

Research Article

Effects of Organic and Inorganic Materials on Soil Acidity and Phosphorus Availability in a Soil Incubation Study

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We tested the effects of two organic materials (OMs) of varying chemical characteristics that is, farmyard manure (FYM) and *Tithonia diversifolia* (tithonia), when applied alone or in combination with three inorganic P sources, that is, triple superphosphate (TSP), Minjingu phosphate rock (MPR), and Busumbu phosphate rock (BPR) on soil pH, exchangeable acidity, exchangeable Al, and P availability in an incubation study. FYM and tithonia increased the soil pH and reduced the exchangeable acidity and Al in the short term, but the inorganic P sources did not significantly affect these parameters. The effectiveness of the inorganic P sources in increasing P availability followed the order, TSP > MPR > BPR, while among the OMs, FYM was more effective than tithonia. There was no evidence of synergism in terms of increased available P when organic and inorganic P sources were combined. The combination of OMs with inorganic P fertilizers may, however, have other benefits associated with integrated soil fertility management.

1. Introduction

Soil acidity and phosphorus deficiencies limit crop production in many tropical soils [1]. Lime and inorganic phosphate fertilizers are used in developed countries to remedy these problems. However, due to increasing costs and unavailability when needed, their use among smallholder farmers in developing countries is not widespread. This coupled with concerns for environmental protection and sustainability has renewed interest in the use of alternative cheaper locally available materials. The use of phosphate rocks (PR) and organic materials has in particular received increased attention in recent years in eastern Africa [2–4]. In addition to provision of P, PRs have Ca and Mg which makes them assume a significant role as a potential tool for sustaining soil productivity by reducing soil acidity through its liming effect [5]. Although most OMs are low in P, they can influence soil parameters such as soil pH, exchangeable Al, and Ca, which greatly influence crop growth [3].

There are a number of PR deposits of variable reactivity in eastern Africa which, however, differ greatly in their

suitability as sources of P in P-deficient soils [6]. The most promising of these PRs are Minjingu in northern Tanzania and Busumbu in eastern Uganda [7], but their low solubility makes them unsuitable for direct application [1]. Techniques aiming to increase the solubility of BPR through blending with soluble phosphate fertilizers such as TSP or partial acidulation are likely not to have positive effects in terms of increasing P availability and uptake by plants [1, 8]. Enhancing the solubility of PRs by combining them with OMs has been tried in western Kenya, but there is no consensus as to whether or not these combinations enhance P availability [9]. Interactions of OMs with inorganic P nutrient inputs and their effect on P availability and soil acidity therefore merit further study. The objective of this study was to investigate the effect of inorganic phosphorus sources (TSP, MPR, and BPR) when applied alone or in combination with OMs (tithonia or FYM) on soil pH, exchangeable acidity, exchangeable Al, and P availability acid P-deficient soils.

1.1. Materials and Methods. The study was conducted from April to July 2008 at Moi University, using soils collected at

TABLE 1: Initial surface (0–15 cm) soil properties.

Parameter	Bukura	Kakamega
pH (H ₂ O) (1 : 2.5)	4.80	5.10
Exchangeable acidity (cmol _c kg ⁻¹)	0.88	0.35
Exchangeable Al (cmol _c kg ⁻¹)	0.63	0.13
Ca	1.94	2.1
Mg	1.01	1.8
K	0.12	0.2
ECEC	3.95	4.85
Al saturation (%)	22	7.2
Organic C (%)	3.2	2.7
Total N (%)	0.3	0.3
C : N ratio	10.6	9.0
Total P (%)	0.04	0.03
Olsen P (mg kg ⁻¹)	5.6	2.5
P sorbed at (0.2 mg kg ⁻¹)	260	45
Texture (%)		
Sand	52	54
Silt	18	28
Clay	30	18
Soil classification (FAO System)	Orthic ferralsol	Ferralic cambisols

two sites in western Kenya which were selected on the basis of contrasting characteristics (Table 1).

Surface soil (0–15 cm) samples were randomly taken from each site and thoroughly mixed by hand to produce one homogenous sample per site. Two hundred gram samples of air-dried soil (<2 mm) from each site were weighed into plastic polythene bags which were kept in upright positions in a laboratory. Finely ground (<1 mm) tithonia, FYM (obtained from cattle), BPR, MPR, or TSP were added to the soils according to the treatments given in Table 2 and thoroughly mixed. The treatments were arranged in a completely randomized design with three replications. The procedure used by [10] was used with slight modifications. This involved incubation of the samples for 16 weeks at room temperature. Moisture content in the soil samples was adjusted to field capacity and maintained at that level during the entire period of incubation. Soils were sampled twice from each treatment, that is, at 4 and 16 weeks after the start of the incubation (WAI), air-dried, and sieved before being analyzed.

