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RESEARCH ARTICLE

Decomposition and nutrient release temporal pattern of oil palm residues

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Abstract

The decomposition and nutrient release temporal patterns of three oil palm residues used as soil mulch were studied. Empty fruit bunches (EFB; 1000 kg plot^{-1}), Eco-mat (processed EFB carpet; 30 kg plot^{-1}), and pruned palm fronds (180 kg plot^{-1}) were left to decompose (and sampled monthly) on the soil surface for 8 months. The frond's leaflets had the highest initial concentration for most nutrients, and the frond's rachis and Eco-mat the lowest. The order of residue quality and rate of residue mass loss were: leaflets > fronds > EFB > Eco-mat > rachis. EFB however had a higher mass loss rate than the fronds. Residue mass loss and nutrient release rates were faster at the beginning than at the end of the decomposition period. Leaflets released the highest total amount of nutrients (except for K), and rachis the lowest. The fronds released either significantly higher (for N and Ca) or not significantly different (for P and Mg) total amount of nutrients than EFB. Converting EFB into Eco-mat had resulted in nutrient losses (e.g. N, K and Mg) and a residue quality reduction in Eco-mat. This study's results would aid in better soil and oil palm fertilisation management.

Introduction

Crop residues can be used as organic mulches or be incorporated into the soil because these residues improve soil fertility. These residues contain essential plant nutrients which are released into the soil during residue decomposition. The degree by which these nutrients are released depends on several factors such as: type of crop residue (Brady & Weil, 2002; Reshi & Tyub, 2007; Karberg *et al.*, 2008), climate (Tian *et al.*, 1992; Mugendi & Nair, 1997), soil microbial activities (Wagner & Wolf, 1998; Brady & Weil, 2002), and the concentrations of nutrients in the crop residue (Oladoye *et al.*, 2008).

The use of crop residues as mulches is an important agriculture practice in certain countries like Malaysia. As the second largest palm oil producer in the world, Malaysia every year produces huge amounts of oil palm residues such as pruned palm fronds and empty fruit bunches (EFB). On the basis of the report by Chan *et al.* (1980), it is estimated that 34 t ha^{-1} yr^{-1} pruned fronds are produced in the field. This is equivalent to over 142 million tonnes of pruned oil palm fronds produced every year in Malaysia.

EFB, on the other hand, is a major solid waste of the palm oil milling process, and EFB accounts for 22% of the oil palm fresh fruit bunches (Lim & Zaharah, 2000). In 2010, 4.20 million ha of mature oil palm plantations in Malaysia produced about 17 million tonnes of EFB every year (MPOB, 2010). In the past, EFB was incinerated to generate steam (Ma *et al.*, 1993) and the resultant ash was used as a K-rich fertiliser (Uribe & Bernal, 1973). But the introduction of the zero burning policy by the Malaysian government has stopped this incineration practice. Today one main use of EFB is mulch.

EFB, however, is bulky, making its storage, transportation, and field application difficult and expensive. One recent effort to reduce EFB's bulkiness is to shred and compress the EFB fibres into a material known as Eco-mat. The result is a carpet-like material that is easier to handle, store and apply in the field than EFB.

These three oil palm residues (EFB, Eco-mat and palm fronds) are used mainly as mulch in oil palm plantations to protect the soil against erosion and to maintain or improve soil fertility. Therefore, knowledge about their decomposition and nutrient release temporal patterns is important to better manage soil fertility in terms of balancing the soil nutrients and determining the fertiliser requirements for oil palm. Unfortunately, studies on these three oil palm residues are disproportionate: EFB has been studied much more than Eco-mat or pruned oil palm fronds. The temporal decomposition and nutrient release by Eco-mat or pruned oil palm fronds, for instance, have been studied very little.

Nonetheless, several important observations can be gathered from these past studies. Firstly, the decomposition rate of EFB and Eco-mat followed an exponential pattern. Zaharah & Lim (2000) and Wingkis (1998) observed that EFB lost 50% of its dry matter weight within 3 months, 70% within 8 months (Zaharah & Lim, 2000), and 90% within 10 months (Wingkis, 1998). Eco-mat experienced 55% dry weight loss within 5.5 months and nearly complete mass loss within 12 months (Wan Asma, 2006; Teh *et al.*, 2010). The decomposition rate of pruned palm fronds however depended on the two components of fronds: leaflets and rachis. Khalid *et al.* (2000) observed a faster decomposition rate for leaflets than for rachis. Leaflets and rachis, for instance, lost 90% of their weights within 12 and 18 months, respectively.

Secondly, the nutrients in these crop residues were released into the soil at different rates. Khalid *et al.* (2000) found that the release rates of nutrients from the pruned palm fronds were in the order of K > Ca > Mg > P > N, and that compared to rachis, leaflets, due to their higher decomposition rate, had a higher release rate for all these nutrients. Similarly, Wingkis (1998) and Lim & Zaharah (2000) found that K in EFB was released at a much faster rate than N.

Thirdly, the nutrient concentrations of N, P, Ca and Mg in EFB increased as EFB's decomposition progressed, whereas K concentration in EFB decreased with increasing decomposition (Lim & Chan, 1987; Wingkis, 1998; Rosenani & Wingkis, 1999).

Fourthly, the C/N ratio of the decomposing EFB decreased with time (Lim & Chan, 1987). Rosenani & Hoe (1996), for instance, recorded that the C/N ratio of EFB decreased from 57 to 31 in 15 weeks of EFB decomposition. It is well established that the C/N ratio as well as the lignin content are two important indicators of crop residue quality. Crop residues with low C/N ratios or low lignin content decompose and release nutrients faster than that for crop residues with high C/N ratios or high lignin content. This is because the latter type of crop residues do not contain sufficient N to satisfy the requirements of soil microorganisms.

