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Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation

Abolfath Moradi[a,*], Christopher Teh Boon Sung[b], Kah Joo Goh[c], Ahmad Husni Mohd Hanif[b], Che Fauziah Ishak[b]

[a] Department of Soil and Water Research, Fars Research Center for Agriculture and Natural Resources, Shiraz, Iran
[b] Department of Land Management, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[c] Applied Agricultural Resources Sdn. Bhd., No. 11, Jalan Teknologi 3/6, Taman Sains Selangor 1, Kota Damansara, 47810 Petaling Jaya, Selangor, Malaysia

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ABSTRACT

Mulching materials from oil palm residues such as pruned palm fronds (OPF), empty fruit bunches (EFB), and Eco-mat (ECO; a compressed EFB mat) are often the recommended soil and water conservation practices (CP) for oil palm plantations on hill slopes. Another recommended CP is the construction of silt pits or trenches (SIL) across the hill slope to capture runoff and then return the water and nutrients into the surrounding soil. Although these four CP are recommended practices, their relative effects on improving soil physical properties and on increasing the soil water content have never been compared with one another. Consequently, the objective of this study was to fill in this knowledge gap. A three-year field experiment was conducted in a non-terraced oil palm plantation, and soil samples from 0 to 0.15, 0.15 to 0.30, and 0.30 to 0.45 m depths were collected every three months and analyzed for their soil physical properties. Soil water content up to 0.75 m depth was also measured daily. EFB released the highest amount of organic matter and nutrients into the soil compared to OPF, ECO, and SIL. Hence, EFB was most effective to increase soil aggregation, aggregate stability, soil water retention at field capacity, available soil water content, and the relative proportion of soil mesopores. Due to these improved soil physical properties, EFB also gave the highest soil water content. Unlike ECO that concentrated more water in the upper soil layers, EFB distributed the soil water more uniformly throughout the whole soil profile, but SIL concentrated more soil water in the lower soil layers (>0.30 m) because the water levels in the pits were often below 0.30 m from the soil surface. The large opening area of the silt pits could have also caused large evaporative water losses from the pits. EFB mulching is recommended as the best CP, particularly for oil palm plantations on hill slopes.

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is the world's highest yielding oil crop, producing nearly 5 t ha^{-1} of oil per year which is 13, 8, and 7 times more than the oil produced from soybean, sunflower, and rapeseed, respectively (Chang, 2014). Palm oil accounts for 33% of the world's vegetable oil and 45% of edible oil production worldwide. Moreover, palm oil is the world's largest source for cooking oil and biodiesel (Tye et al., 2011).

Oil palm is a tropical crop, and it is planted in 43 countries over a total land area of 16.4 million ha (FAO, 2014). Malaysia is the second largest palm oil producer, after Indonesia and the area under oil palm in Malaysia has expanded rapidly from 55,000 ha in 1960 to 5.23 million ha in 2013 (equivalent to 16% of Malaysia's total land area) (MPOB, 2013). However, due to limited arable land, new oil palm plantations in some countries such as Malaysia and Indonesia have expanded into marginal land areas such as hill slopes (Moradi et al., 2012; Witt et al., 2005). But hill slopes face high risks of surface runoff and soil erosion which degrade soil physical and chemical properties (Abu Bakar et al., 2011; Teh et al., 2011) and ultimately, lower soil fertility. Degraded soil properties may also cause flooding, sedimentation, and reduction in water supply and quality (Nkonya et al., 2008; Stocking, 2001; Troeh et al., 2004).

Despite the high annual rainfall in the tropics, periodic water stress still occurs in oil palm plantations as a result of uneven rainfall distribution and high atmospheric evaporation demand on the crop due to high air temperatures (Arif et al., 2003). The use of irrigation has shown little promise due to its high installation and maintenance costs (Arif et al., 2003). Therefore,

* Corresponding author. Tel.: +98 9174346656; fax: +98 7124222471.
E-mail address: moradi1373@gmail.com (A. Moradi).

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proper soil and water conservation practices are needed to increase or conserve soil water, thereby, lowering the risk of water stress and also to reduce soil erosion and maintain soil productivity.

Organic mulching is one effective and established way to conserve soil and water. Utilization of oil palm residues such as pruned oil palm fronds (OPF) and empty fruit bunches (EFB) as a mulching material is a common conservation practice in oil palm plantations especially on non-terraced hill slopes (Anderson, 2008; Moradidalini et al., 2011). The popularity of using oil palm residues as mulching materials is because oil palm produces large amounts of biomass that have to be reused to avoid large amounts of wastes. 96% of oil palm's total annual dry matter production is stored in its above ground biomass (trunk, fronds, and bunches) (Corley and Tinker, 2003), and for every ton of palm oil produced from a fresh fruit bunch, approximately 1 t of EFB, 0.7 t of palm fibers, 0.3 t of palm kernels, and 0.3 t of palm shells are generated, which amounts to a total oil palm biomass of 2.3 t. In 2012, for instance, Malaysia's palm oil industry produced 43 million tons of biomass (Chang, 2014).

Oil palm residues like OPF and EFB contain essential plant nutrients that can be released into the soil during their decomposition, and they also provide organic matter which is a key factor to improve many soil properties. The beneficial effects of EFB and, to a much lesser extent, pruned OPF on soil chemical properties have been well reported. Their application as a mulch has shown to increase many soil chemical properties such as pH, exchangeable K, Ca and Mg, CEC, organic C, total N, and available P (Budianta et al., 2010; Kheong et al., 2010; Lim and Zaharah, 2002; Ortiz et al., 1992; Rosenani and Wingkis, 1999; Zaharah and Lim, 2000; Zolkifli and Tarmizi, 2010). EFB mulching has also led to higher oil palm vegetative growth and yield (Chan et al., 1980; Hamdan et al., 1998; Ortiz et al., 1992) and higher oil palm leaf K and N levels (Lim and Zaharah, 2002).

Nevertheless, one major disadvantage of EFB is it is bulky; thereby, making its storage, transportation, and field application cumbersome and expensive. One recent method to reduce EFB's bulkiness is to comb out the EFB's fibers and compress them into a carpet-like material known as Eco-mat (ECO) (Yeo, 2007). ECO has been shown to increase the vegetative growth of young oil palm trees by 5–14% and their N, P, and K uptake by 10–24% (Khalid and Tarmizi, 2008; MPOB, 2003). ECO has also helped to increase soil water content by 17% and 9% in the 0–200 mm and 200–400 mm soil depth, respectively (Xin-Fu, 2004) and by 44% in the 0–200 mm depth (Liu et al., 2005).