1.2. Analyses of Soils and the Organic Materials. The soils and the OMs were analyzed using the following methods; organic C was determined by Walkley and Black sulphuric acid-dichromate digestion followed by back titration with ferrous ammonium sulphate [11]. Total N and P in the soils were determined by digesting 0.3 g of the soil sample in a mixture of Se, LiSO₄, H₂O₂, and concentrated H₂SO₄ [12]. The N and P contents in the digests were determined

colorimetrically. Total soluble polyphenols in tithonia and FYM were determined by the Folin-Ciocalteu method [11], while the lignin content was determined using the acid detergent fiber (ADF) method as described by [11]. Soil pH was determined using a glass electrode pH meter at 1 : 2.5 soil : water ratio [13]. The basic cations (Ca, Mg, and K) were extracted using ammonium acetate at pH 7 [13]. Exchangeable Ca and Mg in the extract were determined using atomic absorption spectrophotometry, and exchangeable K by flame photometry. Exchangeable acidity and exchangeable Al were extracted using unbuffered 1 M KCl [11].

2. Results

2.1. Characteristics of the Organic Materials Used in the Study. Tithonia contained higher amounts of C, N, Ca, Mg, and K than FYM, but its total P content and pH were lower (Table 3). The C : N ratios of tithonia and FYM were 13.5 and 20, respectively, and a net mineralization of N would therefore be expected to occur from both OMs [14]. The C : P ratios were 140 for tithonia and 90 for FYM. Tithonia had low (<15%) while FYM had high (>15%) lignin content. Both OMs had low polyphenol content (<4%). According to the criteria proposed by [14], tithonia would be a high-quality OM, while FYM would be a medium-quality OM.

2.2. Effect of Organic and Inorganic Amendments on Soil pH. Results for soil pH as affected by the treatments for the Bukura and Kakamega soils are presented in Tables 4 and 5, respectively. Averaged across all treatments, the soil pH at Bukura at 4 WAI (4.91) and 16 WAI (4.27) was lower than at Kakamega at similar times (5.31 and 4.65, resp.). The pH of the soils at 4 WAI was lowest for the control treatment and highest for tithonia applied in combination with MPR for both soil types. All the tithonia treatments (applied alone or in combination with the inorganic inputs), apart from Tithonia (20 kg P ha⁻¹), showed a significant increase in pH above the control treatment at 4 WAI for the Bukura soil. All the other treatments had no significant effect on soil pH at this time for this soil. At Kakamega, all the tithonia treatments with the exception of Tithonia (20 kg P ha⁻¹) + TSP (40 kg P ha⁻¹) and Tithonia (20 kg P ha⁻¹) significantly increased the soil pH above that of the control. FYM when applied alone or in combination with the inorganic P sources generally increased soil pH of both soil types, although statistical significance was not always attained. There was no significant treatment effect on soil pH at 16 WAI for soils from both sites.

Averaged across the three inorganic P sources, the soil pH followed the trend Tithonia > FYM > no OM at both sites. Averaged across the OMs, MPR gave a significantly higher soil pH than TSP and BPR at both sites at 4 WAI. There was a decline in soil pH in all the treatments at 16 WAI compared to 4 WAI for both soil types. Averaged across all the treatments, the pH of the Bukura and Kakamega soils declined by 0.67 and 0.64 units, respectively. In general, the acidification over time was more pronounced with the tithonia treatments at both sites.

TABLE 2: The experimental treatments.

Treatment	P source	P rate (kg ha ⁻¹)		Total P
		From organics	From inorganics	
(1) Control	—	0	0	0
(2) Tithonia (60 kg P ha ⁻¹)	Tithonia	60	0	60
(3) FYM (60 kg P ha ⁻¹)	FYM	60	0	60
(4) MPR (60 kg P ha ⁻¹)	MPR	0	60	60
(5) TSP (60 kg P ha ⁻¹)	TSP	0	60	60
(6) BPR (60 kg P ha ⁻¹)	BPR	0	60	60
(7) Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	Tithonia and MPR	20	40	60
(8) Tithonia (20 kg P ha ⁻¹) + (TSP 40 kg P ha ⁻¹)	Tithonia and TSP	20	40	60
(9) Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	Tithonia and BPR	20	40	60
(10) FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	FYM and MPR	20	40	60
(11) FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	FYM and TSP	20	40	60
(12) FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	FYM and BPR	20	40	60
(13) Tithonia (20 kg P ha ⁻¹)	Tithonia	20	0	20
(14) FYM (20 kg P ha ⁻¹)	FYM	20	0	20
(15) MPR (40 kg P ha ⁻¹)	MPR	0	40	40
(16) TSP (40 kg P ha ⁻¹)	TSP	0	40	40
(17) BPR (40 kg P ha ⁻¹)	BPR	0	40	40

FYM: farmyard manure; TSP: triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock.

TABLE 3: Average chemical composition of tithonia and farmyard manure used in the study over the three seasons.

	m.c.	% C	% N	C:N ratio	% P	% Ca	% Mg	% K	pH	% Lig	% Poly
Tithonia	80%	42	3.1	13.5	0.30	2.0	0.6	4.1	6.5	13	3.17
FYM	30%	36	1.8	20.0	0.40	0.9	0.5	2.2	7.7	21	0.84

FYM: farmyard manure; lig.: lignin; poly.: polyphenol; m.c.: moisture content.

