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THE EFFECT OF INCORPORATING PALM RESIDUES AT REPLANTING ON PHOSPHATE DYNAMICS IN AN INLAND SOIL IN MALAYSIA

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ABSTRACT

The effects of adding approximately 200 mg P kg^{-1} *soil in three different palm residue treatments (pulverized, shredded and partially-burned) at replanting on P fractions were investigated in a field experiment at Kluang, Johor, two and three years after oil palm replanting. The three treatments led to about two- to four-fold increases in the organic P pool over the control. This indicates the importance of biological activity, stimulated by incorporation of palm residues, in the distribution of P fractions. Organic P and microbial P are thought to be the main soil P fractions involved in P cycling in the soil when added through palm residues. The results also suggest that when palm residues were incorporated, the amount of P adsorbed was reduced by 40% to 50% after two years and by 45% to 50%, three years after replanting. Decreasing P sorption together with increasing P desorption in the soil is one important aspect for improving plant P uptake efficiency. Amending the soil with palm residues may supply a greater percentage of residual P to oil palm. Therefore, with incorporation of palm residues, P fertilization probably can be reduced for the two years following replanting.*

Keywords: oil palm residues, soil P fractions, replanting.

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INTRODUCTION

The current practice of utilizing oil palm residues at replanting supplies significant amounts of nutrients to support the growth of the following oil palm crop. Khalid *et al.* (1999) reported that, at the time of felling, old stands of oil palm contained 85 t ha^{-1} of above-ground biomass and 16 t ha^{-1} of below-ground biomass. This biomass contributed up to 58 kg P ha^{-1}, whereby appropriate management of the palm residues could maximize the carry-over of P to support the growth of the young palms. Furthermore, it also resulted in a saving in fertilizer costs of about USD 140 ha^{-1} yr^{-1} (Khalid *et al.*, 1999). The use of organic materials such as farmyard manure, crop residues and green manures together with phosphate rock (PR) has been shown to enhance PR dissolution and thus plant uptake of P (Bah *et al.*, 2006). Growing of leguminous crops such as *Mucuna bracteata* (MB) as soil covers that is practiced in oil palm plantations could have a positive effect on soil fertility and could recycle the P when these covers die, thereby improving P availability in the soil (Ng *et al*., 2005).

This practice of incorporating oil palm residues during replanting can alter the dynamics of organic matter turnover in the soils, and subsequently may change the dynamics of P and its cycling, as well as its availability to crops. Phosphorus cycling in the soil can be described in terms of the biological, biochemical and geochemical processes involved (Walbridge *et al.*, 1991), but these processes have been examined independently, without consideration of possible interactions among them (Compton and Cole, 1998). Biological processes include uptake by plants and microorganisms, production and decomposition of organic residues, and release of mineralized P. Geochemical processes include the weathering of primary minerals and the adsorption and desorption of organic and inorganic phosphate by soil surfaces. Most mineral soils can adsorb a large amount of P, which explains the low availability of

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P in many soils. The two dominant biological P pools are total soil organic P and microbial biomass P (Di *et al.*, 1997). Some of the inorganic P can be inactivated by adsorption onto soil particles, or can be assimilated microbially and transformed into organic P (Wetzel, 1998).

The effective management of oil palm residues requires a detailed understanding of the amounts and forms of P in the soil and their potential mobility, and of the changes in form and their potential loss due to continued accumulation of P in the soil during replanting. Several pathways of P transformation occur in the soil and these require further investigation, especially with regard to the effects of organic matter dynamics under oil palm plantation management. The solubility and bioavailability of P are expected to be different between soil with added organic residues and 'unamended' soil. Several workers reported the usefulness of P fractionation in the identification of biogeochemical soil P pools in a variety of ecosystems (Hedley and Stewart, 1982; Tiessen *et al.*, 1984). Both soluble and solid-phase organic matter have the potential of influencing P dynamics. Thus, the objective of this study was to investigate whether the adoption of palm residue management, without subsequent inorganic P fertilizer input, would affect the distribution of P within the inorganic and organic pools and in the soil P fractions during the replanting of an oil palm plantation.

MATERIALS AND METHODS

The study was carried out on the Rengam soil series, in an ongoing trial investigating nutrient cycling dynamics with a zero-burning replanting technique (oil palm residues were recycled in the field) at PORIM (now MPOB) Research Station in Kluang, Johor, except the partially burnt treatment, where about 50% of the residues were burnt. The study area was located at latitude 1º 57′ N, and longitude 103º 22′ N (Khalid *et al.*, 1999).

The experimental plots were established following the felling of a 23-year-old oil palm plantation of first plant rotation with a planting density of 136 palms ha^{-1}. The plantation has three zones or areas, namely, weeded circles, harvester paths and frond piles, which contributed to 60%, 20% and 20% of the plantation, respectively. The site rainfall was more than 2000 mm yr^{-1}. Dry months occurred only once or twice per year, and were not usually consecutive.

The Rengam series is a member of the clayey kaolinitic isohyperthermic family of Typic Paleudults (Paramanthan, 1978). They are derived from granitic parent materials, and have thin brown coarse sandy clay A horizons and deep uniform brownish yellow to yellowish brown coarse sandy clay-to-clay B horizons. The Rengam series occurs on slopes ranging from gently undulating through rolling to hilly. Terrain is the only limiting factor of this soil, and the soil is prone to erosion on steeper slopes. The Rengam series is probably the most widespread soil in Peninsular Malaysia. This soil has 0.12% of total N, 1.3% of organic C, a pH of 4.5, CEC of 9.4 (cmol + kg^{-1}), 47% of clay, 4% of silt content, 15% of fine sand and 34% of coarse sand.