Another common soil and water conservation practice in oil palm plantations is the construction of silt pits (SIL) (Lim, 1989; Soon and Hoong, 2002). SIL are long and wide soil trenches (normally 3–6 m long and 0.5–1 m wide; Lim, 1989; Moradidalini et al., 2011; Soon and Hoong, 2002), and they are usually constructed between planting rows and perpendicular to the hill slope direction. The purpose of SIL is to collect runoff water which contains eroded sediments and nutrients which would otherwise be lost from the field. The collected water and nutrients are then redistributed back into the plant root zone around the pits after the rainfall event. SIL have been shown to be beneficial in several ways such as increasing the forage and oil palm yield by 100% (Schuster, 1996) and 13% (Murtilaksono et al., 2009), respectively; increasing the amount of soil water by 43% (Jahantigh and Pessarakli, 2009); reducing surface runoff by 10–18% (Hickey and Dortignac, 1963) and 23% (Soon and Hoong, 2002); and reducing soil loss by 3 t ha^{-1} (Lim, 1989), 0.52 t ha^{-1} (Soon and Hoong, 2002), and 5–14 t ha^{-1} (George et al., 2003).

Favorable effects of EFB, but to a much lesser extent for pruned OPF, ECO, and SIL, on various soil chemical properties have been well documented by studies conducted in different countries such as in Malaysia (Abu Bakar et al., 2011; Khalid and Tarmizi, 2008; Lee et al., 2012; Lim and Zaharah, 2002; Moradi et al., 2012; Soon and Hoong, 2002); in Costa Rica (Ortiz et al., 1992); in Indonesia (Budianta et al., 2010); in Thailand (Jantaraniyom et al., 2001); and in India (George et al., 2003). However, their effects on the soil physical properties and water conservation, especially on non-terraced hill slopes, have received less attention. Furthermore, there is no single study, to our knowledge, that compares the relative effects of these four recommended soil and water conservation methods on the soil physical properties and on increasing soil water content. Therefore, the objective of this work was to compare the relative effects of these four soil and water conservation practices (OPF, EFB, ECO, and SIL) on the soil physical properties and soil water content in a non-terraced oil palm plantation. Results from this study would be applicable to countries where oil palm is planted in particular for oil palm planted on hill slopes. As stated earlier, oil palm produces large amounts of biomass that needs to be reused. This study would help to determine the benefits of using these oil palm residues (OPF, EFB, and ECO), as well as to compare their benefits with SIL which is not a mulching material.

2. Materials and methods

2.1. Site description and experimental design

A field experiment was conducted in the Balau Estate oil palm plantation (2.9325° N and 101.8822° E), Semenyih, Selangor, Malaysia for three years from December 2007 until September 2010. In the first two years, the effects of four soil and water conservation practices on the soil physical properties and soil water content were evaluated. In the third year, nutrient release from the mulching materials during their decomposition in the field was measured. Results from the third year work were used to explain the results obtained in the first two years. The area was cultivated with eight-year old oil palm (*Elaeis guineensis* Jacq.) trees in a 8 by 8-m triangular spacing on a hill slope of 6°. Average annual rainfall in the area was 2105 mm for the year 2008 and 2009. Daily mean air temperature in the area was 26.9 °C. The soil of the experimental area is classified as a Typic Paleudult (Rengam series) which has a sandy clay loam texture in the topsoil (0–0.15 m depth) and sandy clay in the subsoil layers (0.15–0.30 and 0.30–0.45 m) (Table 1).

Table 1
Initial soil properties at the experimental site.

Soil depth (m)	pH	EC dsm^{-1}	CEC cmol (+) kg^{-1}	OC g $(100 g)^{-1}$	BD Mg m^{-3}	Particle size (μm) <2 Clay g $(100 g)^{-1}$	 2–50 Silt g $(100 g)^{-1}$	 >50 Sand g $(100 g)^{-1}$
0.0–0.15	4.79	1.11	7.29	2.65	1.37	28.9	12.6	58.5
0.15–0.30	4.78	0.93	8.33	1.75	1.49	44.1	7.7	48.1
0.30–0.45	4.48	0.84	7.88	1.51	1.40	28.3	7.8	63.8

EC: electrical conductivity; CEC: cation exchange capacity; OC: organic carbon; and BD: bulk density.

The field experimental layout was a split-split block arranged in a randomized complete block design with three replications. The soil and water conservation practices were allocated to the whole plot, where the conservation practices consisted of mulching the soil with EFB, ECO, and pruned OPF stacked on the soil surface, and the construction of SIL. Soil sampling times (T) and soil depths (SD) were considered as sub- and sub-sub plot, respectively.

The applications of EFB and ECO and the construction of the SIL were first carried out in January 2008. Empty fruit bunches were applied in the middle of each EFB treatment plot at a rate of 1000 kg per plot per year in a single layer following the field practices in Malaysia (Chan et al., 1980; Lim, 1989; Lim and Zaharah, 2000). Four pieces of 1×2 m ECO, having 20 mm thickness, were placed in a single layer on the soil surface between the trees in the center of each ECO treatment plot. The SIL were constructed by digging trenches along the hill contour, so that each trench had a dimension of 4.0, 1.0, and 0.5 m in length, width, and depth, respectively. The length of each trench was in perpendicular to the hill slope direction. The pits were also located in the middle of each SIL treatment plot. The EFB and ECO were re-applied and the silt pits re-constructed in January 2009. For the OPF treatment (considered as control in this study), two oil palm fronds were pruned each month (following the conventional field practice), and the pruned fronds were stacked on the soil surface between the tree rows. This meant 24 pruned fronds per palm were added to the fronds heap per year.

2.2. Mulch and soil sampling and analyses

The mulching materials (OPF, EFB, and ECO) were sampled once to determine their initial characteristics. Ten EFB and 10 pruned OPF were selected randomly and their weight, length, width, and thickness measured. Six mat pieces of ECO having 2 m length, 1 m width, and 20 mm thickness were also sampled and weighed. The EFB, ECO, and pruned OPF samples were then used for the determination of their chemical properties. To determine their moisture content, a sub sample of each EFB, ECO, and pruned OPF were placed in the oven at the same temperature (70 °C) until their weights became constant.

