicated by the results of SOC content in each BIHC treatment with different types of compost, which did not show any significant effect (Table 3).

The increase in SOC content results in a lower bulk density. The SOC can reduce bulk density due to the two things, namely the particle density of organic matter is lower compared to mineral, and organic matter can increase soil aggregation and total soil porosity (Bauer and Black, 1992; Olness and Archer, 2005). The addition of organic matter on BIHC indicated an increase in AWC. Organic material has a large surface area (Franzluebbers, 2002) so that it can play a role as the cement that stabilizes soil aggregates and results in a high volume of soil pores. Numerous studies showed that soil water content within WHC range affected by soil organic matter content, but the different texture will show the different result (Russell et al., 1952; Russell and Shearer, 1964; Barrow, 1969; Hamblin and Davies, 1977; Emerson, 1995).

SOC content affects the improvement of soil physical quality. Organic fertilizer application improved the soil aggregation, decreased soil bulk density, and created a higher volume of soil pore. It has resulted in higher soil's ability to store water. The application of biopores on clove plantation using grasses litter (residues) with a hole depth of 50 cm, an increase of AWC at a depth of 20-40 cm showed the best effect and significant results (Umasugi et al., 2021). Therefore, there is an increase of SOC content, an increase in soil storage capacity and a decrease in the rate of evaporation and percolation (Umasugi et al., 2021). The theory is supported by the results of the correlation of each observation parameter. The soil AWC is influenced by other soil physical properties, such as soil bulk density, soil porosity, and soil water retention (pF 0, 2.5, and 4.2). All of these parameters are positively correlated with the soil AWC, except for soil bulk density. The soil bulk density has a significant negative correlation ($p \leq 0.01$), at a soil depth of 0-20 cm (r = -0.503 **, $p \leq 0.01$), at a soil depth of 20-40 cm (r = -0.552 **, $p \leq 0.01$), at a soil depth of 40-60 cm (r = 0.379 *, $p \leq 0.01$). In addition, the total soil porosity at a depth of 0-20 cm had a significant positive correlation (r = 0.466*, $p \leq 0.05$), while at other depths, it was not significantly correlated. The soil water content at pF 0 at a soil depth of 0-20 cm has a significant correlation (r = 0.624 **, $p \leq 0.01$), at a soil depth of 20-40 cm (r = 0.5 **, $p \leq 0.01$), and at a soil depth of 40- 60 cm (r = 0.572 **, $p \leq 0.01$). The soil water content at pF 2.5 or field capacity at a soil depth of 0-20 cm (r = 0.849 **, $p \leq 0.01$), at a soil depth of 20-40 cm (r = 0.829**, $p \leq 0.01$), and at a soil depth of 40-60 cm (r = 0.869**, $p \leq 0.01$). The soil water content at pF 4.2 or permanent wilting point suggests a non-significant correlation with the other soil characteristics. In addition, BIHC technology plays a role in optimizing water entering the soil. The mechanism of water entering the soil through BIHC is by minimalism the runoff so that the water enters the BIHC.

The results showed that the BIHC treatment was able to increase soil moisture content up to 65% at a depth of 0-20 cm, 60% at a depth of 20-40 cm, and 51% at a depth of 40-60 cm. P5 and P6 treatments showed higher results but not significantly different from P2, P3, and P4. BIHC technology is also a hole for the decomposition of organic matter. With this, BIHC is expected to increase the activity of soil biota to create more pores in the soil. The pores that are formed can become water channels in the soil and can become water reserves for the soil and plants. The BIHC technology optimizes the application of compost to prevent surface runoff or erosion by inserting the compost into the BIHC technology.

Table 3. The effectiveness of BIHC on organic C content of the soil.

Code	Treatment	Soil organic carbon in each soil layer (%)		
		0-20 cm	20-40 cm	40-60 cm
P0	Control	0.61 a	0.44 a	0.14 a
P1	Hole depth 30 cm + goat manure	1.93 d	1.13 bc	0.81 b
P2	Hole depth 30 cm + coffee pulp compost	1.40 bc	0.80 b	1.01 bc
P3	Hole depth 60 cm + goat manure	1.74 cd	1.04 bc	1.10 bc
P4	Hole depth 60 cm + coffee pulp compost	1.63 bcd	1.16 c	0.99 bc
P5	Hole depth 30+60 cm + goat manure	1.26 b	1.04 bc	0.98 bc
P6	Hole depth 30+60 cm + coffee pulp compost	1.50 bc	1.23 c	1.21 c

Remarks: Numbers followed by the same letters in the same column are not significantly different at the 5% DMRT level.