EXPERIMENTAL DESIGN AND TREATMENTS

The experiment consisted of 16 plots, which were laid out in a randomized complete block design (RCBD) with four replicates. The four treatments (techniques) involving the use of palm residues during replanting were: chipped and shredded (S), chipped and pulverized (P), partial burning (B), and no residues or complete removal of palm residues (C). The palm trunk was initially chopped into pieces about 10 cm thick in all plots except for the C plots. Each plot consisted of 4 x 5 palms (0.15 ha), with 12 recording palms and 20 border palms as shown in *Figure 1*. As reported by Khalid *et al*. (1999), the content of P in palm residues is 58 kg ha^{-1}. Only 20% of every hectare received palm residues and these were incorporated to a depth of 15 cm. Thus, P added for the Treatment S and Treatment P plots was about 200 mg P kg^{-1} soil, while about 100 mg P kg^{-1} soil was added to the Treatment B plots, assuming a 50% loss of residues following burning.

The experimental plots were established as follows:

- chipped and shredded (S). The palm trunks and fronds were chipped and shredded into pieces about 10 cm thick, and spread evenly in strips about 3-4 m wide, in between the old stand and new planting to avoid thick pile formation.
- chipped and pulverized (P). The palm trunks and fronds were chipped and shredded to about 10 cm, as above, but after one week, the residues were pulverized into small pieces about 3 to 4 cm in length using a pulverizing machine and spread as above.
- partially burned (B). This involved partial burning of chipped and shredded residues, and the remaining residues (unburnt materials) were spread as above, which consisted of 50% of the chipped material, were left in the field to decompose.
- no residues (C). The trunks and fronds of felled palms were loaded onto a truck and removed from the site.

The above treatments were laid on the new frond pile area. No fertilizers were applied during the experimental period of about two years after replanting except for an initial application of 250 g

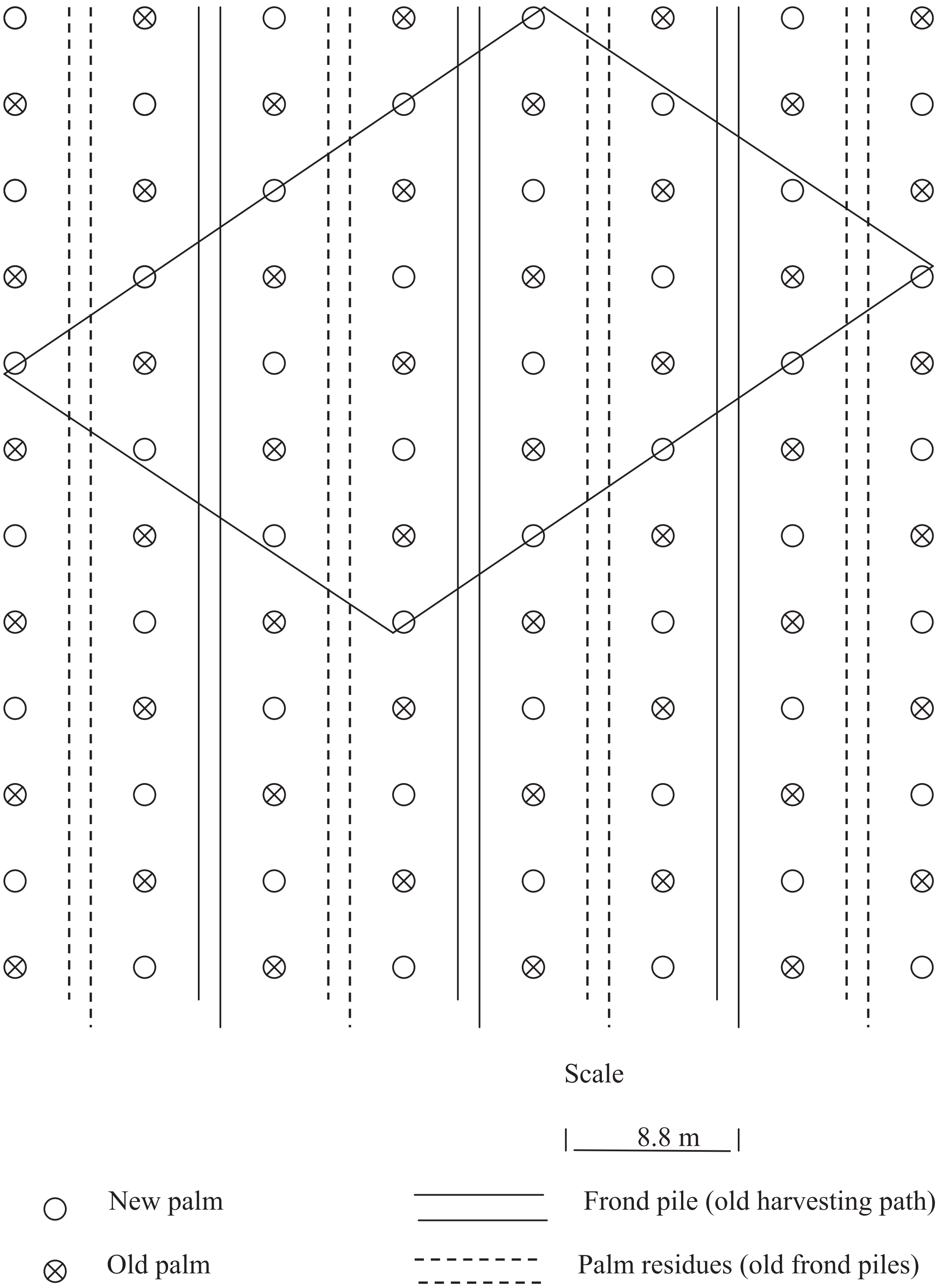

Figure 1. Plan of an experimental plot showing the pattern of adding palm residues and the planting position of the old stand and new palms.

of PR, *i.e.*, about 35 mg P, in each planting-hole (all treatment plots) at the time of planting. Therefore, this P applied in the planting hole did not affect the amount of P in the soil analysed because the soil samples were taken from where the plant residues were applied as shown in *Figure 1*.