For soil analysis, three soil depths were sampled: 0–0.15, 0.15–0.30, and 0.30–0.45 m. Once every three months, disturbed composite soil samples from each of these three depths were taken using an auger. To collect a composite sample, soil samples were taken at three randomly selected points in each treatment plot (OPF, EFB, and ECO) and mixed. For the SIL treatment plots, soil samples were taken at four points at a distance of 0.5 m around each pit and mixed. A total of 324 disturbed soil samples were collected in this research. The soil samples were transported to the laboratory and spread on plastic sheets to be air dried for one week.

A portion of the soil samples were crushed to pass through a 2-mm sieve and analyzed for soil particle size analysis by the pipette method (Gee and Bauder, 1986), soil pH in a soil–water suspension with a soil-to-water ratio of 1:2.5 (McLean, 1982) using a pH meter (Metrohm, 827pH Lab), soil electrical conductivity (EC) in a soil–water suspension with soil to water ratio of 1:5 (Rhoades et al., 1990), soil organic C (OM) by the combustion method (Skjemstad and Baldock, 2008) using the 412-Leco Carbon Auto-Analyzer, and cation exchange capacity (CEC) by the leaching method using neutral 1 M ammonium acetate (NH4OAc) solution (Thomas, 1982).

The portion of uncrushed soil samples was used to determine the aggregate size distribution (aggregation) and aggregate stability. Aggregate stability was measured by the wet-sieving method (Kemper and Rosenau, 1986). For aggregation, the air-dried soil samples were placed on a set of nested sieves and shaken to separate the aggregates into 8.0, 4.76, 2.83, 2.0, 1.0, 0.5, 0.3, and <0.3 mm size fractions (Kemper and Rosenau, 1986). The aggregate size distribution was represented by the mean weight diameter (MWD) index (Van Bavel, 1949).

To determine the soil bulk density, total porosity, and soil water retention curve, two undisturbed soil samples for the centers of two soil depths (0–0.15 and 0.15–0.30 m) were taken randomly from each treatment plot by using core rings (40 mm in height and 56 mm in diameter). Soil sampling was done once every three months. Soil bulk density was determined by the core ring method (Blake and Hartge, 1986). Soil total porosity was calculated from the measured soil bulk density data assuming the particle density as 2.65 Mg m^{-3} and using the following equation (Baver et al., 1972):

$$\text{Total porosity} = \left(1 - \frac{\text{bulk density}}{\text{particle density}}\right) \times 100 \quad (1)$$

Soil water retention curve for matric potentials 0.0 to −1.5 MPa was measured by the pressure plate method (Richards, 1947). Soil water content at field capacity (FC) and permanent wilting point (PWP) were considered as the amount of water held in the soil at −0.03 and −1.5 MPa, respectively. Soil available water content (AWC) was calculated as the difference between the soil water content at FC and PWP. Soil pore size distribution was determined from the soil water characteristics data using the interrelations between soil water content, matric potential, and equivalent pore diameter by assuming that the soil pores are cylindrical capillaries. Soil pores were then classified in macropores, mesopores, and micropores according to Kay's (1990) soil pore classification system. In this system, soil pores of equivalent cylindrical diameter (ECD) at >30 μm are defined as macropores, 0.2 < ECD < 30 μm as mesopores, and <0.2 μm as micropores. Soil water content in each treatment plot was measured at 0.15-m intervals from the soil surface down to 0.75 m soil depth by using the Aqua Pro-Sensor (Aquatic Sensors, Nevada). Soil water content was measured once a day between 8.00 and 9.00 am.

2.3. Nutrient release of EFB, OPF, and ECO during their decomposition

Two pieces of EFB were placed in a screened litter bag and left on the soil surface in the center of each EFB treatment plot. One piece of 0.4×1 m ECO was placed in a litter bag and put in the middle of each ECO treatment plot in the same manner as done for the EFB. Three pruned OPF were also randomly selected and each one placed in a litter bag on the soil surface in the middle of each fronds heap. All the screened litter bags were weighed monthly for measuring the remaining dry matter and sampled for measuring their nutrient concentrations by the dry ashing method (Jones, 2001). The monthly amount of a given nutrient released from each residue was calculated by multiplying the initial amount of nutrient added by each residue to the unit land area of each treatment plot by the corresponding monthly percentage of nutrient release from the residue.

2.4. Statistical analysis

The data were analyzed statistically by using the ANOVA procedure in SAS version 9.2 (SAS Institute, Cary, NC), and means separation was by the Protected Least Significant Difference (LSD) test. The SAS command codes based on Federer and King (2007) were used to analyze the split-split block experimental design, and the LSD tests were based on Carmer and Walker (1982). Randomized complete block designs with and without sub-sampling was also used to analyze the data of soil water content and chemical composition of the mulches, respectively.

Table 2
Mean (±standard error) of the chemical and physical characteristics of EFB, Eco-Mat and palm fronds.

Parameter	OPF	EFB	ECO
C (g kg^{-1})	499.42 ± 0.82 b	486.42 ± 1.42 cd	484.70 ± 0.47 d
N (g kg^{-1})	12.36 ± 1.04 b	8.73 ± 0.39 c	6.00 ± 0.40 cd
P (g kg^{-1})	0.54 ± 0.01 b	0.51 ± 0.06 b	0.30 ± 0.02 c
K (g kg^{-1})	15.07 ± 0.68 bc	18.90 ± 0.82 a	11.26 ± 0.24 d
Ca (g kg^{-1})	6.38 ± 0.21 b	2.04 ± 0.19 d	1.72 ± 0.09 d
Mg (g kg^{-1})	0.71 ± 0.02 bc	1.22 ± 0.15 b	0.50 ± 0.03 d
Na (g kg^{-1})	0.15 ± 0.01 bc	0.27 ± 0.04 a	0.20 ± 0.02 ab
Lignin (g kg^{-1})[a]	224.5	285.0	294.5
C/N	41.38 ± 2.90 d	56.15 ± 2.40 c	82.09 ± 4.99 b
Lignin/N	18.16 ± 1.30 c	32.65 ± 1.39 b	49.08 ± 3.08 a
Weight (kg)	10.50 ± 0.19	3.65 ± 0.30	7.39 ± 0.14[b]
Length (m)	6.91 ± 0.18	0.41 ± 0.02	2.00 ± 0.001
Width (m)	2.01 ± 0.03	0.24 ± 0.02	1.00 ± 0.001
Thickness (m)	0.04 ± 0.001	0.15 ± 0.01	0.02 ± 0.001
Water content (w/w, %)	65.57 ± 0.76 ab	64.17 ± 1.70 b	12.58 ± 0.58 c
Bulk density (Mg m^{-3})[c]	N/A	0.11	0.24
Total porosity (%)[c]	N/A	91.53	81.54
Saturated hydraulic conductivity (mm s^{-1})[c]	N/A	5.40	3.50
Slope of water retention curve (power function)[c]	N/A	−0.13	−0.23

In each row values with the same letter are not significantly different at 5% level of significance according to mean separation test by LSD. The values for nutrient concentrations are on a dry weight basis. OPF, EFB and ECO denote oil palm fronds, empty fruit bunches, and Eco-mat, respectively.
N/A–not measured/available.
[a] Lignin concentration for the leaflets, rachis, and fronds were from Khalid et al. (2000), EFB from Lim and Zaharah (2000), and Eco-mat from Wan Asma (2006).
[b] Weight of each 1 × 2 × 0.02 m Eco-mat (pre-cut in factory).
[c] Data from Teh et al. (2010).