TABLE 4: Effect of organic and inorganic materials on soil pH, exchangeable acidity and exchangeable Al for the Bukura soils in the incubation study.

Treatment	pH			Exchangeable acidity (cmol kg ⁻¹)			Exchangeable Al (cmol kg ⁻¹)		
	4 WAI	16 WAI	Δ pH	4 WAI	16 WAI	Δ ex. acidity	4 WAI	16 WAI	Δ ex. Al
(1) Control	4.63	4.24	-0.39	0.89	0.87	-0.02	0.63	0.62	-0.01
(2) Tithonia (60 kg P ha ⁻¹)	5.43	4.28	-1.15	0.31	0.48	0.17	0.16	0.17	0.01
(3) FYM (60 kg P ha ⁻¹)	4.78	4.26	-0.52	0.66	0.77	0.11	0.42	0.49	0.07
(4) MPR (60 kg P ha ⁻¹)	4.84	4.31	-0.53	0.68	0.81	0.13	0.45	0.61	0.16
(5) TSP (60 kg P ha ⁻¹)	4.68	4.25	-0.43	0.79	0.84	0.05	0.67	0.59	-0.08
(6) BPR (60 kg P ha ⁻¹)	4.76	4.28	-0.48	0.91	0.83	-0.08	0.54	0.61	0.07
(7) Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	5.67	4.38	-1.29	0.52	0.61	0.09	0.21	0.37	0.16
(8) Tithonia (20 kg P ha ⁻¹) + (TSP 40 kg P ha ⁻¹)	5.39	4.44	-0.96	0.53	0.65	0.12	0.25	0.47	0.22
(9) Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	5.25	4.28	-0.97	0.41	0.65	0.24	0.21	0.53	0.32
(10) FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	4.84	4.25	-0.59	0.61	0.79	0.18	0.41	0.60	0.19
(11) FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	4.81	4.18	-0.63	0.77	0.79	0.02	0.47	0.65	0.18
(12) FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	4.72	4.28	-0.44	0.77	0.83	0.06	0.55	0.65	0.10
(13) Tithonia (20 kg P ha ⁻¹)	4.75	4.23	-0.52	0.66	0.82	0.16	0.32	0.55	0.23
(14) FYM (20 kg P ha ⁻¹)	4.76	4.29	-0.47	0.71	0.83	0.12	0.48	0.65	0.17
(15) MPR (40 kg P ha ⁻¹)	4.82	4.35	-0.47	0.73	0.81	0.08	0.47	0.60	0.13
(16) TSP (40 kg P ha ⁻¹)	4.73	4.18	-0.55	0.83	0.90	0.07	0.57	0.71	0.14
(17) BPR (40 kg P ha ⁻¹)	4.70	4.17	-0.53	0.84	0.95	0.11	0.58	0.68	0.10
SED	0.14	N.S.		0.11	0.07		0.10	0.07	
CV %	3.50			18.9	11.5		27.5	11.50	

WAI: weeks after incubation; FYM: farmyard manure; TSP: triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock; N.S.: not significant; SED: standard error of difference between means; Ex: exchangeable.

TABLE 5: Effect of organic and inorganic materials on soil pH, exchangeable acidity, and exchangeable Al for the Kakamega soils in the incubation study.

Treatment	pH			Exchangeable acidity (cmol kg ⁻¹)			Exchangeable Al (cmol kg ⁻¹)		
	4 WAI	16 WAI	Δ pH	4 WAI	16 WAI	Δ ex. acidity	4 WAI	16 WAI	Δ ex. Al
(1) Control	5.16	4.67	-0.49	0.24	0.28	0.04	0.08	0.09	0.01
(2) Tithonia (60 kg P ha ⁻¹)	5.41	4.35	-1.06	0.21	0.23	0.02	0.01	0.00	-0.01
(3) FYM (60 kg P ha ⁻¹)	5.36	4.71	-0.65	0.21	0.24	0.03	0.01	0.00	-0.01
(4) MPR (60 kg P ha ⁻¹)	5.34	4.75	-0.59	0.24	0.27	0.03	0.03	0.00	-0.03
(5) TSP (60 kg P ha ⁻¹)	5.20	4.73	-0.47	0.25	0.26	0.01	0.06	0.06	0.00
(6) BPR (60 kg P ha ⁻¹)	5.20	4.73	-0.47	0.32	0.29	-0.03	0.10	0.08	-0.02
(7) Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	5.77	4.75	-1.02	0.21	0.21	0.00	0.03	0.00	-0.03
(8) Tithonia (20 kg P ha ⁻¹) + (TSP 40 kg P ha ⁻¹)	5.32	4.61	-0.71	0.25	0.25	0.00	0.04	0.00	-0.04
(9) Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	5.39	4.38	-1.01	0.24	0.31	0.07	0.05	0.00	-0.05
(10) FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	5.36	4.82	-0.54	0.23	0.25	0.02	0.03	0.00	-0.03
(11) FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	5.33	4.74	-0.59	0.24	0.27	0.03	0.02	0.03	0.01
(12) FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	5.36	4.61	-0.75	0.24	0.28	0.04	0.02	0.04	0.02
(13) Tithonia (20 kg P ha ⁻¹)	5.28	4.33	-0.95	0.23	0.24	0.01	0.07	0.00	-0.07
(14) FYM (20 kg P ha ⁻¹)	5.21	4.68	-0.53	0.24	0.26	0.02	0.02	0.00	-0.02
(15) MPR (40 kg P ha ⁻¹)	5.33	4.78	-0.55	0.23	0.27	0.04	0.04	0.00	-0.04
(16) TSP (40 kg P ha ⁻¹)	5.20	4.70	-0.50	0.25	0.29	0.04	0.07	0.00	-0.07
(17) BPR (40 kg P ha ⁻¹)	5.21	4.68	-0.53	0.28	0.31	0.03	0.08	0.08	0.00
SED	0.10	N.S.		N.S.	0.014		N.S.	0.018	
CV %	2.0			5.6			40.00		