Soil Sampling

For each plot, 10 to 15 soil samples were taken randomly in the area where the palm residues were applied (old palm residues as shown in *Figure 1*) using a screw auger at depths of 0-15 cm and 15-30 cm. Each set of sub-samples was bulked into composite samples weighing approximately 2 kg for each plot. The soil samples were collected on two occasions, two years and three years after replanting. Before chemical analyses were carried out, the soils were hand-sorted to remove root materials, air-dried, and sieved to separate the < 2 mm fraction.

Chemical Analyses

Duplicate soil samples from each plot were analysed for fractions of P, including total P, Pi strip P, Bray 2 P, organic P and microbial biomass P, and for microbial biomass C.

Total P was determined by digesting air-dried soil samples in a concentrated sulphuric acid and 30% perchloric acid mixture (Anderson and Ingram, 1993). Two grams of soil were placed in a 23 x 248 mm digestion tube and then 6 ml of the acid digestion mixture were added. The tubes were placed in a digestion block and heated to 200°C until the reaction was completed (a white cloudy solution was formed). The P was then determined colorimetrically by the molybdenum blue method, with ascorbic acid as the reducing agent (Murphy and Riley, 1962). The molybdenum blue method is based on the principle that in an acid molybdate solution containing orthophosphate ions, a phosphomolybdate complex forms that can be reduced by ascorbic acid to a blue colour.

The iron oxide coated strip (Menon *et al.*, 1989a, b) was prepared by soaking a Whatman No. 50 filter paper in a 0.5 M $FeCl_3$ solution for about 10 min. The excess $FeCl_3$ solution was allowed to drain, before the filter was immersed in 2.7 M NH_4OH for about 45 s. The papers thus treated were thoroughly rinsed with distilled water and air-dried. The dry papers were cut into 2 x 10 cm strips. Inorganic P in the soils was extracted by adding 1 g of soil to 40 ml of a 0.01 M $CaCl_2$ solution containing two strips. The sample was shaken for 16 hr. After shaking, the strips were thoroughly washed free of any soil particles adhering to the strips using deionized water, and the strips were shaken in a 0.2 M H_2SO_4 solution for about 1 hr to remove the P adsorbed by the Fe oxide-coated strip. The P was determined by using the Murphy and Riley (1962) procedure. This Pi is referred to as plant-available P.

Bray 2 P was measured by extracting an air-dried soil sample for 1 min with the Bray No. 2 extractant which is a mixture of 0.1 M HCl plus 0.03 M NH_4F (Bray and Kurtz, 1945). Two grams of soil were weighed into 125 ml conical flasks and 20 ml of extracting solution were added. The mixture was shaken for 1 min and filtered before P was determined using the Murphy and Riley procedure (Murphy and Riley, 1962). This extractant removes a proportion of both acid-soluble and adsorbed forms of P.

Organic P was estimated from the difference between acid-extractable P from non-ignited and ignited soil samples (Anderson and Ingram, 1993). Approximately 1 g of air-dried soil was weighed and placed in a porcelain crucible. The sample was ignited in a muffle furnace by first slowly heating to 550°C over 2 hr, and then ashing at that temperature for a further 1 hr. A second sample of 1 g of air-dried soil was weighed and transferred to a 50-ml conical flask; 50 ml of H_2SO_4 were added to each flask and shaken using a horizontal shaker for 16 hr. The soil extracts were then filtered, and P was determined using the molybdenum blue method (Murphy and Riley, 1962). The amount of organic P was calculated by subtracting the P extracted from a non-ignited sample from that extracted from an ignited sample.

Microbial biomass P and C were determined using the chloroform fumigation method. The soils were sampled and hand-sorted to remove large pieces of plant debris, earthworms, *etc*. Moisture contents were adjusted to 40% of field water-holding capacity using distilled water. Soils were then 'conditioned' for 10 days at 25°C and 100% relative humidity. After this initial incubation, the soils were either used immediately, or stored at 2°C. Before use in further experiments, the stored soils were kept at 25°C for about 24 hr. The fumigation procedure described by Jenkinson and Powlson (1976), Brookes *et al.* (1982) and Wu *et al.* (1990) was used. Five grams of fresh soil (in four replicates) were weighed into glass jars and exposed to alcohol-free $CHCl_3$ vapour for 24 hr in a vacuum desiccator at room temperature. The jars were then placed in a clean desiccator, and residual $CHCl_3$ removed by evacuation for 15-20 min. Fumigated portions, together with equivalent non-fumigated portions, were extracted with 100 ml of 0.03 M NH_4F and 0.1 M HCl (Bray 2). Prior to analysis, all extracts were filtered using Whatman No. 42 filter paper. Biomass P was calculated from the increase in extractable P in the fumigated soil over that in the non-fumigated sample using a conversion factor (Kp) of 0.4 (Hedley and Stewart, 1982). Biomass C was measured by the fumigation-extraction method (Vance *et al.*, 1987). The fumigation process was similar to the procedure for determining microbial biomass P. The soils were shaken for 30 min with 0.5 M K_2SO_4 (4:1 solution to soil ratio). Organic C in the extract was determined by dichromate digestion (Vance *et al.*, 1987). Biomass C was then estimated as follows: biomass C=2.22 E_c, where E_c is the difference between C extracted from the fumigated and non-fumigated soil samples. The value of 2.22 is a proportionality constant to account for the fact that the $CHCl_3$ treatment does not render the entire microbial biomass C extractable by 0.5 M K_2SO_4 (Vance *et al.*, 1987; Wu *et al.*, 1993).

Amounts of P in the sequential fractionation procedures were determined by measuring orthophosphate in extractants added in the following order: (i) 0.1 M NaOH and 1 M NaCl (NaOH P), (ii) 0.3 M citrate ($Na_3C_6H_5O_7.2H_2O$) plus 1 M

$NaHCO_3$ (heated to 85°C for 15 min with 1 g dithionite [$Na_2S_2O_7.2H_2O$] (occluded P), and (iii) 1 M HCl (Ca P).