3. Results

3.1. Chemical and physical characteristics of the oil palm residues

EFB had significantly higher K and Mg, but significantly lower C, N and Ca concentrations compared with pruned OPF (Table 2). The P concentration in pruned OPF was not significantly different from EFB. OPF had significantly higher concentration for most nutrients than ECO. The industrial process of turning EFB into ECO had resulted in the loss of some nutrients and water, decrease in total porosity and saturated hydraulic conductivity, but increase in bulk density, C/N, and

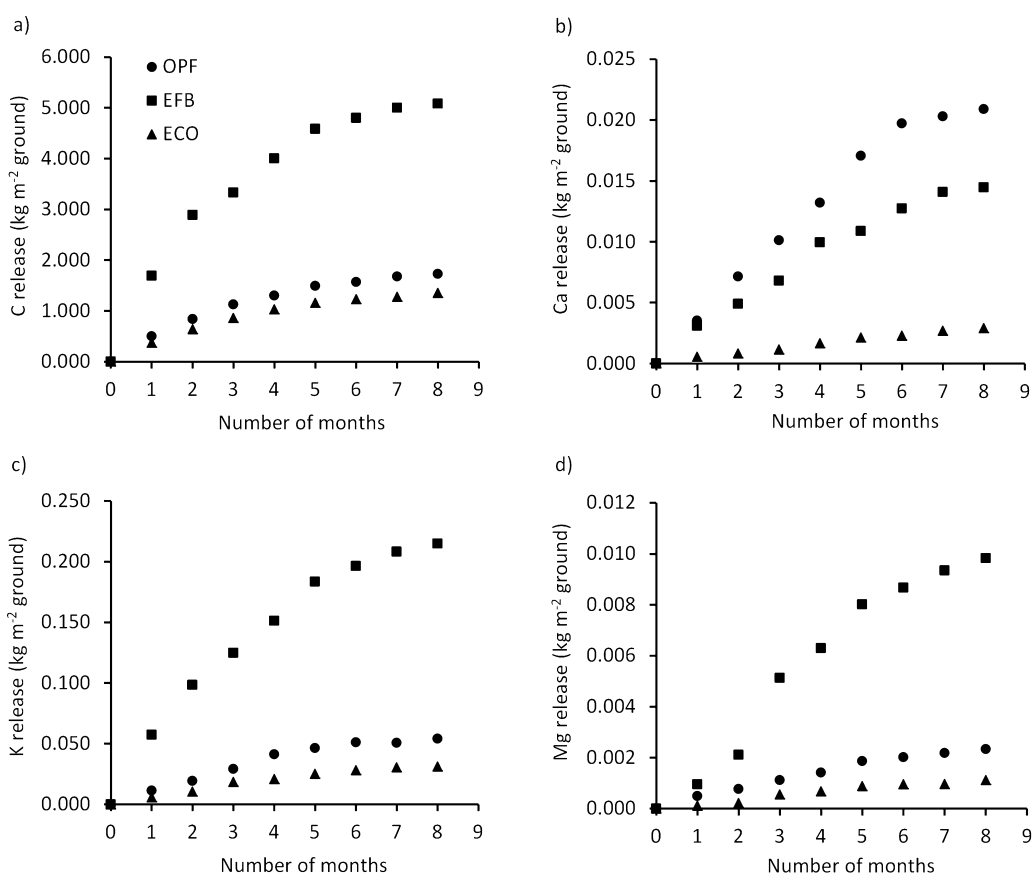

Fig. 1. Amount of nutrients released by the EFB (empty fruit bunches), ECO (Eco-mat), and OPF (oil palm fronds) during their decomposition.

lignin/N (Table 2). Compared to EFB, ECO's nutrient concentrations were either significantly lower (for P, K, and Mg) or not significantly different (for N, Ca, and Na).

The C/N and lignin/N ratios of the mulches were in the ascending order of OPF < EFB < ECO. On per piece basis, OPF was 2.9 times heavier than EFB and 1.4 times heavier than ECO. EFB was 7.5 and 3.5 times thicker than ECO and OPF, respectively. Both EFB and OPF had water contents statistically similar with each other, but both had significantly higher water content than ECO. Compared to ECO, EFB had 2.2 times lower bulk density, but 1.5 times higher saturated hydraulic conductivity. Finally, the slope of water retention curve represents how strongly the mulching materials could hold onto water. Table 2 shows that EFB would hold the water more strongly than ECO (slope of EFB < ECO).

3.2. Nutrients release during decomposition of oil palm residues

EFB released higher amounts of C, K and Mg per unit land area than ECO and OPF (Fig. 1a, c, and d). However, the amount of Ca released by EFB was lower and higher than that by OPF and ECO, respectively (Fig. 1b). The amount of nutrients released by OPF was slightly higher than those by ECO.

3.3. Changes in soil physical properties

ANOVA results (Table 3) revealed that CP × SD (conservation practices × soil depth) effect was significant on aggregate stability, available soil water content (AWC), soil water content at field capacity (FC), and on the relative percentage of mesopores. Soil aggregation (aggregate size distribution) was significantly affected only by the main effect CP. For the other soil physical properties (bulk density, total porosity, and the soil water content at saturation and permanent wilting point) were not significantly affected by CP.