From the literature surveyed, it can be summarised that the nutrient concentrations in crop residues and the amount of nutrients released would change during residue decomposition. Furthermore, the nutrient concentrations in crop residues and nutrient release patterns depend on the characteristics and quality of the residues. Because these three oil palm residues have different quality from one another, their decomposition and nutrient release patterns would consequently be different from one another as well. The decomposition and nutrient release temporal patterns of these three oil palm residues have never been compared with one another in a same study. Therefore, the main objective of this research was to compare the decomposition and nutrient release temporal patterns of three oil palm residues (EFB, Eco-mat and pruned palm fronds) carried out in the same field and time. The temporal changes in the nutrient concentrations in these oil palm residues were also examined.

Materials and methods

Site description and experimental design

A field experiment was conducted in Balau Estate oil palm plantation (2.9325°N and 101.8822°E), Semenyih, Selangor, Malaysia from January to September 2010. The area was cultivated with 8-year old oil palm (*Elaeis guineensis*) trees in 8 m × 8 m triangular spacing on a hill slope of 6°. Average annual rainfall in the area was 2105.2 mm, and the daily mean air temperature 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 (USDA scheme) at 0–0.15 m and a sandy clay texture at 0.15–0.30 m soil depths, respectively. Other soil characteristics of the experimental site are shown in Table 1.

The field experimental layout was a split block design with three blocks. The oil palm residues (EFB, Eco-mat and pruned oil palm fronds) were allocated as whole plots and sampling times as sub plots. Each of the three blocks was located at different hill elevations but with the same slope of 6°. The application of oil palm residues on the soil surface was done in January 2010.

Decomposition in the field

The EFB were applied as a single layer in the middle of each EFB treatment plot at a rate of 1000 kg per plot per year, following the field practices in Malaysia (Chan *et al.*, 1980; Loong *et al.*, 1987; Lim, 1989; Lim & Zaharah, 2000). EFB were applied on the soil surface such that

Table 1 Field site soil properties before the start of the field experiment

						Particle Size (μm)		
Soil Depth (m)	pH	EC (dS m^{-1})	CEC (cmol(+) kg^{-1})	OC (%)	BD (Mg m^{-3})	<2 (%)	2–50 (%)	>50 (%)
0–0.15	4.79	1.11	7.29	2.65	1.37	28.88	12.55	58.49
0.15–0.30	4.78	0.93	8.33	1.75	1.49	44.11	7.71	48.07
0.30–0.45	4.48	0.84	7.88	1.51	1.40	28.25	7.82	63.84

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

the gaps between the fruit bunches were minimal. Four pieces of Eco-mat carpet were placed as a single layer on the soil surface in the centre of each Eco-mat treatment plot. Each piece of Eco-mat carpet measured 1 m × 2 m, with a 0.02-m thickness, and weighed nearly 7.5 kg.

Two pieces of EFB were randomly selected and placed in a screened bag. The bags were clipped with wire and placed on the soil surface in the centre of each EFB treatment plot. One piece of the 0.4 m × 1 m Eco-mat was placed in the bag and placed in the middle of each Eco-mat treatment plot in the same manner as done for the EFB. Three pruned oil palm fronds were also randomly selected, and each frond separated for leaflets and rachis, and weighed. The leaflets and rachis were then placed together in each screened bag and left on the soil surface in the middle of each frond heap.

Sampling

To determine the moisture and nutrient contents, four EFB from each EFB plot were randomly sampled. Eco-mat samples were also taken from four randomly selected places within each Eco-mat treatment plot. These samples were then mixed to obtain composite samples, oven dried at 70°C, and ground before being used for nutrient concentration measurements. A subsample from each composite sample was also taken and oven dried until constant weight for the determination of its moisture content by the gravimetric method.

For the oil palm fronds, each litter bag was opened and separated for leaflets and rachis. The leaflets and rachis were sampled from each bag, and the remaining parts were placed back into the bag and clipped. The samples were cleaned, cut into smaller pieces, and oven dried at 70°C until constant weight to calculate their water content. The samples were then ground for chemical composition measurements.

Mass loss

To determine the dry matter mass loss, all the screened litter bags were weighed monthly. For oil palm fronds, the litter bags were opened and the leaflets and rachis were weighed separately.

Dry matter remaining (%) at each month was calculated using the following equation:

$$D\,(\%) = \frac{100\mathrm{DM}_t}{\mathrm{DM}_0} \tag{1}$$

where D is the percentage of dry matter remaining at time t; and DM_0 and DM_t are the weight of dry matter at the beginning of the experiment ($t = 0$) and at time t, respectively. The percentage of mass loss was calculated using the percentage of dry matter remaining as follows:

$$\text{Mass loss}\ \ (\%) = 100 - D \tag{2}$$

Decomposition rates for different mulching materials were calculated using an exponential decay function (Olson, 1963):

$$W = W_0 \exp{(-kt)} \tag{3}$$

where W is the amount of dry matter remaining at time t (month); W_0 is the initial amount of dry matter; and k is the decomposition rate constant (month^{-1}), where the larger the k value, the higher the rate of decomposition.

Nutrient release by oil palm residue mulches

Nutrient release (%) by the oil palm residues mulches was calculated using the following equations:

$$N_{\mathrm{r}}\,(\%) = \frac{100\,(N_0 - N_t)}{N_0} \tag{4}$$

where N_{r} is the percentage of nutrient release by the mulch at time t; and N_0 and N_t are the nutrient contents at the beginning ($t = 0$) and at time t, respectively, and they were calculated by

$$N_0\,(g) = C_0\,(\%) \times \mathrm{DM}_0\,(g) \tag{5}$$

$$N_t\,(g) = C_t\,(\%) \times DM_t\,(g) \tag{6}$$

where C_0 and DM_0 are the initial nutrient concentration and dry matter weight of the mulch, respectively; and C_t and DM_t are the nutrient concentration and dry matter weight of the mulch at time t, respectively.

Data on the percentage of dry matter remaining, decomposition rate constant, nutrient concentrations and the percentage of nutrient remaining were subjected to ANOVA. Least significant difference (LSD) test was used to compare the significant means. Finally, all the data were analysed using SAS version 9.2 (SAS Institute Inc., Cary, NC, USA) statistical software package.