Phosphate Sorption and Desorption

Phosphate sorption and desorption by soils were measured by determining the amount of P adsorbed and desorbed from known amounts of P added as KH_2PO_4 in 0.01 M $CaCl_2$ electrolyte (Dubus and Becquer, 2001).

Phosphate sorption was determined by weighing approximately 1 g of soil into a centrifuge tube and adding 40 ml of a known P solution in 0.01 M $CaCl_2$ (2 -15 mg P litre^{-1}), shaking for 16 hr, and centrifuging for 15 min at 2000 rpm. The supernatant solution was transferred into a conical flask without disturbing the compact soil residue. The soil residue, with entrapped solution, was weighed for use later in the phosphate desorption process. The P in solution was analysed using the Murphy and Riley (1962) procedure. The amount of P adsorbed by the soil was calculated by substracting the amount of P in solution from the amount of P added to the soil.

A linear form of the Langmuir equation, $C/X = C/Smax + 1/KSmax$, was used to evaluate the adsorption constants of the soils. In the equation, C is the P concentration at equilibrium condition (mg P litre^{-1}), X is the amount of P adsorbed (mg P kg^{-1}), Smax is the adsorption maximum, and K is a constant related to the binding energy. The Smax was determined from the slope of the graph plot of C/X against C, and K was calculated from the intercept. The amount of P required by the soils to attain 0.2 mg P L^{-1} was extrapolated from a graph of P adsorbed against P concentration at equilibrium.

Phosphate desorption was determined by adding approximately 40 ml of 0.01 M $CaCl_2$ to the soil by weighing the soil plus solution to give the same weight as before the supernatant was removed following the sorption step. The mixture was then shaken for 16 hr before centrifuging the suspensions at 2000 rpm (as in the sorption step). The P in solution was also analysed using the Murphy and Riley (1962) procedure. The amount of desorbed P was measured by subtracting the weight of entrapped P from the weight of P desorbed (final P concentration in the solution during the desorption process). The percentage of desorbed P was calculated from the amount of P adsorbed.

Statistical Analysis

The effects of the four replanting techniques, soil depths, and time after planting on various forms of P were tested using the general linear model (GLM) test. Where the F test was significant ($p<0.05$), the means were compared using Tukey's Studentized range test. The same procedure was used to compare soil depths within treatments, and time effects within treatments.

RESULTS AND DISCUSSION

Effect of Palm Residues Treatments on the Various Soil P Fractions

In general, P input (200 mg kg^{-1} soil) via application of palm residues (*Table 1*) during the three years after replanting increased all fractions of P, which included total P, extractable P (Pi strip and Bray 2 P), NaOH P, Ca P, occluded P, organic P and microbial biomass P, for all three methods of replanting compared with the control (no residues). This suggests that incorporation of organic residues affects the nutrient cycle, alters the sink size for P, and changes the various forms of P in the soil with time, indicating the importance of biological activity (Sharpley *et al.*, 1984).

Overall, incorporation of organic residues increased the amount of total P in the soil with all three palm residue treatments, compared with the control, because of the added P in the organic residues. Total P content in soil treated with palm residues is the total amount of P in the soil plus the amount of P added from the palm residues. Adding pulverized and shredded palm residues (200 mg P kg^{-1} soil) contributed 192 and 186 mg P kg^{-1} soil, respectively, which were slightly more than double the total P in the soil as found in the control, with the total P ranked in the order: pulverized = shredded > partially-burned residues > control. The large increases in total P in soils treated with pulverized and shredded residues were mainly due to the increase in organic P in the soil as a result of the addition of palm residues, but the values were still smaller than the sum of added P (estimated at 200 mg P kg^{-1} soil) and that from the soil (about 90 mg P kg^{-1} soil), probably due to some of the P being removed by plant uptake and/or lost from the system. About 34% and 37% of total P from the soil and that added through pulverized and shredded residues, respectively, were probably lost from the system and/or was taken up by the plant. The smaller amount of total P (131 mg P kg^{-1} soil) recovered in the treatment with the partially burned residues was due to only half of the palm residues remaining on the soil following burning. The correlation coefficients for total P and other P fractions show that total P was highly correlated with almost all P fractions in the soil treated with palm residues. The correlation coefficients were: Pi ($r=0.94^{***}$), Bray 2 P ($r=0.92^{***}$), NaOH P ($r=0.99^{***}$), Ca P ($r=0.97^{***}$), occluded P ($r=0.95^{***}$), microbial biomass P ($r=0.95^{***}$) and organic P ($r=0.98^{***}$) in soils treated with palm residues.

TABLE 1. OVERALL EFFECTS OF TREATMENTS WITH PALM RESIDUE ON VARIOUS FRACTIONS (mg kg^{-1} soil) OF SOIL P FOR ALL DATES AND DEPTHS COMBINED

P fraction	Treatment			
	Control (no residues)	**Residues pulverized**	**Residues shredded**	**Residues partially burned**
Pi	3.0c ± 0.2	4.5a ± 0.3	4.1a ± 0.3	3.4b ± 0.2
Bray 2 P	7.7c ± 0.4	20.1a ± 0.8	21.4a ± 0.7	14.8b ± 0.6
NaOH P	25.3b ± 1.1	40.4a ± 1.8	40.3a ± 2.0	26.8b ± 1.2
Ca P	6.6b ± 0.2	12.1a± 0.5	12.6a ± 0.6	7.2b ± 0.4
Occluded P	13.5b ± 0.8	25.8a± 1.6	25.7a±1.5	15.5b±1.1
Microbial biomass P	1.5c±0.1	7.1a±0.3	7.8a±0.4	4.6b±0.2
Organic P	27.8d± 2.1	103a± 6.2	94.7a±5.4	44.9b±3.5
Total P	88.9d± 10	192a±21	186a±15	113b±12

Note: Values followed by the same letters in the same row are not significantly different at the 5% level, as determined by Tukey's Studentized range test.