The EFB treatment gave the highest aggregation (Fig. 2), aggregate stability (Fig. 3), available soil water content (Fig. 4), and soil water content at FC (Table 4) compared to the other conservation practices. However, the effects of OPF, ECO, and SIL on these four soil properties were not significantly different from one another. The effect of EFB on aggregate stability and the soil water content at FC were significant only for the top soil layer (Fig. 3 and Table 4) and although EFB significantly increased the soil water retention at FC, there was no appreciable effect due to EFB on the slope of the soil water retention curve (Table 4). As stated earlier, this slope indicates a soil's ability to hold water. Therefore, EFB mulching affected soil water retention curve by increasing the amount of water held at FC rather than the strength of the soil to hold the water.

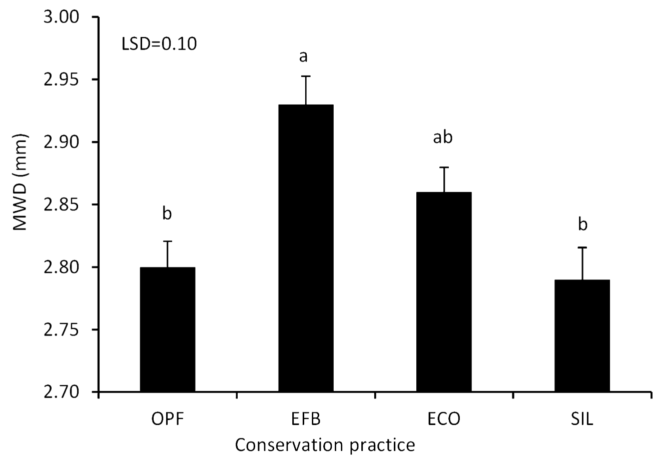

Fig. 2. Aggregation as represented by the index mean weight diameter (MWD) for the four soil and water conservation practices (averaged across all soil depths and time). Means with the same letter are not significantly different at 5% level. OPF, EFB, ECO, and SIL denote oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

Soil pore size distribution was significantly affected by the conservation practices but only for the topsoil layer (Table 3 and Fig. 5). In general, the pore size distribution of the soil was in the order of micropores > mesopores > macropores (Fig. 5). This is expected because the soil used in this study was a fine textured soil with more than 28 g $(100\,g)^{-1}$ clay content in the 0–0.15 m and 44 g $(100\,g)^{-1}$ in the 0.15–0.30 m soil depth (Table 1). In the topsoil layer, EFB increased the relative proportion of soil mesopores (0.2–30 μm) significantly higher than the other conservation practices. Other soil pore size classes were not significantly affected by any of the conservation practices. This finding is in agreement with Bescansa et al. (2006) who found that their crop residues increased the relative proportion of only the soil mesopores. Likewise, Kirchmann and Gerzabek (1999) found that the application of animal manure and sewage sludge had the most effect on increasing the soil pores with diameter between 1 and 30 μm (which is within the mesopores range).

3.4. Effects of soil and water conservation practices on soil water content

Changes in the daily total soil water content due to the four conservation practices are shown in Fig. 6. Soil water content would rise after every rainfall and decline during dry or non-rain periods.

Generally, EFB gave higher soil water contents than the other conservation practices (Fig. 6 and Table 5). Over the whole period of the experiment, the average daily soil water content in the whole soil profile (0–0.75 m) was significantly the highest for EFB (296.1 mm) and the lowest for OPF (246.8 mm) (Table 5). The highest soil water content in the EFB plots was more due to the significant increase in soil water content in the topsoil layer (0–0.15 m) because the soil water content in the EFB plots in the lower soil layers (0.15–0.75 m) was not significantly different from that in the OPF, ECO, and SIL plots. EFB was effective in increasing soil water content more uniformly over the whole soil profile, while ECO and SIL tended to concentrate more water in the topsoil and subsoil layers, respectively, but both of them still giving lower soil water content than EFB.

Table 3
Statistical analysis of the treatment effects on the soil physical properties.

	Source of variation			
Soil property	CP	CP × T	CP × SD	CP × T × SD
Aggregate size distribution	*	Ns	Ns	Ns
Aggregate stability	Ns	Ns	**	Ns
Bulk density	Ns	Ns	Ns	Ns
Total porosity	Ns	Ns	Ns	Ns
Available water content (AWC)	**	Ns	*	Ns
Saturation (SAT)	Ns	Ns	Ns	Ns
Field capacity (FC)	**	Ns	**	Ns
Permanent wilting point (PWP)	Ns	Ns	Ns	Ns
Macropores (>30 μm)	Ns	Ns	Ns	Ns
Mesopores(0.20–30 μm)	Ns	Ns	*	Ns
Micropores (<0.20 μm)	Ns	Ns	Ns	Ns

CP, T, and SD denote conservation practices, time, and soil depth, respectively.
Ns: not significant at 5% level.
* $p < 0.05$.
** $p < 0.01$.

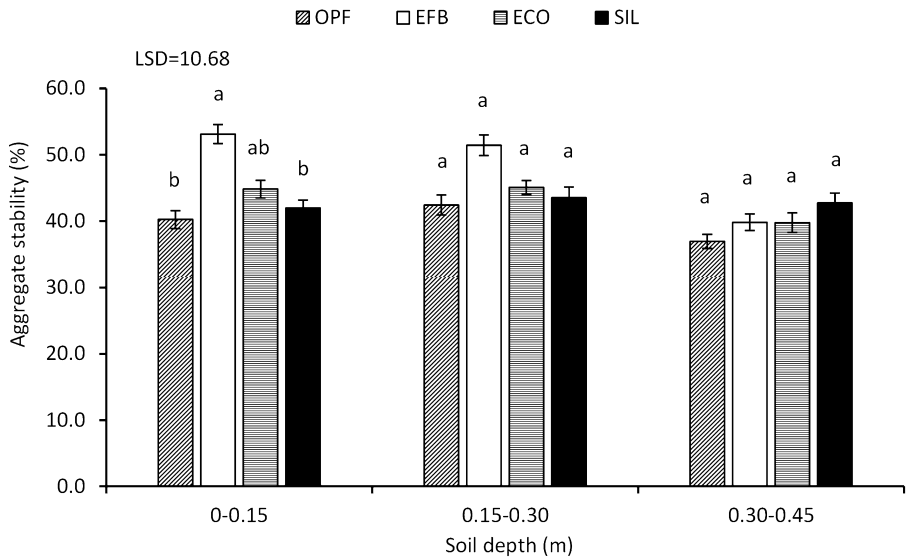

Fig. 3. Changes in soil aggregate stability for the four soil and water conservation practices over the soil depth. In each depth means with the same letter are not significantly different at 5% level. OPF, EFB, ECO, and SIL denote oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