WAI: weeks after incubation; FYM: farmyard manure; TSP: triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock; N.S.: not significant; SED: standard error of difference between means; Ex: exchangeable.

2.3. Exchangeable Acidity and Exchangeable Aluminum. At 4 WAI, tithonia when applied alone or in combination with the inorganic P sources significantly reduced the exchangeable acidity with respect to the control for the Bukura soil (Table 4). The largest reduction (65%) at this sampling time was obtained with tithonia applied at a rate of 60 kg P ha⁻¹. FYM also significantly reduced exchangeable acidity at 4 WAI, but only when it was applied at rate of 60 kg P ha⁻¹ (26%) or in combination with MPR (31%). There was generally an increase in exchangeable acidity in the soils sampled at 16 WAI compared to those at 4 WAI. At this time (16 WAI), all the tithonia treatments, other than tithonia (20 kg P ha⁻¹), gave significant reduction in the exchangeable acidity with respect to the control at Bukura. The inorganic P sources did not significantly reduce the exchangeable acidity at both sampling times at Bukura although the MPR treatments had generally lower levels of exchangeable acidity than TSP or BPR.

There were no significant treatment effects on exchangeable acidity for the Kakamega soil at 4 WAI (Table 5). However, at 16 WAI, all the treatments with tithonia applied alone or in combination with inorganic P sources, except tithonia (20 kg P ha⁻¹) + BPR (40 kg P ha⁻¹), significantly reduced the exchangeable acidity at this site. FYM, when applied alone at 60 kg P ha⁻¹ or in combination with MPR, also significantly reduced exchangeable acidity but not when applied at 20 kg P ha⁻¹ or in combination with TSP or BPR. The inorganic P sources had no significant effect on

exchangeable acidity when applied alone at 16 WAI at Kakamega (Table 5).

The exchangeable Al trends among the treatments were generally similar to those of exchangeable acidity for the Bukura soil, at both sampling times (Table 4). The Kakamega soil showed wide variations especially in the samples taken at 16 WAI in which exchangeable Al could not be detected in several treatments. When averaged across the three inorganic P sources, tithonia gave significantly lower exchangeable acidity and exchangeable Al levels compared to FYM and no OM. The effect of inorganic P sources on exchangeable acidity and exchangeable Al was not significant at Bukura, but at Kakamega, MPR had significantly lower amounts of exchangeable acidity than TSP and BPR at 16 WAI. Although FYM gave lower exchangeable acidity and exchangeable Al levels than when no OM was applied at both sampling times at Bukura, these differences were not statistically significant.

There was a strong significant negative correlation between the soil pH with both the exchangeable acidity ($r^2 = 0.74$; $P < 0.001$) and exchangeable aluminum ($r^2 = 0.73$; $P < 0.001$) at 4 WAI at Bukura. At 16 WAI, there was also a significant but weak correlation between the soil pH and exchangeable acidity ($r^2 = 0.34$; $P < 0.05$), but the correlation between soil pH and exchangeable Al was not significant at this time for the Bukura soil. At Kakamega, there was no significant correlation between the soil pH and exchangeable acidity or exchangeable Al at both sampling times.

TABLE 6: Effect of organic and inorganic P amendments on Olsen P (mg P kg⁻¹) at Bukura and Kakamega in the laboratory incubation study.