Results and discussion

Characteristics of the oil palm residues

The leaflets had the highest concentration for all nutrients (except K which was the highest in EFB) and the lowest C/N and lignin/N ratios (Table 2). Compared to other residues, rachis, followed by Eco-mat, had the lowest nutrient concentrations and the highest C/N and lignin/N ratios. Compared to leaflets and oil palm fronds, EFB had significantly lower C, N and Ca concentrations but significantly higher concentrations of K and Na and higher C/N and lignin/N ratios. The P and Mg concentrations in the pruned oil palm fronds were not significantly different from EFB.

Processing EFB into Eco-mat had resulted in a significant loss of some nutrients and a significant increase in the C/N and lignin/N ratios. Compared to EFB, Eco-mat's nutrient concentrations were either significantly lower (for P, K and Mg) or not significantly different (for N, Ca and Na). According to Yeo (2007), Eco-mat is produced by shredding the EFB fibres. The fibres then undergo a high pressure hydraulic compression to remove impurities such as water, sludge and oil traces. The EFB is finally dried in high temperatures to about 15% gravimetric water content before being trimmed to the required size and packed for shipping.

Residue quality is defined as the characteristics of the residue which would in turn influence the residue's decomposition rate (Swift *et al.*, 1979; Brady & Weil, 2002). Residue quality has been suggested as a major regulatory factor in the decomposition of organic residues. The quality of a plant residue is characterised by several parameters including the N (Yavitt and Fahey 1986), P (Soon & Arshad, 2002), lignin and polyphenols contents (Dux *et al.*, 2006) as well as the ratios of C/N (Taylor *et al.*, 1989; Nicolardot *et al.*, 2001), lignin/N (Melillo *et al.*, 1982), polyphenols/N (Seneviratne, 2000) and (lignin + polyphenols)/N. However, the most important and frequently used quality indicators of organic residues are the C/N and lignin/N ratios (Swift *et al.*, 1979; Tian *et al.*, 1995; Seneviratne, 2000; Brady & Weil, 2002). The lower the C/N and lignin/N ratios, the higher the residue quality. Therefore, based on these ratios, the qualities of the oil palm residues were in the decreasing order of: leaflets > oil palm fronds > EFB > Eco-mat > rachis.

Mass loss of the oil palm residues

The loss of dry matter for all oil palm residues followed an exponential rather than a linear decrease, where for the first 5 months, their decompositions were relatively faster than that after 5 months (Fig. 1). For instance, the leaflets lost 34% of their dry mass in the first 3 months but only 6% in the last 3 months.

Mass loss follows an exponential decrease because the more easily decomposable materials such as soluble sugars, amino acids, organic acids, cellulose and hemicelluloses decompose faster than the more recalcitrant materials such as lignin and waxes (Swift *et al.*, 1979; Foth, 1990; Green *et al.*, 1995; Rosenani *et al.*, 1996). Soluble sugars, amino acids and organic acids, for example, decompose 20 times faster than lignin, and

Table 2 Initial mean (± SE) chemical composition and residue quality of the oil palm residues[a]

Property	Leaflets	Rachis	Fronds	EFB	Eco-mat
C (g kg^{-1})	509.02 ± 0.71 a	487.94 ± 0.29 c	499.42 ± 0.82 b	486.42 ± 1.42 cd	484.70 ± 0.47 d
N (g kg^{-1})	23.25 ± 2.06 a	4.41 ± 0.34 d	12.36 ± 1.04 b	8.73 ± 0.39 c	6.00 ± 0.40 cd
P (g kg^{-1})	1.12 ± 0.07 a	0.24 ± 0.01 c	0.54 ± 0.01 b	0.51 ± 0.06 b	0.30 ± 0.02 c
K (g kg^{-1})	13.40 ± 1.32 cd	17.18 ± 1.60 ab	15.07 ± 0.68 bc	18.90 ± 0.82 a	11.26 ± 0.24 d
Ca (g kg^{-1})	10.92 ± 0.84 a	4.19 ± 0.27 c	6.38 ± 0.21 b	2.04 ± 0.19 d	1.72 ± 0.09 d
Mg (g kg^{-1})	1.63 ± 0.07 a	0.29 ± 0.01 d	0.71 ± 0.02 bc	1.22 ± 0.15 b	0.50 ± 0.03 d
Na (g kg^{-1})	0.08 ± 0.01 c	0.21 ± 0.03 ab	0.15 ± 0.01 bc	0.27 ± 0.04 a	0.20 ± 0.02 ab
Lignin (g kg^{-1})[b]	249.6	209.6	224.5	285.0	294.5
C/N	22.53 ± 1.82 e	112.77 ± 7.36 a	41.38 ± 2.90 d	56.15 ± 2.40 c	82.09 ± 4.99 b
Lignin/N	10.74 ± 0.88 d	47.53 ± 3.16 a	18.16 ± 1.30 c	32.65 ± 1.39 b	49.08 ± 3.08 a
Water content (w/w, %)	68.02 ± 0.87 a	64.10 ± 0.91 b	65.57 ± 0.76 ab	64.17 ± 1.70 b	12.58 ± 0.58 c

EFB, empty fruit bunches.

[a]In the same row, means with the same letter are not significantly different from one another at 5% level of significance according to the mean separation test by LSD. The values for concentrations are on a dry weight basis.

[b]Lignin concentration for the leaflets, rachis and fronds were from Khalid *et al.* (2000), EFB from Lim & Zaharah (2000), and Eco-mat from Wan Asma (2006).