Incorporation of P by applying pulverized and shredded palm residues at about 200 mg P kg^{-1} soil, and of 100 mg P kg^{-1} soil through partially burned residues (again based on an estimated 50% of P being lost following burning) increased the amount of organic P and microbial biomass P to the largest extent compared to the control. Soils treated with pulverized palm residues (103 mg organic P kg^{-1} soil) and shredded palm residues (94.7 mg organic P kg^{-1} soil) appeared to have significantly more organic P than the treatment which received partially burned (44.9 mg organic P kg^{-1} soil) residues. The same trend was found for the microbial biomass P fraction, where the shredded (7.8 mg P kg^{-1} soil) palm residues contributed the same amount of microbial biomass P as the pulverized (7.1 mg P kg^{-1} soil) residue-treated soil, and they were significantly larger than in the treatment which was treated with partially burned residues (4.6 mg P kg^{-1} soil). The organic P accounted for about 32% of total P in the untreated control soil, but adding 200 mg P kg^{-1} soil through incorporation of palm residues increased organic P by approximately 20%, as measured by the ignition-extraction procedure. Organic P constituted about 53%, 51% and 40% of total P in the soils treated with pulverized, shredded and partially burned residues, respectively. As reported by Smith *et al*. (1998), plant materials contain about the same percentages of organic P and inorganic P; thus, stimulating the incorporation of organic P and microbial biomass P, immobilization of inorganic P and the mineralization process. Increases in organic P and microbial biomass P with the three different treatments of incorporating palm residues are expected to affect the distribution of all fractions of P in the soil, probably through the process of mineralization of organic P. Microbial biomass P was also an important, dynamic P pool in the soil, and contributed to 3.7%-4.7% of the total P (*Table 1*). Soil amended with shredded palm residues supplied the largest amount of microbial biomass P, whereas the lowest amount of microbial biomass P was found in the soil treated with partially burned residues, (not considering the control). Microbial biomass P controls the turnover of P through its link with the decomposition of organic residues, releasing inorganic P or forming organic P fractions, solubilizing insoluble mineral P forms through the release of chelating agents and/or organic acids (Rajan *et al.*, 1996). The values obtained in this experiment suggest that amending the soil with organic residues increased microbial biomass P to a larger extent than that reported by Stevenson (1986), where it represented about 1%-2% of the total P present in the soil.

The Pi and Bray 2 P fractions were among the smallest found in the soil under all replanting treatments. The Pi fraction represents soil solution P and soluble phosphate originating from loosely-adsorbed inorganic P on the surface of hydrous oxides of Fe and Al and equivalent to that determined by anion exchange resin (Sharpley, 1991). As in the case of Pi, addition of palm residues increased Bray 2 P values, with slightly larger values than for Pi. The relatively strong reagents used in the Bray 2 procedure may have extracted a larger amount of P compared with Pi. It has been suggested that inorganic P extracted from the soil with dilute 0.01 M $CaCl_2$ is an appropriate measurement of potentially-mobile P (Brookes *et al.*, 1997). The procedure involved using strips of iron oxide-impregnated filter paper (Pi method) to adsorb P from a suspension of soil in a 0.01M $CaCl_2$ solution. Incorporation of palm residues affected the distribution of Pi in the soil compared with the control, being dependent on the organic P incorporated from the pulverized, shredded, and partially burned residues and the mineralization of organic P. Addition of palm residues contributed 4.5

and 4.1 mg P kg^{-1} soil of Pi from pulverized and shredded residues, respectively, compared to the control (3.0 mg P kg^{-1} soil) and to partially burned residues (3.4 mg P kg^{-1} soil). The amounts of Pi and Bray 2 P were significantly lower ($p<0.05$) with the partially burned than with the shredded and pulverized residues, and this was again possibly due to 50% of the P being lost as a result of burning. The formation of Al and Fe complexes by organic acids would increase the Pi and Bray 2 P in soil, where carboxyl and hydroxyl functional groups were reported to be involved in reactions between metals and (i) organic acids (Huang and Violante, 1986), or (ii) compounds, such as aliphatic acids, amino acids, phenolic acids, 2-ketogluconic acid and polymeric phenols (Stevenson, 1994). A major reaction involves acidic COOH and phenolic groups with metals to form stable complexes (Tan, 1986). These cations bound to P by organic acids would result in the release of P into the soil solution and thus increase Pi and Bray 2 P in soil treated with pulverized and shredded palm residues compared with partially burned residues and the control.

Incorporation of palm residues also affected the distribution of other inorganic P fractions (NaOH P, Ca P, and occluded P) in the soil by increasing the amount of these fractions over the control. For NaOH P there was no significant difference ($p < 0.05$) in values between the treatments with pulverized (40.4 mg P kg^{-1} soil) and with shredded (40.3 mg P kg^{-1} soil) residues, but these values were significantly larger than that for the treatment with partially burned (27.8 mg P kg^{-1} soil) residues. The smaller value for NaOH P in the partially burned residues was possibly due to the smaller amount of total P added (50% of the P added was presumed lost after burning). However, the NaOH P fraction accounted for about 21% of total P in soils treated with pulverized and shredded residues, and for 24% of total P in the soil treated with partially burned residues. The same was observed for occluded P in the soils treated with pulverized and shredded palm residues compared with the control and treatment with partially burned residues, but in this case occluded P accounted for only 13%-14% of the total P. These P fractions are mainly dependent upon the chemical and physical properties of the soil, but at the same time may control other variables, such as organic matter accumulation (Cole and Heil, 1981). It was reported that the NaOH extractant removed P that is less related to P plant uptake than the Pi method or resin P, and extracts P that is bound to Fe (McDowell and Condron, 2000). However, the amounts of these inorganic P fractions in the shredded and pulverized treatments were significantly larger when compared to the treatment with partially burned residues. Organic residues contributed more to NaOH P and occluded P because the soil studied, being very acidic, would favour the formation of Al P and Fe P. NaOH P was expected to be a more dominant inorganic P fraction than Ca P, because this acid soil was richer in non-crystalline Fe and Al hydrous oxides than the primary mineral apatite P. The same observation was made when organic residues (wheat straw and alfalfa) were added to a Rwanda soil and was found to contribute a large amount of NaOH P (Iyamuremye *et al*., 1996). It is not clear why palm residues increased Ca P, two-fold compared with the control. This is possibly due to some of the Ca present in the residues precipitating and resulting in an increase in Ca P two to three years after incorporation of the palm residues.