Treatment	Bukura			Kakamega		
	4 WAI	16 WAI	Δ Olsen P	4 WAI	16 WAI	Δ Olsen P
(1) Control	7.3	8.9	1.6	3.2	4.3	1.1
(2) Tithonia (60 kg P ha ⁻¹)	13.1	14.7	1.6	8.2	9.6	1.4
(3) FYM (60 kg P ha ⁻¹)	16.0	16.5	0.5	9.5	10.0	0.5
(4) MPR (60 kg P ha ⁻¹)	13.4	16.3	2.9	6.9	8.0	1.1
(5) TSP (60 kg P ha ⁻¹)	18.2	17.7	-0.5	9.8	10.1	0.3
(6) BPR (60 kg P ha ⁻¹)	11.0	11.5	0.5	4.5	6.0	1.5
(7) Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	14.1	13.9	-0.2	7.9	6.3	-1.6
(8) Tithonia (20 kg P ha ⁻¹) + (TSP 40 kg P ha ⁻¹)	17.4	15.8	-1.6	8.9	8.6	-0.3
(9) Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	12.4	12.6	0.2	4.4	5.1	0.7
(10) FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	15.0	15.7	0.7	7.4	9.3	1.9
(11) FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	14.5	17.7	3.2	8.0	6.0	-2.0
(12) FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	13.1	16.1	3.0	5.9	5.8	-0.1
(13) Tithonia (20 kg P ha ⁻¹)	11.2	13.9	2.7	4.6	7.3	2.7
(14) FYM (20 kg P ha ⁻¹)	12.7	15.6	2.9	5.7	7.5	1.8
(15) MPR (40 kg P ha ⁻¹)	12.5	14.9	2.4	6.3	6.6	0.3
(16) TSP (40 kg P ha ⁻¹)	14.2	16.6	2.4	6.7	7.3	0.6
(17) BPR (40 kg P ha ⁻¹)	9.8	9.6	-0.2	4.4	5.6	1.2
SED	0.9	1.3		0.7	0.7	
CV %	9	11		10	10	

WAI: weeks after incubation; FYM: farmyard manure; TSP: triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock; SED: standard error of difference between means.

2.4. Effect of Phosphorus Sources on the Olsen Phosphorus in Soils. All the applied inputs generally increased the Olsen P levels compared with the control for both soil types at 4 WAI (Table 6). The highest Olsen P values for both soil types, at both sampling periods, were obtained with TSP (60 kg P ha⁻¹). When applied alone at the same P rate of 60 kg P ha⁻¹, there were no significant differences in Olsen P between FYM and TSP, but the two P sources had significantly higher Olsen P levels than tithonia, MPR, and BPR for the Bukura soil at 4 WAI. A similar trend was also observed for the Kakamega soil. FYM gave slightly higher but non significant Olsen P levels compared to tithonia at a similar P application rate applied at 20 kg P ha⁻¹. In general, at the same P rate, the effectiveness in increasing the available P among the inorganic sources followed the order, TSP > MPR > BPR, while among the OMs, FYM was more effective than tithonia.

The combined application of the OMs, that is, tithonia or FYM, with TSP or the PRs did not result in synergy, whereby the available P increased more than the sum of the increase from either of the P sources applied singly. This is illustrated in Figures 1, 2, 3, 4, 5 and 6 for the Bukura soil. In general, the expected increase in the available P due to the additive effects of applying the inorganic and organic P sources separately was always greater than the actual increase obtained by combining the inorganic and organic P sources, at the same total P application rate (Figures 1–6). Combined application of organic and inorganic P sources generally resulted in observed increases in Olsen P intermediate to those of sole applications of the organic or inorganic P sources (Figures 1–6).

3. Discussion

The application of both FYM and tithonia generally increased the soil pH at 4 WAI with tithonia-treated soils having a higher pH than the FYM-treated soils at this time. The soil pH, however, declined by 16 WAI with tithonia-treated soils showing the highest pH reductions. The increase in soil pH due to application of OMs at 4 WAI in this study is consistent with results reported by several other workers (e.g., [15, 16]). The principal mechanisms involved in increasing soil pH by various types of OMs differ considerably and according to [17], and a broad distinction can be made between the mechanisms of undecomposed plant materials such as tithonia and humified materials such as FYM and composts. The initial increase in the soil pH by FYM in the present study can primarily be attributed to the high pH of FYM (7.7) at the time of its application. It may also partly be explained by proton (H⁺) exchange between the soil and the added manure [18, 19]. During the initial decomposition of manures, prior to their collection, some formation of phenolic, humic-like material may have occurred [16]. It is these organic anions that consume protons from the soil, thus tending to raise the equilibrium pH [20]. Another mechanism that has been proposed to explain the increase in soil pH by such materials as FYM is the specific adsorption of humic material and/or organic acids (the products of decomposition of OMs) onto hydrous surfaces of Al and Fe oxides by ligand exchange with corresponding release of OH⁻ as suggested by [21]. On the other hand, [15] attributed the soil pH changes observed with fresh materials, for example, tithonia, in an incubation study, mainly to