Minimizing the loss of compost that has been applied is expected to improve soil quality and crop production. BIHC is adjusted to the range of plant roots so that the application of BIHC in the field can increase nutrient uptake by plant roots. Soil improvement around the active roots of plants can create more optimal conditions for plant growth. The SOC of BIHC treatments was significant ($p \leq 0.05$) on the control treatment (Table 3). The addition of soil organic matter, such as coffee pulp compost and goat manure compost, can increase SOC. The response from BIHC was the highest shown at a depth of 0-20 cm, treatment P1 showed the highest results, but not significantly different from treatment P3 and P4. Then, at a soil depth of 20-40 cm, P6 treatment had the highest yield but was not significantly different from P1, P3, P4, P5, and P6. Meanwhile, at a soil depth of 40-60 cm, P6 treatment also had the highest yields, but it was not significantly different from P2, P3, P4, and P5. From this data, it was found that the combination of 30 cm and 60 cm BIHC treatment was able to increase the content of C-organic and organic matter to a soil depth of 40-60 cm. SOC content at 0-60 cm increased from 1.8% to 7.64%. Table 3 shows that the difference in the type of compost has no significant effect on SOC levels. However, P1 and P2 were significantly different; the application with goat manure had the highest yield, namely 1.93%, while the treatment with compost coffee pulp application. This can happen because the goat manure has a lower C/N ratio (13.16%), so that the rate of weathering is higher. Organic materials with lower C/N ratios have less material which is difficult to decompose. Treatment of P1 and P2 with a depth of 30 cm has a significant effect on a depth of 0-20 cm, but not at other depths. This means that BIHC with 30 cm of depth has a stronger effect at a depth of 0-20 cm than at other depths.

With this increase, biopores are able to increase AWC. Organic materials can improve soil structure, repair water and water circulation system, increase soil ability to hold water, reduce water loss due to evaporation, maintain soil moisture, and also be a source of nutrients (García et al., 2014; Strosser, 2010). The results of correlation between soil AWC and SOC is significant and positive correlation (r = 0.454*, $p \leq 0.05$) at a soil depth of 0-20 cm, at a soil depth of 20-40 cm is significant (r = 0.483**, $p \leq 0.01$), and at a soil depth of 40-60 cm is significant (r = 0.751**, $p \leq 0.01$). Soil organic matter has an important function in improving soil quality, such as increasing porosity and soil water content at various soil matrix (Evanylo et al., 2008) and can modify water dynamics in the soil and increase soil WHC (Milla et al., 2013). Biochar applications increase water content both in the FC, PWP, and AWC for plant compared to control treatment (Barus, 2016). Similar studies have shown the same results, increasing FC, pore distribution, and water content at various soil matrix (Fischer and Glaser, 2012; Bass et al., 2016).

Coffee tree characteristics

The data revealed that the leaves number of coffee tree are affected by the AWC of soil (Figure 2). Correlation and regression analysis between leaves number and soil AWC suggest a significant coefficient of correlation.

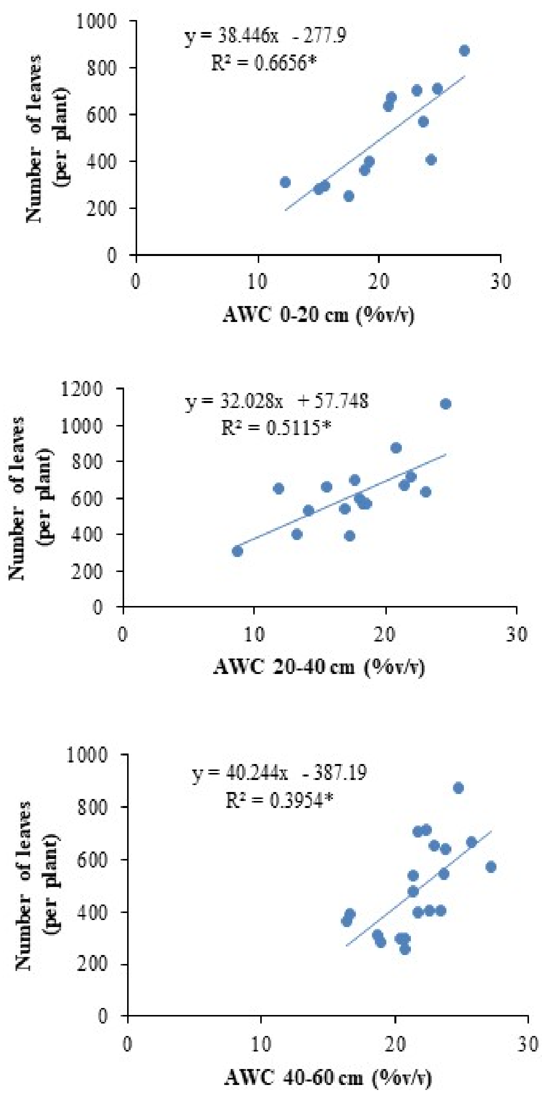

Figure 2. Relationship between leaves number of coffee tree and AWC of soil.