Effects of Palm Residues Treatments on Phosphate Sorption and Desorption

The amounts of P adsorbed and desorbed by soils receiving palm residues at two and three years after replanting are presented in *Tables 2* and *3*, respectively. Two years after pulverized palm residues were added (*Table 2*), the amount of P adsorbed and desorbed in the soil ranged from 75-409 mg P kg^{-1} soil and from 2.22-47.7 mg P kg^{-1} soil at equilibrium P concentrations of 0.13-4.76 mg litre^{-1} and 0.06-1.19 mg litre^{-1}, respectively. For shredded residues, the amount of P adsorbed and desorbed ranged from 77-462 mg P kg^{-1} soil and from 0.94-32.8 mg P kg^{-1} soil at equilibrium P concentrations of 0.07-3.44 mg litre^{-1} and 0.02-0.82 mg litre^{-1}, respectively. For the treatment with partially burned residues, the amount of P adsorbed and desorbed ranged from 76-507 mg P kg^{-1} soil and from 1.32-24.5 mg P kg^{-1} soil at equilibrium P concentrations of 0.09-2.33 mg litre^{-1} and 0.03-0.61 mg litre^{-1}, respectively, whereas in the control they ranged from 78-526 mg P kg^{-1} soil and 1.16-23.3 mg P kg^{-1} soil at equilibrium P concentrations of 0.05-1.84 mg litre^{-1} and 0.03-0.58 mg litre^{-1}, respectively. The amounts of P adsorbed three years after addition of the plant residues showed a similar trend (*Table 3*), but with lower values compared to after two years.

The percentages of desorbed P at added P of 600 mg kg^{-1} soil were small, ranging from 4.4% (control) to 11.6% (pulverized residues) of the P added, and from 6.4% (control) to 11.3% (shredded residues) of the P added, at two and three years, respectively after the addition of palm residues. The possible reasons are irreversible reactions of adsorbed P with soil compounds and that desorption equilibrium had not been reached, probably due to the desorption process being slower than adsorption.

TABLE 2. AMOUNTS OF ADDED P ADSORBED AND DESORBED BY THE SOIL TWO YEARS AFTER INCORPORATING PALM RESIDUES

Treatment with residues	Added P (mg kg^{-1} soil)	P eq. (mg litre^{-1})	Adsorbed P (mg kg^{-1} soil)	% adsorbed* P	P eq. (mg litre^{-1})	Desorbed P (mg kg^{-1} soil)	% desorbed** P
Partially burned	80	0.09	76.3	95.4	0.03	1.32	1.8
	160	0.21	151	94.6	0.09	3.69	2.4
	320	0.51	299	93.7	0.20	8.10	2.7
	480	1.11	435	90.7	0.43	17.1	3.9
	600	2.33	507	84.5	0.61	24.5	4.8
Pulverized	80	0.13	74.8	93.6	0.06	2.22	3.0
	160	0.30	148	92.4	0.15	5.95	4.0
	320	1.26	270	84.3	0.48	19.1	7.1
	480	2.84	366	76.4	0.75	29.9	8.2
	600	4.76	409	68.3	1.19	47.7	11.6
Shredded	80	0.07	77.1	96.3	0.02	0.94	1.2
	160	0.19	152	95.2	0.07	2.84	1.9
	320	0.80	288	89.9	0.32	12.8	4.5
	480	2.00	400	83.3	0.66	26.3	6.6
	600	3.44	462	77.1	0.82	32.8	7.1
Control (no residues added)	80	0.05	78.2	97.7	0.03	1.16	1.5
	160	0.12	155	97.1	0.09	3.52	2.3
	320	0.36	305	95.5	0.20	7.81	2.6
	480	0.94	442	92.2	0.48	19.1	4.3
	600	1.84	526	87.7	0.58	23.3	4.4

Notes:
* Percentage of P added.
** Percentage of P adsorbed.

TABLE 3. AMOUNTS OF ADDED P ADSORBED AND DESORBED BY THE SOIL THREE YEARS AFTER INCORPORATING PALM RESIDUES

Treatment with residues	Added P (mg kg^{-1} soil)	P eq. (mg litre^{-1})	Adsorbed P (mg kg^{-1} soil)	% adsorbed* P	P eq. (mg litre^{-1})	Desorbed P (mg kg^{-1} soil)	% desorbed** P
Partially burned	80	0.07	77.3	96.6	0.06	2.50	3.2
	160	0.16	154	96.1	0.14	5.70	3.7
	320	0.92	283	88.5	0.40	16.1	5.7
	480	2.54	378	78.8	0.62	24.9	6.6
	600	3.55	458	76.4	0.99	39.5	8.6
Pulverized	80	0.09	76.5	95.7	0.08	3.10	4.0
	160	0.22	151	94.5	0.17	6.80	4.5
	320	0.90	284	88.7	0.43	17.3	6.1
	480	2.28	389	81.0	0.86	34.4	8.8
	600	3.95	442	73.7	1.14	45.8	10.4
Shredded	80	0.13	74.8	93.5	0.07	2.80	3.8
	160	0.31	147	92.2	0.18	7.30	4.9
	320	0.84	286	89.5	0.56	22.3	7.8
	480	1.34	426	88.8	0.91	36.5	8.6
	600	3.28	468	78.1	1.32	52.9	11.3
Control (no residues added)	80	0.04	78.5	98.1	0.06	2.20	2.8
	160	0.07	157	98.1	0.12	4.80	3.1
	320	0.31	308	96.1	0.28	11.1	3.6
	480	0.99	440	91.7	0.52	20.7	4.7
	600	2.01	520	86.6	0.83	33.3	6.4

Notes:
* Percentage of P added.
** Percentage of P adsorbed.