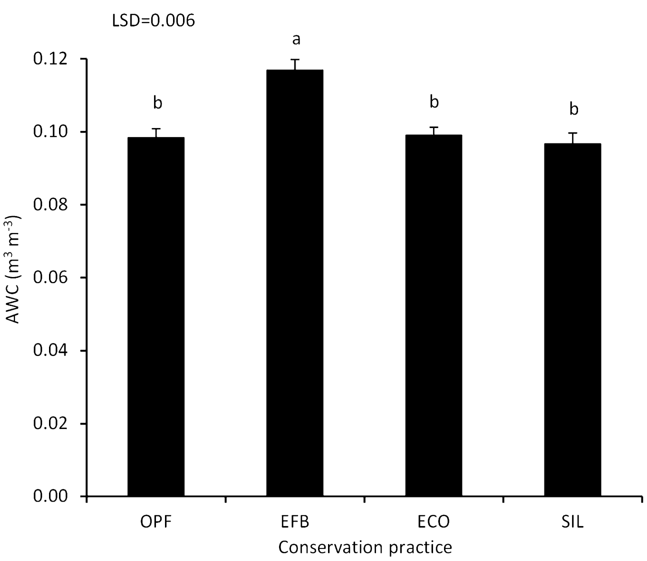

Fig. 4. Soil AWC (available water content) for the four soil and water conservation practices (averaged across all soil depths and time). Means with the same letter are not significantly different at 5% level. OPF, EFB, ECO, and SIL denote oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

4. Discussion

Results showed that soil aggregation, soil aggregate stability, soil water retention at FC, soil AWC, relative percentage of soil mesopores (0.2–30 μm) and soil water content were significantly higher in EFB than in the ECO, SIL, and OPF treatments. This is because EFB released the highest amount of organic C and exchangeable cations (K, Ca, and Mg) into the soil (Fig. 1) than the other treatments. Organic matter (OM) acts as a bridge between soil particles via exchangeable – Ca, Mg, and K cations (Brady and Weil, 2008; Edwards and Brenner, 1967; McLaren and Cameron, 1996) to produce microaggregates which are further bound together by plant roots, fungal hyphae, and other stabilizing agents to form soil's macroaggregates (Oades, 1984). Since both humus molecules and clay particles are net negatively-charged and cannot easily bind each other, polyvalent cations, in particular, complex with the hydrophobic humus molecules, allowing them to bind to clay surfaces (Brady and Weil, 2008). Organic matter not only increases the sizes of soil aggregates but also stabilizes soil aggregates by increasing soil hydrophobicity and increasing aggregates inter-particle cohesion (Chenu et al., 2000; Oades, 1984). Goh (2004) reported that soil organic carbon was significantly correlated with aggregate size and stability via the binding effect of humic substances and other microbial by-products.

The largest soil microbial population in the EFB treatment (Fig. 7) is another reason for the highest soil aggregate size and stability by EFB. Soil microbes promote soil aggregation by excreting mucilaginous products such as polysaccharides, hemicelluloses, uronides, levanes, and several other natural

Table 4
Soil water retention characteristics for the four soil and water conservation practices at 0.0–0.15 m soil depth averaged across time.

Soil water level (%, v/v)	Conservation practice			
	OPF	EFB	ECO	SIL
Saturation (SAT)	50.49 ± 0.62 a	56.35 ± 0.80 a	52.52 ± 0.67 a	51.45 ± 0.64 a
Field capacity (FC)	30.71 ± 0.41 b	34.82 ± 0.51 a	31.62 ± 0.40 b	31.53 ± 0.57 b
Permanent wilting point (PWP)	20.76 ± 0.34 a	21.81 ± 0.46 a	21.43 ± 0.43 a	21.74 ± 0.48 a
Available water content (AWC)	9.94 ± 0.35 b	13.02 ± 0.36 a	10.19 ± 0.32 b	9.80 ± 0.39 b
Slope of water retention curve	−0.22	−0.23	−0.22	−0.21

In the same row, means with the same letter are not significantly different at 5% level.
OPF, EFB, ECO, and SIL denote oil palm frond, empty fruit bunch, Eco-mat, and silt pit, respectively.

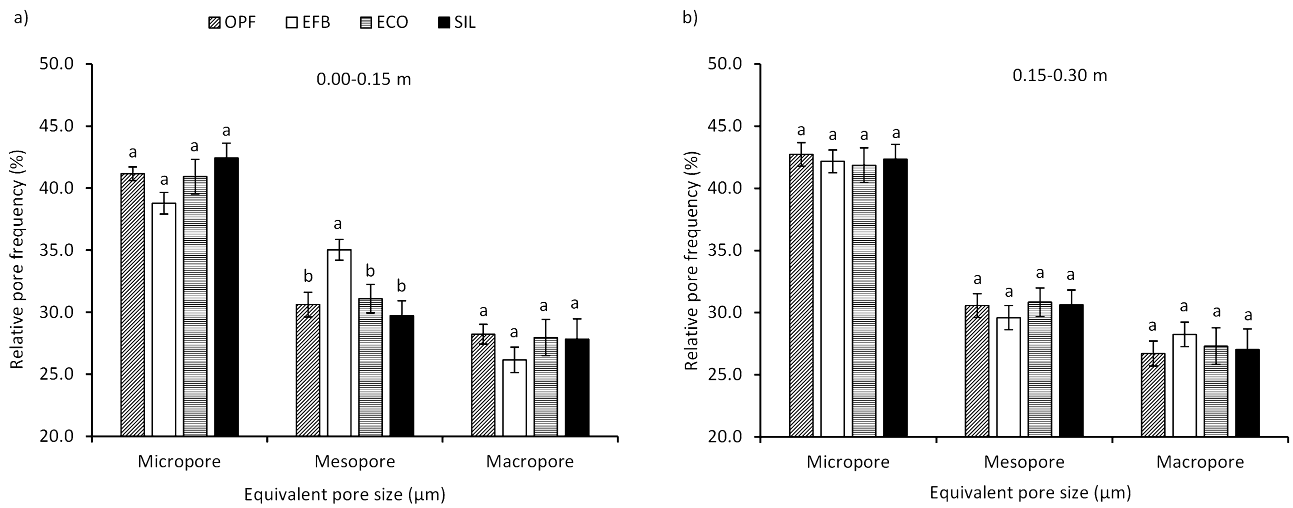

Fig. 5. Soil pore size distribution for the four soil and water conservation practices in the: (a) 0–0.15 and (b) 0.15–0.30 m soil depths. In each soil pore size class means with the same letter are not significantly different at 5% level. OPF, EFB, ECO, and SIL denote oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

polymers which act as glues and are able to bind soil particles (Coleman and Crossley, 1996; as cited in Hillel, 1998).