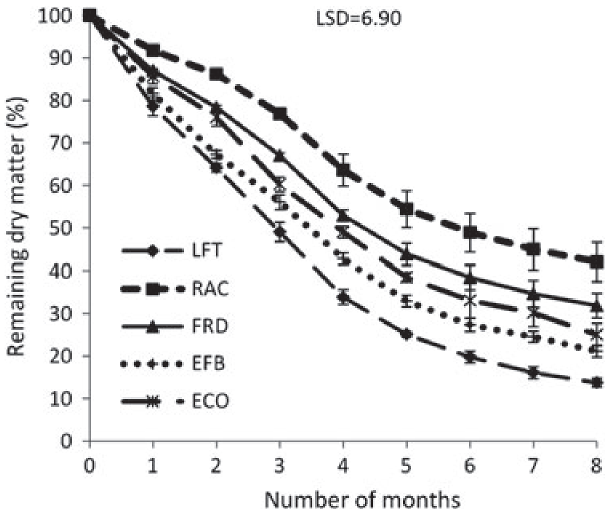

Figure 1 Changes in dry matter mass loss (100% − %dry matter remaining) for various oil palm residues due to their decomposition. LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

cellulose and hemicelluloses decompose 8 times faster than lignin (Reshi & Tyub, 2007). Furthermore, the more easily decomposable materials can be used by a larger number of microorganisms as compared to the more recalcitrant materials (Duong, 2009). Consequently, in the early periods of residue decomposition, the more easily decomposable materials of the residue would decay rapidly, leaving behind increasingly more of the recalcitrant materials (which decay slower).

The loss of dry matter was the fastest for the leaflets and the slowest for the rachis and fronds. There was no significant difference in the mass loss between EFB and Eco-mat and between Eco-mat and oil palm fronds. However, the mass loss was significantly higher for EFB than for the oil palm fronds over the whole decomposition period. At the end of the experiment, EFB lost about 79% of its original mass which was significantly lower than for the leaflets (86%) and significantly higher than that for rachis (58%) and oil palm fronds (68%).

The decomposition rate constant (k) was the highest for the leaflets and the lowest for the rachis (Table 3). The k for EFB was statistically similar to that for the Eco-mat. EFB however decomposed at a faster rate than rachis and oil palm fronds but at a slower rate than the leaflets. There was no significant difference in k between Eco-mat and oil palm fronds.

Using Eqn 3 and the k values from Table 3, the estimated number of months for the oil palm residues to decompose to 10% of their initial respective weights are 9, 12, 13, 15 and 19 for leaflets, EFB, Eco-mat, oil palm fronds and rachis, respectively.

Table 3 Decomposition rate constant (k) for the oil palm residues[a]

Oil Palm Residue	k (month^{-1})
Leaflets	0.26 d
Rachis	0.12 a
Fronds	0.15 ab
Empty fruit bunches	0.20 c
Eco-mat	0.18 bc

[a]Means with the same letter are not significantly different from one another at 5% level of significance according to the mean separation test by LSD.

Changes in nutrient concentrations in the oil palm residues

The C and K concentrations in all oil palm residues decreased with time (Fig. 2). For organic residues, their C loss is in proportion to their mass loss (Moore *et al.*, 2006). Furthermore, K is not a structural component of plant tissues but exists in ionic form in the cell sap of vacuoles. Consequently, K is released during decomposition from plant residues mainly via a gradual process of leaching, and K release is less affected by soil microbial activities and residue quality (Swift *et al.*, 1979; Reshi & Tyub, 2007).

The concentrations of N, P, Ca and Mg in all oil palm residues increased with time but with some exceptions. The concentrations of these four nutrients in the leaflets initially increased, then decreased. But for the oil palm fronds, their N, P and Ca concentrations decreased with time. The Mg concentration in the fronds, as well as in the rachis, showed no significant change over time. Lastly, the Ca concentration in the rachis, EFB and Eco-mat did not significantly change over time.

The concentrations of N, P, Ca and Mg in some oil palm residues increased with time because the rate of release of these nutrients through mineralization is slower than the residue's rate of mass or C loss. But for some oil palm residues, some of their nutrient concentrations did not significantly change over time because the residues' rate of mass or C loss was similar to the rate of nutrient mineralization.

As stated earlier, the N, P, Ca and Mg concentrations in the leaflets increased initially and then decreased. Leaflets comprised two components: lamina and midrib, where lamina decomposes easier than midrib (Khalid *et al.*, 2000). Consequently, at the early leaflet decomposition stage, lamina's faster rate of mass or C loss than the rate of nutrient mineralization caused the nutrient concentrations in the leaflets to increase over time. But as increasingly more lamina was lost over time, the leaflet's rate of mass or C loss would increasingly slow down because decomposition became increasingly more focused on the recalcitrant midrib. Thus, the reduction