Typical phosphate sorption isotherms, at two and three years after incorporation with palm residues are presented in *Figures 2* and *3*, respectively. The amounts of P adsorbed at a given equilibrium P concentration in solution were decreased in the soils treated with palm residues during replanting compared to the control after two and three years.

The results indicate that there are variations in the sorption capacity of the soil at different levels of equilibrium solution P. At each level of P addition, incorporation with palm residues resulted in a higher P concentration at equilibrium. The amounts of P adsorbed at a soil solution P concentration of 0.2 mg litre^{-1} are summarized in *Table 4*. The amount of P

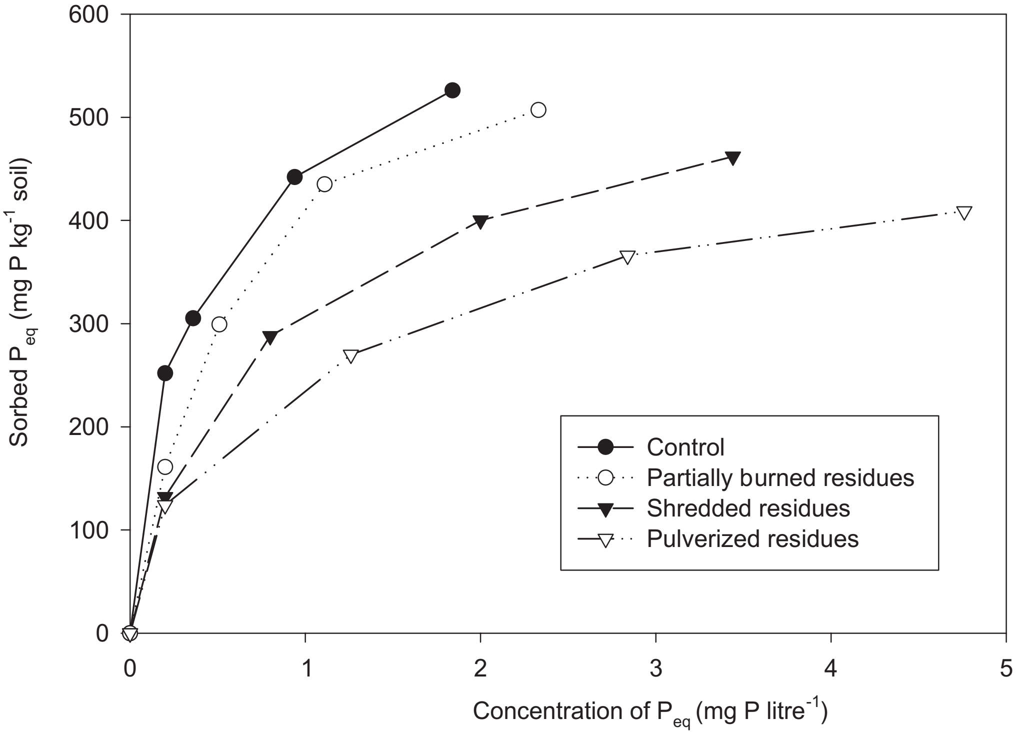

Figure 2. Phosphate sorption isotherms for soils at two years after incorporation of palm residues.

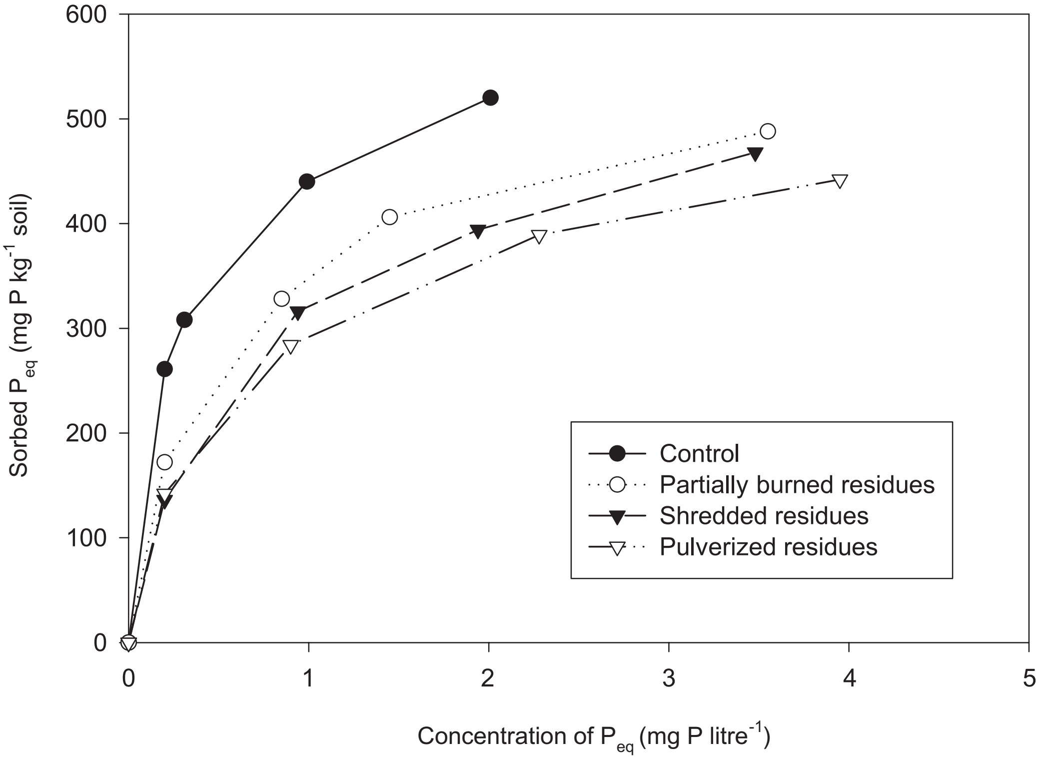

Figure 3. Phosphate sorption isotherms for soils at three years after incorporation of palm residues.

adsorbed decreased by about 40%-50% after two years, and by 45%-50% after three years, to attain 0.2 mg litre^{-1} in the soil solution in the soils treated with palm residues, compared with the control. If 0.2 mg litre^{-1} P in the soil solution is a realistic optimum concentration required for oil palm, then addition of palm residues had reduced the sorption capacity of the soil by about 50% for pulverized residues, compared with the control, at two and three years after application.