Soil aggregation and aggregate stability are two important soil physical properties that measure soil resistance to erosion. Therefore, increasing the size and stability of soil aggregates due to EFB mulching, especially on non-terraced hill slopes, can improve the soil's ability to resist erosion particularly in a tropical climate with heavy rainfall events (Barthes and Roose, 2002; Huntington, 2003; Maapa and Gunasena, 1995; Morgan, 2005). This is in agreement with Barthes and Roose (2002) who concluded that aggregate stability of the topsoil was strongly and negatively correlated with the amount of surface runoff and soil erosion.

The increase in soil aggregation and aggregate stability, enhanced by the higher soil organic C and exchangeable cations, in turn increased the percentage of soil mesopores (0.2–30 μm) in the EFB treatment by as much as 14.4% which resulted in the highest soil water content at FC and subsequently highest soil AWC in the EFB plots. Increase in soil AWC is important in reducing irrigation frequency. For instance, oil palm has the majority of its feeding or active roots in the top 0.60 m (Lim et al., 1994) soil depth. Oil palm also experiences an average evapotranspiration of 5.0 mm day^{-1} (Goh, 2000; Ling, 1979). So, by taking 65% of AWC as readily available water for oil palm (Allen et al., 1998) and this value constant up to 0.60 m depth, the amount of readily available soil water in EFB and OPF plots would be depleted in 10 and 8 days, respectively, before oil palm starts to experience water stress. Therefore, by using EFB as a mulch, the period in which a rainfed crop like oil palm can experience no water stress can be prolonged.

Soil water content at SAT and PWP were not significantly affected by the conservation practices. Soil water content at SAT depends mainly on soil total porosity rather than pore size distribution. Total porosity which is directly related to soil bulk density was not affected by the conservation practices as found in this research. This is probably because the experiment was conducted for only two years which may not be sufficiently long for both these properties to be affected by the increased soil organic carbon content. No significant changes in soil bulk density and total porosity even after a long period of 3–10 years of soil organic mulching were reported by other researchers (such as by Acosta-Martinez et al., 1999; Bescansa et al., 2006; Karlen et al., 1994; Onweremadu et al., 2007).

The reason why soil water content at PWP was not affected significantly by the soil and water conservation practices is PWP depends more on soil texture than on soil structure. According to Hillel (1998) and Lal and Shukla (2004) soil water content at FC depends on both soil texture and structure. Soil structure is a function of soil organic matter content. Therefore, any practices (e.g., mulching) that increase soil organic matter would improve soil structure and hence water retention at FC. In contrast, soil water content at PWP is not significantly influenced by aggregation, structural porosity, and soil organic matter content, but primarily influenced by the magnitude and nature of the clay content (Lal and Shukla, 2004).

Soil water content was higher in the EFB plots than in the plots of other conservation practices (Table 5 and Fig. 6). The highest soil water content in the EFB plots was caused by several reasons. EFB had higher total porosity, water holding capacity, and saturated hydraulic conductivity than ECO (Table 2). This meant that compared to ECO, EFB was able to absorb more water and to allow more water to enter the soil. About 65% of OPF comprised of rachis which is a hard (woody) material. Consequently, OPF is expected to have lower total porosity and lower capability to store and hold water than EFB. EFB also released the highest amount of organic matter and nutrients into the soil which in turn caused the largest improvement in soil physical properties, particularly by increasing the soil's AWC (Fig. 4). In an experiment conducted in the same field as this research, Junaidah (2009) further found that the water infiltration rate was higher in the EFB plots than that in the other treatment plots. She reported that the average water infiltration rates (over seven months) for EFB, ECO, SIL, and OPF treatments were 31.0, 21.0, 18.6, and 10.7 mm h^{-1}, respectively. The highest water infiltration rate for EFB meant that EFB plots would allow the largest increase in soil water content.

SIL concentrated more soil water in the lower than in the upper soil layers (Table 5). During the experiment, the water level in the silt pits was observed to be often lower than 0.30 m from the soil surface. This was why SIL was not as effective as EFB and ECO in increasing the soil water content in the upper soil layers (0–0.30 m). This is in agreement with the results reported by Arif et al. (2003) who found that SIL was not effective in increasing the soil water content in the first 0.20 m soil depth. Moreover, the large opening area of the silt pits (4 m long and 1 m wide, or 4 m^2) could