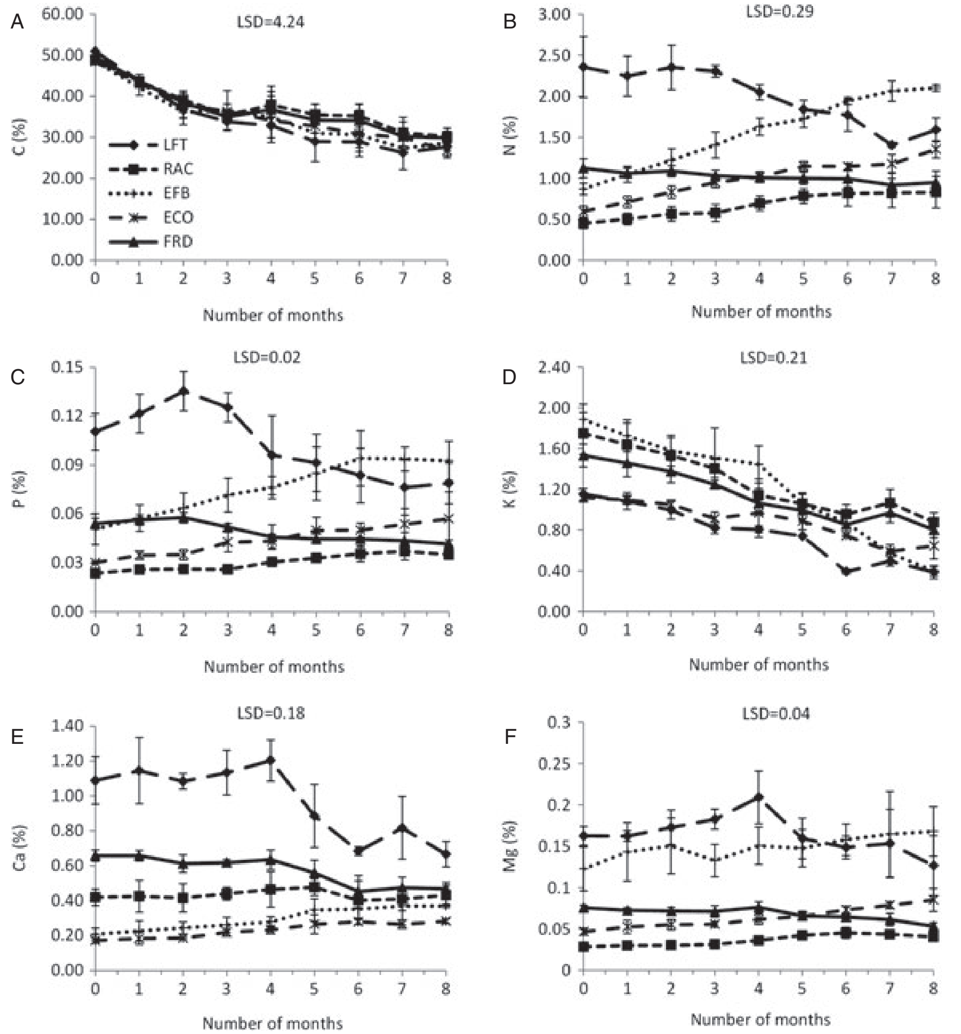

Figure 2 Changes in nutrient concentrations in the oil palm residues during their decomposition. LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

in the relative proportion of lamina to midrib caused the nutrient concentrations in the leaflets to decrease instead at the later stage of decomposition.

For the oil palm fronds, their N, P and Ca concentrations decreased with time. This is because oil palm fronds comprised two materials: leaflets (low C/N ratio, so easier to decompose; Table 2) and rachis (high C/N ratio, so less easier to decompose). These two materials have contrasting initial nutrient concentrations (Table 2). The leaflets, for example, have five times higher N and P concentrations and nearly three times higher Ca than that in the rachis. Consequently, in the early decomposition stage, the nutrient concentrations in the fronds were mostly represented by the more nutrient-rich leaflets than by the rachis (Fig. 3). But over time, the nutrient concentrations in the fronds would continue to decrease because increasingly more leaflets would be lost, leaving behind increasingly more rachis to decompose. Fig. 3 shows that 65% of the initial total weight of fronds consisted of rachis, and after 8 months of decomposition, this proportion increased to 85% due to the faster rate of loss of the leaflets (that decreased from 35% to 15%).

Nutrient release during oil palm residue decomposition

Organic mulches such as oil palm residues are sources of C and plant nutrients which are released during residue decomposition. When an organic mulch is placed on the soil surface, it will be attacked by soil biota to obtain the C and energy required for their growth and reproduction. This results in the release of C and plant nutrients which

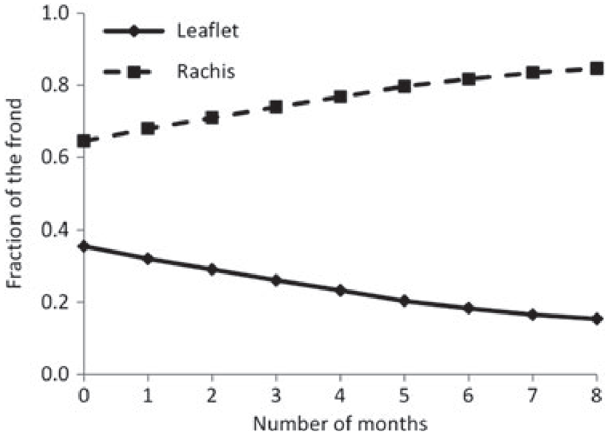

Figure 3 Changes in the fraction of rachis and leaflets in the fronds during frond decomposition.

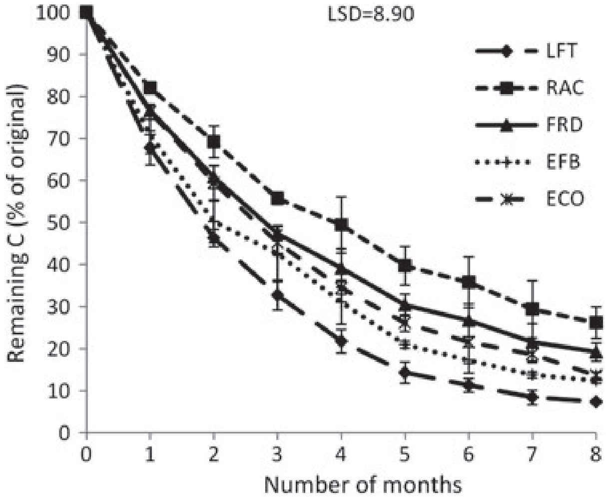

Figure 4 The %C remaining in various oil palm residues during decomposition (note: %C released = 100% − %C remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

can be added to the soil nutrients pool or be lost through surface runoff.

Carbon (C) release

The temporal patterns of %C release (Fig. 4) were similar to that of the mass loss (Fig. 1): a relatively faster initial phase followed by a slower phase. As stated earlier, the C loss in organic residues is in proportion to the mass loss (Moore *et al.*, 2006). C loss is also dependent on the residue quality, where the higher the residue quality, the larger and faster the C loss. In this study, the leaflets released %C significantly faster than other oil palm residues except for EFB. Generally, %C released by the EFB was not significantly different from that by the leaflets and Eco-mat but significantly higher than that by the fronds and rachis. At the end of the decomposition period, the leaflets, EFB, Eco-mat, oil palm fronds and rachis released 92%, 88%, 86%, 81% and 74% of their C content, respectively.