The P sorption characteristics varied with the palm residue treatments. The amount of P adsorbed by the soil with pulverized residues was smaller than those with shredded residues and with partially burned residues, and that of the control, two years after application of palm residues (*Table 2*). However, after three years (*Table 3*), the soil with shredded residues adsorbed the least P, but at a higher concentration of P in the equilibrium solution, while the ranking was similar at two (*Table 2*) and three years (*Table 3*) after application of the palm residues: adsorbed P of the soil with pulverized residues < shredded < partially burned < control. The small difference in the amounts of P adsorbed by the soils treated with pulverized and shredded residues was probably due to the difference in the decomposition rate between these two types of palm residues. The larger particle size of shredded residues would take a longer time to decompose, probably resulting in larger amount of added P being adsorbed by the soil two years after incorporation of the residues, thus minimizing the losses of P from the field.

The amount of P desorbed at a soil solution P concentration of 0.2 mg litre^{-1} was small, ranging from 7.8 mg P kg^{-1} soil (control) to 12.2 mg P kg^{-1} soil (pulverized residues) two years after incorporating the palm residues, and 6.8 mg P kg^{-1} soil (control) to 11.3 mg P kg^{-1} soil (pulverized residues) after three years (*Table 4*). This is probably due to irreversible reactions of adsorbed P with soil compounds, and because the desorption equilibrium was not reached as a result of desorption being a slower process than adsorption.

The P added in pulverized and shredded palm residues was more easily desorbed than that from the partially burned residues and from the control at two and three years after incorporation. The results are in agreement with the reports which suggest that the fixation of P is reduced when organic residues were added to the soil (Iyamuremye and Dick, 1996). Incorporation of P to the soil treated with 200 mg P kg^{-1} soil via the application of palm residues was observed to enhance mineralization and desorption of the added P. This phenomenon may explain why the addition of organic residues decreased P sorption by the soil, and increased the amount of P desorbed by the soil, through anion exchange or ligand exchange on Fe or Al hydrous oxides (Qualls, 2000). The hydroxyl group of the carboxylic acid or phosphate could substitute for the coordinated hydroxyl on the Fe and Al hydrous-oxide surface. Therefore, organic acids compete with phosphate for the same ligand exchange sites on the Fe and Al hydrous-oxide surface, resulting in an increase in the desorption of P and a suppression in the sorption of P (Qualls, 2000).

The finding that the application of palm residues reduced the P-sorption capacity of the soil and increased the capacity of the soil to desorb P, when compared to soil without added organic residues, is in agreement with that obtained by Iyamuremye *et al.* (1996), where organic residues and P released from the organic residues was found to compete for P-sorption sites, and thus decreased P sorption (Hajra and Debnath, 1985), while increasing P in the soil solution. Furthermore, organic residues added to the soil can release significant amounts of SO_4^{2-}, which is a complexing agent for Al and Fe (Iyamuremye *et al.*, 1996). Carboxyl and hydroxyl functional groups are believed to be involved in the

TABLE 4. AMOUNTS OF P ADSORBED AT A SOIL SOLUTION EQUILIBRIUM P CONCENTRATION OF 0.2 mg litre^{-1} AT TWO AND THREE YEARS AFTER INCORPORATION OF PALM RESIDUES

Time	Treatment	P adsorbed at a soil solution equilibrium P concentration of 0.2 mg litre^{-1} (mg P kg^{-1} soil)	P desorbed
Two years after incorporating palm residues	Pulverized	124c±12	12.2a±0.8
	Shredded	32c±15	10.1b±1.2
	Partially burned	161b±16	8.1c±1.2
	Control	252a±18	7.8c ±1.1
Three years after incorporating palm residues	Pulverized	142c±14	11.3a±1.5
	Shredded	136c±10	9.1b±1.1
	Partially burned	172b ±19	7.2c ±0.8
	Control	261a ±18	6.8c ±0.8

Note: Values followed by the same letter in the same column are not significantly different at the 5% level, as determined by Tukey's Studentized range test.

reaction between metals and organic acids (Huang and Violante, 1986). Among the biochemical compounds that have been identified to form complexes with metals are aliphatic acids, amino acids, phenolic acids, and polymeric phenols (Stevenson, 1994). Stevenson (1994) also reported that the presence of certain organic anions can reduce substantially the amount of P precipitated, and the humus and lignin present have the ability to compete for the same adsorption sites which will decrease P sorption. The results of this study support these hypotheses which can explain why the addition of palm residues increased almost all fractions of P in the soil.

CONCLUSION

Incorporation of palm residues is a wise approach to sustainable P management in P fertilization under oil palm plantations, resulting in improvements in plant P availability and uptake efficiency while preserving productivity. Decreasing P sorption together with increasing P desorption in soil is one important aspect of improving plant P uptake efficiency. Amending the soil with plant residues may supply a greater percentage of residual P to oil palm. Therefore, with the addition of plant residues, the application of P fertilizer can be delayed for the next one or two years.

Fractionation of P in soil amended with palm residues gives an indication of the long-term processes and transformations of these P fractions in soil. Development of methods to assess the turnover of available P, however, is required to make meaningful assessments of soil P cycling and availability. Estimates of plant uptake of P and losses through leaching and erosion are also needed to obtain a better picture of P cycling in the soil amended with plant residues. The nature of relationships between soil P status and P mobility, as a result of addition of palm residues in oil palm ecosystems, warrants continued investigation involving a combination of lysimeter and catchment studies, together with appropriate modeling analysis.

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