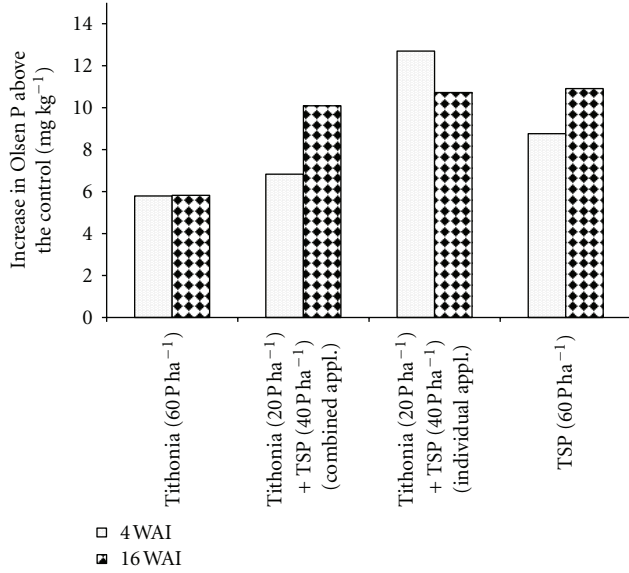


FIGURE 1: Increase in Olsen P above the control treatment as affected by tithonia and TSP at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when tithonia (at 20 kg P ha⁻¹) was applied in combination with TSP (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when tithonia, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when TSP was applied alone at 40 kg P ha⁻¹.

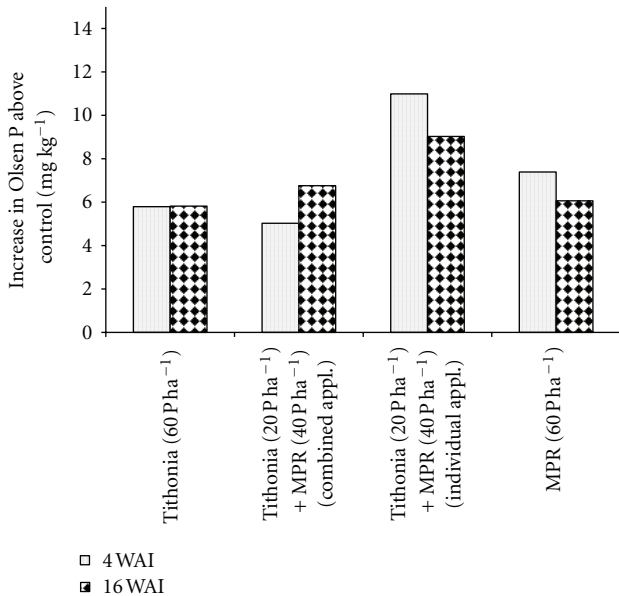


FIGURE 2: Increase in Olsen P above the control treatment as affected by tithonia and MPR at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when tithonia (at 20 kg P ha⁻¹) was applied in combination with MPR (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when tithonia, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when MPR was applied alone at 40 kg P ha⁻¹.

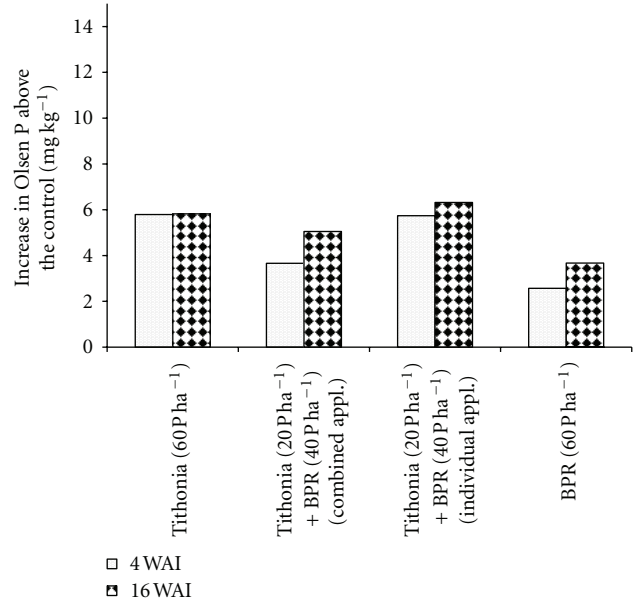


FIGURE 3: Increase in Olsen P above the control treatment as affected by tithonia and BPR at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when tithonia (at 20 kg P ha⁻¹) was applied in combination with BPR (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when tithonia, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when BPR was applied alone at 40 kg P ha⁻¹.