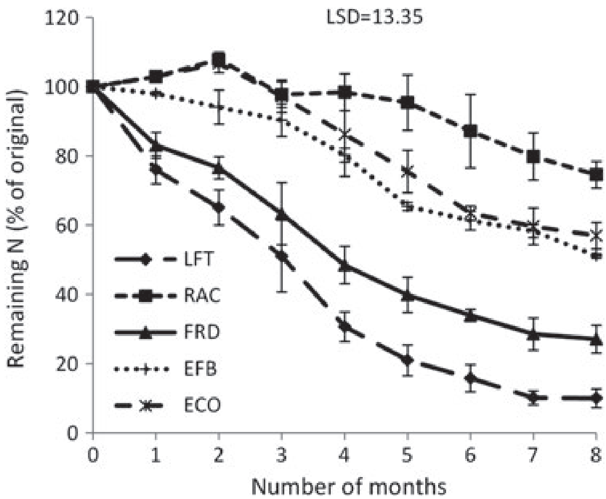

Figure 5 The %N remaining in various oil palm residues during decomposition (note: %N released = 100% − %N remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

Nitrogen (N) release

The leaflets released N faster than rachis especially at the beginning (Fig. 5). While the leaflets released about 90% of their original N within the experimental period, the rachis released only 25%, most of which occurred in the last 3 months.

Both EFB and Eco-mat showed statistically similar %N release of 49% and 43%, respectively, and most of which were released in the last 6 months.

There was a net gain of N in the rachis and Eco-mat during the first 2 months of decomposition. This net gain was due to the transfer of soil N into the organic residues by the soil microorganisms. Rachis and Eco-mat had the two highest C/N ratios (Table 2). According to Kaye & Hart (1997), Schroth (2003), and Bardgett (2005), when materials with high initial C/N ratios are added to the soil, microorganisms would be N-limited, so these microorganisms would resort to using soil N when decomposing these residues. This would result in a net immobilisation (gain) of N in the decomposing residues. Similar results were also reported by Melillo *et al.* (1989)

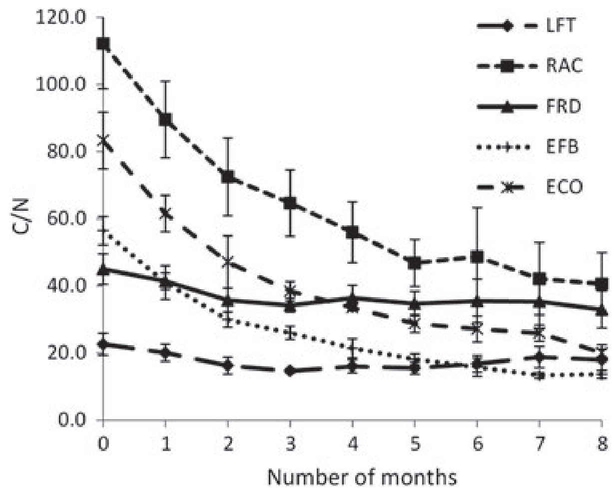

Figure 6 Changes in C/N ratio over time for various oil palm residues during decomposition. LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

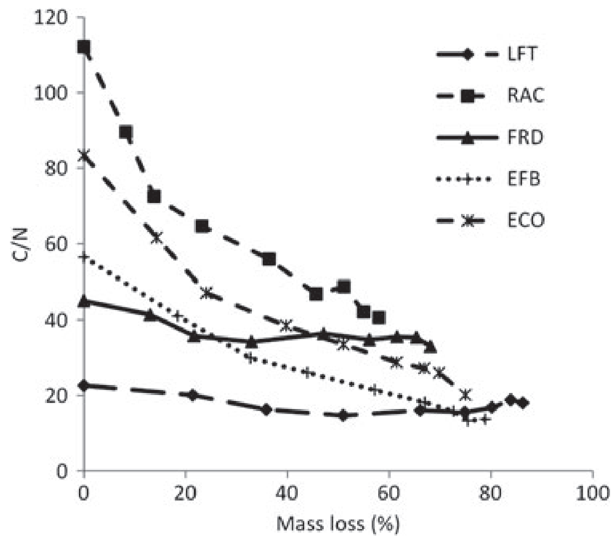

Figure 7 The relationship between C/N ratio and mass loss for various oil palm residues during decomposition. LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

and Hyeong-Tae (2009) who observed a net gain of N in red pine (*Pinus resinosa* Ait.) needle litter (initial C/N ratio of 140) and *Quercus mongolica* (initial C/N ratio of 43.3) during the initial stage of decomposition.

The %N released by EFB was significantly lower than that by the oil palm fronds over the whole period of decomposition. Oil palm fronds released about 73% of their original N content during the experiment, which was 24% higher than that by EFB.

Changes in C/N ratio

All oil palm residues experienced a decrease in their C/N ratios with time (Fig. 6). Plotting the C/N ratios against mass loss showed a similar decrease in C/N ratio with increasing mass loss (Fig. 7). The C/N ratio for the low quality residues (rachis, Eco-mat and EFB) decreased at a faster rate than that for the high quality residues (leaflets and frond). The average reduction in C/N ratios for the rachis, Eco-Mat, EFB, fronds and leaflets were 8.95, 7.91, 5.35, 1.51 and 0.58 units per month, respectively.

The C/N ratio for all residues decreased with time because of the slower rate of N mineralization compared to the rate of C loss. Moore *et al.* (2006), for instance, found that N in a low quality organic residue was released only after 40% of the C content in the residues were released.

Leaflets and oil palm fronds experienced a slower decline in their C/N ratios because these two residues comprised materials having contrasting qualities. The leaflet, as mentioned previously, is composed of lamina (which is soft, more easily decomposable and has a low C/N ratio) and midrib (which is hard and has similar quality to the rachis, less easily decomposable, and has a high C/N ratio) (Khalid *et al.*, 2000). Likewise, the frond comprised leaflets (which are more easily decomposable and have a lower C/N ratio) and rachis (which is less easily decomposable and has a higher C/N ratio).