Results showed that the leaves number and soil AWC had a significant positive correlation at all soil depths had a significant positive correlation ($p \leq 0.05$), for a soil depth of 0-20 cm (r = 0.8158), a soil depth of 20-40 cm (r = 0.7152), and a soil depth of 40-60 cm (r = 0.6288). The availability of soil water also greatly affects the leaves number of the coffee tree. The growth rate of *L.serriola* during 63 days showed that the leaves number was higher in the treatment of 100% and 75% WHC and significant ($p \leq 0.05$) to the treatment of 50% and 25% WHC (Chadha et al., 2019). The frequency of watering every day and every 2 days at 100%-75% of available water significantly increase the leaves number compared to the watering once every 3 days at 50% of available water (Marsha et al., 2014). Other study results show that less frequency of watering has resulted in a lower leaves number of soybean plants (Nugraha et al., 2014). The data revealed that total chlorophyll affected by AWC (Figure 3). The relationship between total chlorophyll and AWC showed in Figure 3. Correlation and regression analysis between total chlorophyll and AWC in a high coefficient of correlation and coefficient of determination.

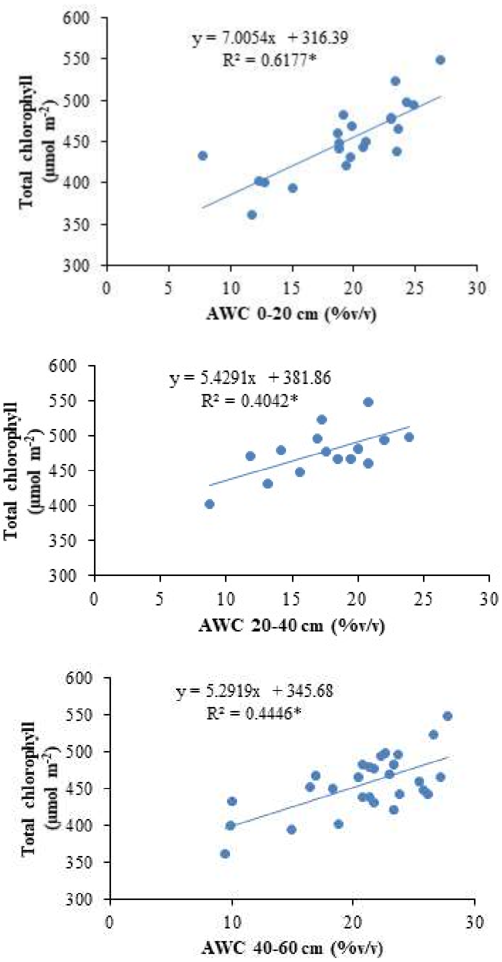

Figure 3. Regression between total chlorophyll content of coffee tree and soil AWC.

The results showed that total chlorophyll and AWC had a positive and significant correlation ($p \leq 0.05$) at all soil depths, for a depth of 0-20 cm (r = 0.7859), a depth of 20-40 cm (r = 0.6358), and a depth of 40-60 cm (r = 0.6668). The effect of the watering frequency on chlorophyll content in tomato plants stated that watering once every 6 days to 9 days have resulted in a significant reduction of total chlorophyll levels compared to controls and watering once every 3 days (Jumawati et al., 2014). Low water content causes the lower transport of ammonium (Hendriyani and Setiari, 2009). In addition, the lower soil water content in the planting medium will inhibit chlorophyll synthesis in leaves. The lack of water availability causes the rate of photosynthesis to decrease and results in a lower chlorophyll synthesis (Hendriyani and Setiari, 2009). Total chlorophyll content and leaves number relationship (regression) are showed in Figure 4. Correlation and regression analysis between total chlorophyll and AWC of soil suggests the significantly high coefficient of correlation. Results show that the leaves number and total chlorophyll content suggest a significant positive correlation ($p \leq 0.05$), namely ($r = 0.6633^*$).

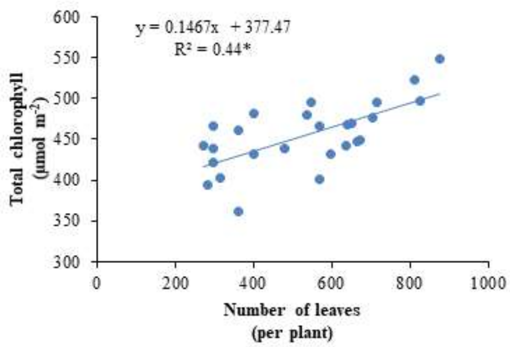

Figure 4. Regression between total chlorophyll content and leaves number of coffee tree.

The BIHC shows its role as a technology for the application of organic matter so that it is not prone to surface runoff and soil erosion and as a technology for water storage in order to supply sufficient water for plants growth. The BIHC technology was able to increase the soil AWC significantly compared to the control treatment, but amongst the BIHC treatments suggested a non-significant difference. This technology is able to improve soil characteristics and soil quality. The manure compost applied significantly increase the SOC content. Increased SOC content has resulted in an increase in the chlorophyll content of coffee leaves.

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