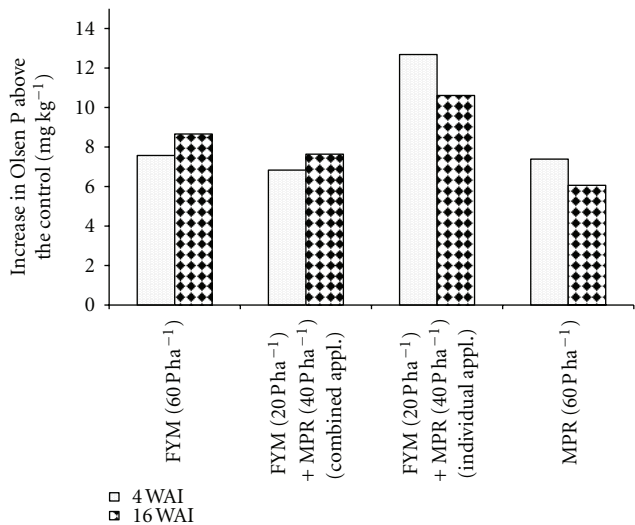


FIGURE 4: Increase in Olsen P above the control treatment as affected by FYM and MPR at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when FYM (at 20 kg P ha⁻¹) was applied in combination with MPR (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when FYM, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when MPR was applied alone at 40 kg P ha⁻¹.

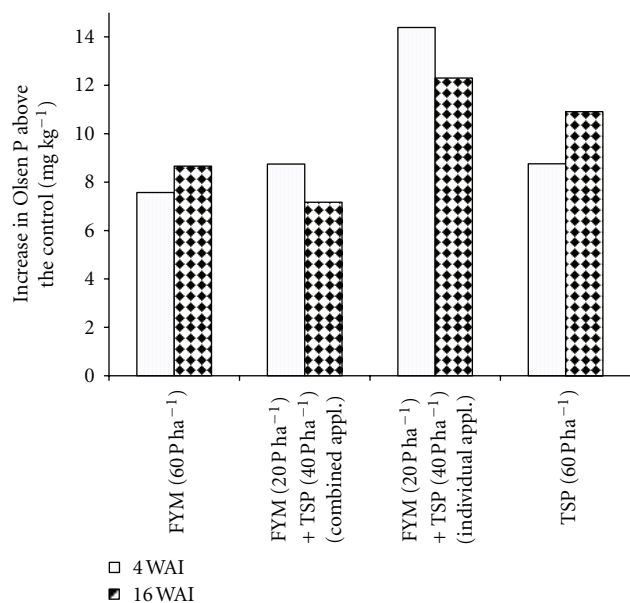


FIGURE 5: Increase in Olsen P above the control treatment as affected by FYM and TSP at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when FYM (at 20 kg P ha⁻¹) was applied in combination with TSP (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when FYM, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when TSP was applied alone at 40 kg P ha⁻¹.

nitrogen transformations and release of metal cations as tithonia decomposed. In this incubation study, soils were amended with the OMs in a closed system without growing plants. Therefore, the effects of plant uptake, root exudates, and leaching are not relevant and the processes responsible for the pH changes are limited to the decomposition and nutrients held in tithonia and N transformations [15]. Under anaerobic conditions, NH₄⁺ produced by the ammonification process would accumulate due to inhibition of nitrification, and the pH would increase. However, under conditions favorable for microbial activity, such as those in the present study, the initial alkalization from plant residue amendment may be neutralized by subsequent nitrification, which is an acidifying process [22]. This is likely why there was a decline in soil pH in all the treatments by 16 WAI. The higher acidification observed for the tithonia-treated soils at 16 WAI in the incubation study is ascribed to its high nitrifiable N content (3.3%) compared to the other treatments. Similar variations in soil pH with time, when different OMs were mixed with soil, were observed by [23]. The failure of the PRs to increase the pH is attributed to their low reactivity and low rates used.

3.1. Exchangeable Acidity and Exchangeable Aluminum. Addition of tithonia, FYM, and MPR had the effect of reducing both the exchangeable acidity and exchangeable Al, but the magnitude of the reduction varied with each of these materials. Tithonia appeared to be more effective in reducing

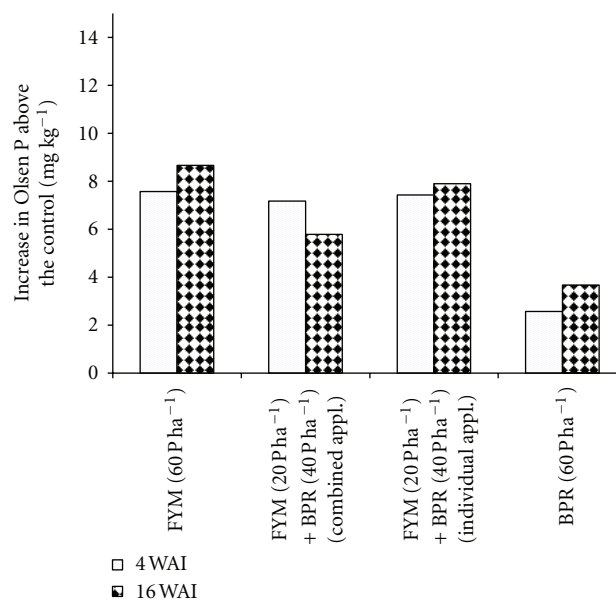


FIGURE 6: Increase in Olsen P above the control treatment as affected by FYM and BPR at Bukura. Note: “combined appl.” refers to the observed increase in Olsen P above the control obtained when FYM (at 20 kg P ha⁻¹) was applied in combination with BPR (at 40 kg P ha⁻¹), while “individual appl.” refers to the increase in Olsen P above the control obtained when FYM, applied alone at 20 kg P ha⁻¹, was added to the increase in Olsen P above the control obtained when BPR was applied alone at 40 kg P ha⁻¹.