In the early stage of leaflet decomposition, the C/N ratio of the leaflet was due to both the lamina and midrib, but as the decomposition progressed, the leaflet's C/N ratio was increasingly more represented by the midrib and increasingly less by the lamina properties. Likewise, for the decomposition of fronds. Over time, the fronds' C/N ratio was increasingly more represented by the rachis and less by the leaflet properties. Because C was continuously being lost from the residues as decomposition progressed (Fig. 4) and leaflets and fronds comprised materials having contrasting qualities, the C/N ratios for these two oil palm residues showed a much slower decline over time as compared to other residues.

For any time period, the C/N ratio for rachis was significantly higher than that for other oil palm residues (Fig. 6). The exception is at after 5 months when the C/N ratio for rachis was not significantly different from that for fronds. There was also no significant difference in the C/N ratios between EFB and fronds for the first 5 months, but after which the C/N ratio for EFB became significantly lower than that for the fronds. In the first 5 months, the changes in the C/N ratio for fronds were mostly represented by the leaflet properties (which were of higher quality than EFB), but in the later decomposition stages, the frond's C/N ratio was

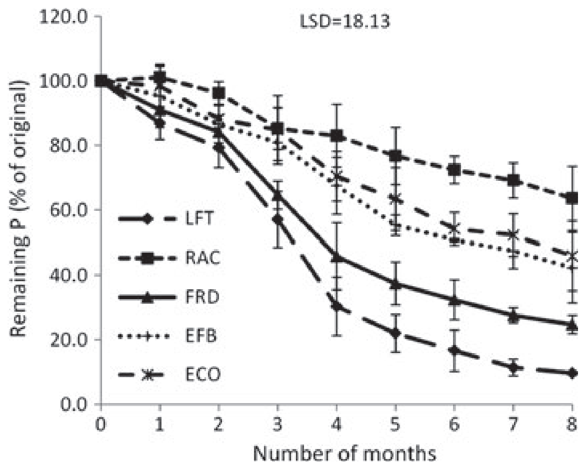

Figure 8 The %P remaining in various oil palm residues during decomposition (note: %P released = 100% − %P remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

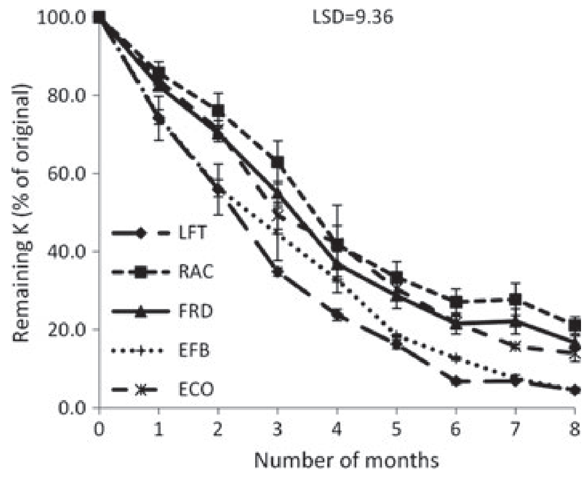

Figure 9 The %K remaining in various oil palm residues during decomposition (note: %K released = 100% − %K remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

increasingly more represented by the properties of rachis (which were of lower quality than EFB).

Phosphorus (P) release

The temporal release patterns for P (Fig. 8) were generally similar to that for N (Fig. 5), as also observed by Berg & Staaf (1980) and Khalid *et al.* (2000). Compared to the leaflets, the rachis released P slower, where only 36% of its initial P content was released within 8 months of the decomposition. This is 2.5 times slower than the P released by the leaflets (90%) in the same period. The fronds released P more rapidly than the rachis. There was no significant difference in the %P released between EFB and Eco-mat, but the %P released by these two residues were significantly lower than that by the oil palm fronds after 2 months of decomposition. At the end of the experimental period, the %P released by the leaflets, oil palm fronds, EFB, Eco-mat, and rachis were 90%, 75%, 58%, 54% and 36%, respectively.

Potassium (K) release

The K release patterns from different oil palm residues showed the similar trend of a relatively faster initial phase for about 6 months followed by a slower phase thereafter (Fig. 9). The %K released by EFB was generally higher than that by the Eco-mat and fronds. However, there was no significant difference in the %K released between the Eco-mat and fronds. The %K released by the leaflets at any given time was significantly higher than that by the rachis. The %K released by the oil palm residues in the first 6 months was the highest for the leaflets (93%) and the lowest for the rachis (73%). During this period, EFB released 87% of its original K, which was significantly higher than that released by Eco-mat and oil palm fronds (both 78%).

Calcium (Ca) release

Calcium release was the fastest for the leaflets followed by the fronds, and the slowest for rachis (Fig. 10). EFB and Eco-mat had similar Ca release patterns. The %Ca released by EFB and Eco-Mat in the first 4 months were not significantly different from each other, but the

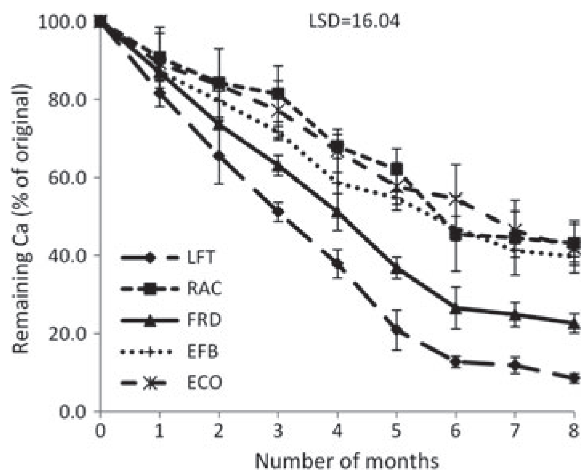

Figure 10 The %Ca remaining in various oil palm residues during decomposition (note: %Ca released = 100% − %Ca remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