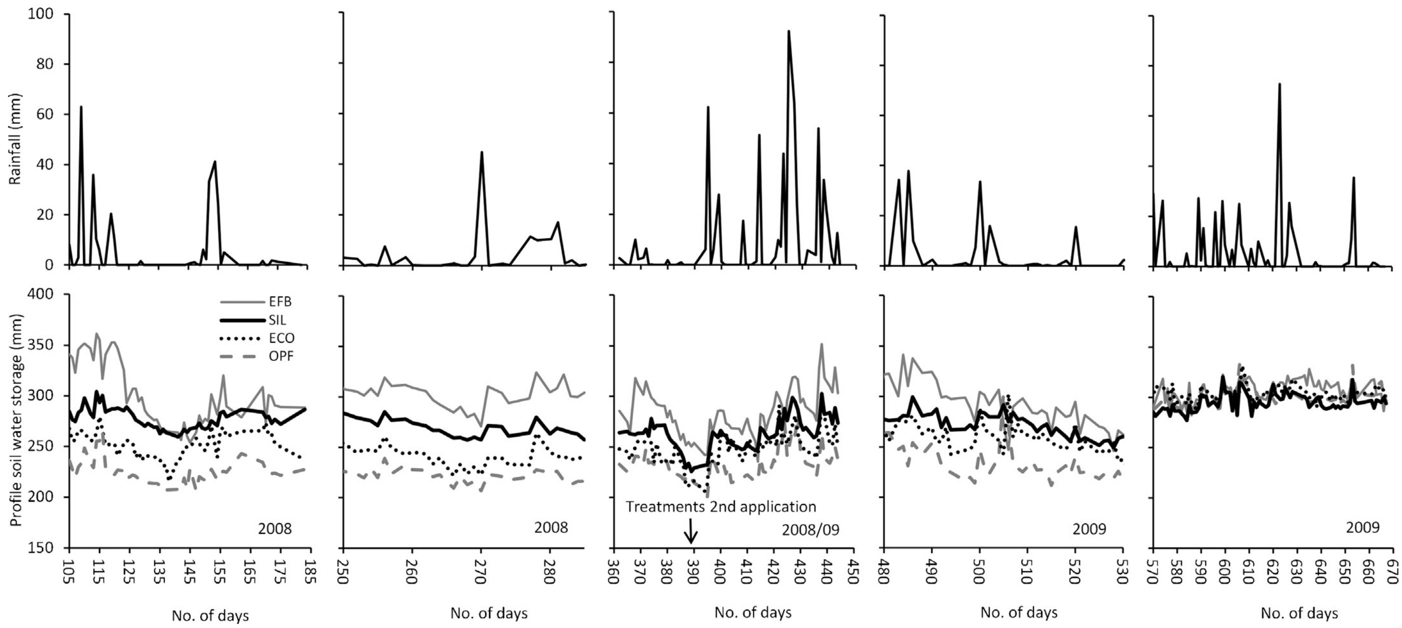

Fig. 6. Time series of daily soil water storage in the upper 0.75 m of the soil profile for the four soil and water conservation practices over time. Data shown are for selected days. "No. of days" is the number of days since Jan. 1, 2008. OPF, EFB, ECO, and SIL denote oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

Table 5
Average daily soil water content (±standard error) (in mm) for the four soil and water conservation practices during the two-year experiment.

Conservation practice	Year	Soil depth (m) 0.0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	0.60–0.75	All (0.0–0.75)
OPF	2008	39.48 ± 0.46	42.93 ± 0.55	39.96 ± 0.32	45.61 ± 0.40	52.04 ± 0.51	220.02 ± 1.55
	2009	49.28 ± 0.50	52.64 ± 0.41	51.05 ± 0.42	52.57 ± 0.36	55.92 ± 0.35	261.46 ± 1.69
	Both	45.82 ± 0.39	49.21 ± 0.37	47.13 ± 0.35	50.11 ± 0.30	54.55 ± 0.30	246.82 ± 1.40
EFB	2008	63.04 ± 0.68	49.31 ± 0.71	54.37 ± 0.70	60.86 ± 0.53	68.92 ± 0.47	296.51 ± 2.12
	2009	59.53 ± 0.39	55.29 ± 0.34	55.34 ± 0.34	58.88 ± 0.29	66.87 ± 0.32	295.91 ± 1.08
	Both	60.77 ± 0.35	53.18 ± 0.35	54.99 ± 0.33	59.58 ± 0.26	67.59 ± 0.27	296.12 ± 1.02
ECO	2008	55.8 ± 0.69	45.43 ± 0.64	41.87 ± 0.68	50.20 ± 0.69	55.17 ± 1.04	248.50 ± 1.94
	2009	56.71 ± 0.46	51.50 ± 0.49	49.87 ± 0.46	55.36 ± 0.47	60.28 ± 0.58	273.73 ± 1.61
	Both	56.40 ± 0.38	49.36 ± 0.40	47.04 ± 0.40	53.54 ± 0.40	58.48 ± 0.53	264.82 ± 1.31
SIL	2008	50.11 ± 0.48	44.91 ± 0.35	52.16 ± 0.42	59.21 ± 0.51	62.47 ± 0.48	268.86 ± 1.43
	2009	53.06 ± 0.36	52.06 ± 0.41	54.63 ± 0.30	56.29 ± 0.23	62.24 ± 0.33	278.27 ± 1.04
	Both	52.02 ± 0.29	49.53 ± 0.32	53.75 ± 0.25	57.32 ± 0.24	62.32 ± 0.27	274.95 ± 0.86

OPF, EFB, ECO, and SIL denote pruned oil palm fronds, empty fruit bunches, Eco-mat, and silt pit, respectively.

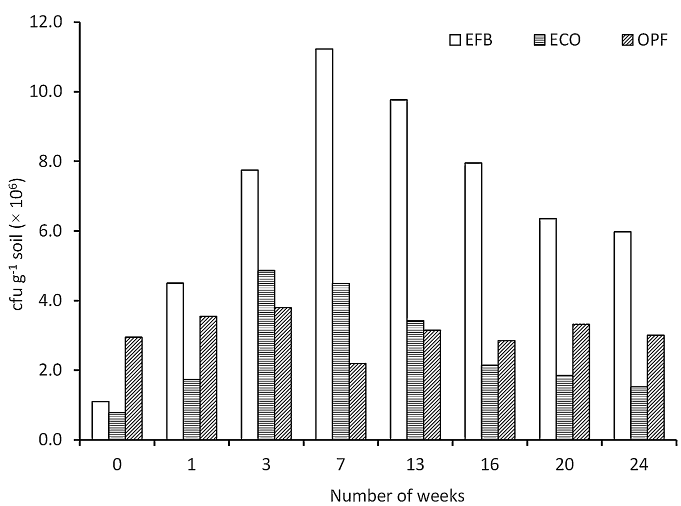

Fig. 7. Changes in soil microbial population under the different oil palm residue mulches during their decomposition at this study's field site (Source: Goh et al., 2011). cfu denotes colony-forming unit.

have caused large evaporative losses of the water inside the pits; thus, leading to a lower amount of water being returned into the surrounding soil (Moradidalini et al., 2011).

5. Conclusion

EFB released the highest amount of organic matter and soil-stabilizing cations into the soil compared to OPF, ECO, and SIL. Consequently, EFB mulch was more effective than the other conservation practices to increase soil aggregation, aggregate stability, soil water retention at FC, AWC, and the relative proportion of soil mesopores. Due to the improved soil physical properties such as higher AWC and higher soil water infiltration rate, EFB also gave the highest soil water content than the other treatments. Another reason for the high soil water content in the EFB plots was the fact that EFB had high total porosity, water holding capacity, and saturated hydraulic conductivity that allowed EFB to absorb more water and to allow more water to infiltrate into the soil. Unlike ECO which tended to concentrate more water in the upper soil layers, EFB distributed the soil water more uniformly throughout the whole soil profile. SIL, however, concentrated more soil water in the lower soil layers (>0.30 m) because the water level in the silt pits was often observed to be below 0.30 m from the soil surface. The large opening area of the silt pits also caused large evaporative water losses from the pits. In conclusion, mulching using EFB is recommended as the best soil and water conservation practices to improve soil physical properties and to increase water content in the soil profile particularly on non-terraced oil palm plantations.

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