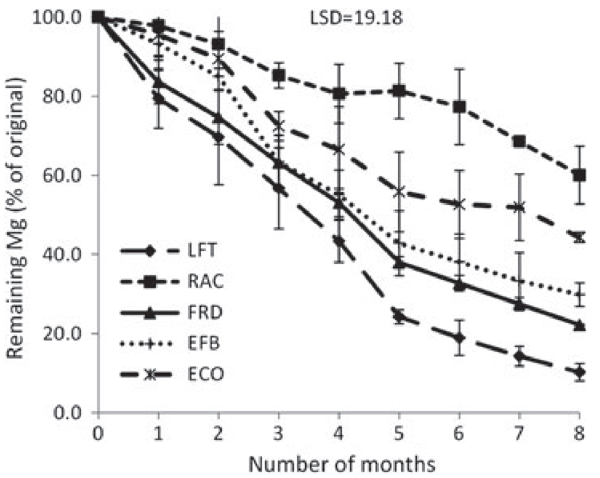

Figure 11 The %Mg remaining in various oil palm residues during decomposition (note: %Mg released = 100% − %Mg remaining). LFT, RAC, FRD, EFB and ECO denote leaflets, rachis, pruned palm fronds, empty fruit bunches and Eco-mat, respectively.

%Ca released by both these residues were significantly different than that by the fronds at any given time. At the end of the experimental period, the leaflets released about 91% of their Ca, which was significantly higher than that by rachis (about 57%), Eco-mat (58%) and EFB (60%) but not significantly different from that by the oil palm fronds (77%).

Magnesium (Mg) release

The temporal release patterns for Mg (Fig. 11) were similar to that for N and P (Figs 5 and 8). The %Mg released by the leaflets was significantly higher than that by the rachis and Eco-mat but not significantly different from that by the fronds and EFB. The %Mg released by EFB was generally similar to that by the fronds and Eco-mat but significantly higher than that by the rachis. At the end of the experiment, the %Mg released by the leaflets, oil palm fronds, EFB, Eco-mat and rachis were 90%, 78%, 70%, 56% and 40%, respectively.

Total amount of nutrients released

After 8 months of decomposition, leaflets released the largest amount of nutrients (except K) compared to other oil palm residues (Table 4). This is because, compared to other residues, leaflets had the highest concentrations of nutrients (except K) and the highest residue quality (Table 2). In contrast, rachis had the lowest nutrient concentrations (except K and Ca) and the lowest residue quality. Consequently, compared to other oil palm residues, the total amount of nutrients released by rachis after 8 months was the lowest (except for K and Ca). Because fronds comprised the nutrient-rich and easily decomposable leaflets, fronds also released total nutrient concentrations that were either significantly higher (for N and Ca) or not significantly different (for P and Mg) than EFB. The total amount of K released by EFB was significantly the highest than that by other oil palm residues. Compared to Eco-mat, EFB released significantly higher amounts of N, K and Mg but not significantly different amounts of P and Ca.

Conclusions

Compared to other oil palm residues, leaflets had the highest initial concentration for most nutrients, and in contrast, rachis and Eco-mat the two lowest. The residue quality and rate of mass loss of the oil palm residues were determined to be in the decreasing order of: leaflets > oil palm fronds > EFB > Eco-mat > rachis. One exception was that EFB's rate of mass loss was higher than that for fronds due to the low quality of rachis in the fronds. The mass loss of oil palm residues due to decomposition followed an exponential decrease, where the rate of mass loss was faster at the beginning than at the end of the decomposition period. Consequently, the temporal release pattern of nutrients by the oil palm residues also followed an exponential decrease. Nutrients were released faster and at larger amounts at the beginning than at the later stage of residue decomposition. After 8 months of decomposition, leaflets released the highest

Table 4 Mean (± SE) total amount of carbon and nutrients released by the oil palm residues after 8 months of decomposition[a]

Property	Leaflets	Rachis	Fronds	Empty Fruit Bunches	Eco-mat
C ($g\,kg^{-1}$)	471.72 ± 1.38 a	360.38 ± 18.19 c	400.42 ± 10.02 b	425.13 ± 3.00 b	418.30 ± 3.58 b
N ($g\,kg^{-1}$)	21.36 ± 3.80 a	1.16 ± 0.25 e	8.28 ± 1.30 b	4.25 ± 0.34 c	2.51 ± 0.04 d
P ($g\,kg^{-1}$)	1.00 ± 0.10 a	0.09 ± 0.03 d	0.41 ± 0.04 ab	0.31 ± 0.10 bc	0.16 ± 0.03 cd
K ($g\,kg^{-1}$)	10.98 ± 0.53 bc	13.72 ± 1.42 b	12.71 ± 0.75 bc	17.99 ± 1.47 a	9.65 ± 0.59 c
Ca ($g\,kg^{-1}$)	9.97 ± 1.28 a	2.42 ± 0.47 b	5.11 ± 0.41 a	1.30 ± 0.37 c	1.02 ± 0.19 c
Mg ($g\,kg^{-1}$)	1.46 ± 0.11 a	0.11 ± 0.02 d	0.59 ± 0.02 b	0.86 ± 0.19 ab	0.26 ± 0.02 c

[a]In the same row, means with the same letter are not significantly different from one another at 5% level of significance according to the mean separation test by LSD. The values for concentrations are on a dry weight basis.

amount of nutrients (except for K) compared to other oil palm residues, and rachis the lowest. Fronds comprised the nutrient-rich and easily decomposable leaflets, so fronds also released total nutrient concentrations that were either significantly higher (for N and Ca) or not significantly different (for P and Mg) than EFB. The industrial process of using high heat and high pressure to convert EFB into Eco-mat had resulted in a loss of some nutrients in Eco-mat, as well as a decrease in residue quality of Eco-mat. Compared to Eco-mat, EFB released significantly higher total amounts of N, K and Mg nutrients. Results from this study would help to better manage soil fertility when these oil palm residues are used as mulch such as to determine a more accurate fertiliser application for oil palm.

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