exchangeable Al, but not exchangeable acidity, compared to FYM. The reduction in exchangeable acidity can partially be attributed to an initial increase in soil pH that was observed with the OMs. Several other workers have measured an increase in soil pH with concomitant decrease in exchangeable Al during decomposition of organic residues in soils [16, 18, 24]. An increase in soil pH results in precipitation of exchangeable and soluble Al as insoluble Al hydroxides [25], thus reducing concentration of Al in soil solution. However, there are other mechanisms involved in the reactions of Al with OMs which are intricate and according to [25] probably involve complex formation with low-molecular-weight organic acids, such as citric, oxalic, and malic acids, and humic material produced during the decomposition of the OMs and adsorption of Al onto the decomposing organic residues. Complexation by soluble organic matter may partially explain why the tithonia treatments were able to significantly reduce exchangeable acidity and Al relative to the control treatment, despite the fact that they had at times low pH that was comparable to that of TSP or BPR. Both TSP and BPR, however, failed to significantly reduce exchangeable Al, likely due to their low content of CaO (19% and 35% CaO for TSP and BPR, resp.).

The Al complexing effect of tithonia is likely to have been stronger than that of FYM given that FYM gave higher soil pH (5.17) than tithonia but still ended up with a higher level of exchangeable Al (0.35 cmol kg⁻¹). Tithonia was applied as a green manure and was thus likely to produce large

quantities of organic acids, which would be involved in complexation reactions [3]. On the other hand, FYM had been exposed to the weather elements for a long time (one year) before its collection for use in this study. It was well rotten and hence likely to be at an advanced stage of decomposition and is therefore unlikely to have had substantial amounts of organic acids [3].

3.2. Soil Olsen P Changes as Affected by Application of Organic and Inorganic Inputs. Addition of P from both organic and inorganic sources generally resulted in increase in the Olsen P relative to the control. The magnitude of the increase in the Olsen P depended on the soil type, time of soil sampling, P source, and rate of P application. On average, addition of P inputs generally resulted in larger increases in Olsen P for the Bukura soil than the Kakamega one. Similar site-specific differences in extractable soil P, in response to applied P fertilizers, were found by [26]. The increase in the Olsen P with time of incubation contrasts with most studies which have reported a decline in the Olsen P with time, usually ascribed to P sorption by the soil (e.g., [27, 28]). However, a few studies [29, 30] have obtained results similar to those of the present study. These authors explained that the increase in P availability with time is likely due to microbially mediated mineralization of soil organic P, to form inorganic P at a faster rate than that of P sorption by the soils of low to moderate P sorption capacity, such as those used in the current study. Also, due to the absence of plants in such incubation studies, the mineralized P is not taken up by plants and hence the observed increase in available P with time.

TSP gave the highest amount of Olsen P compared to the PRs, tithonia, or FYM, applied at the same total P rate at all times. This is ascribed to the higher solubility of TSP compared to the PRs whose dissolution is usually low and slow [31]. The OMs generally gave higher Olsen P values than the PRs at comparable total P rates. This reflects the large percentage of soluble P in both the tithonia tissues and the FYM. High levels of water soluble P in plant tissues (50–80%) have also been reported by [32]. Immediate net P mineralization would in addition be expected to occur because both OMs had a higher P concentration (0.3% in tithonia and 0.4% in FYM) than the critical level of 0.25% required for net P mineralization [32].

The significant increase in Olsen P above the control by MPR indicates that the soil conditions at both sites were conducive to its dissolution. Some of the factors known to increase the dissolution and subsequent release of P in PRs include low soil pH, low exchangeable Ca, and low P [33]. The soils at both sites generally met these criteria. The higher amounts of Olsen P as a result of MPR application compared to BPR application can be attributed to differences in their solubility arising from varying extents of carbonate substitution in the PR [34]. Results of chemical analyses indicate that the BPR is a low-carbonate-substituted type of igneous origin. It has low reactivity in acid solvents with a neutral ammonium acetate (NAC) solubility of 2.3% compared to 5.6% of MPR [35].

The interaction between the OMs and inorganic P sources was significant only on a few occasions. In such instances, it was observed that combining the PRs with tithonia or FYM gave higher Olsen P values than when the PRs were combined with urea. However, when the TSP was combined with tithonia or FYM, it gave lower amounts of Olsen P than when it was combined with urea. This may suggest that tithonia and FYM were enhancing the dissolution of PRs, but retarding the availability of P from TSP. However, closer examination of the data reveals that tithonia and FYM were unlikely to have enhanced the dissolution of the PRs and that combining these two OMs with the PRs has no advantage in terms of increasing the Olsen P compared to their application with urea. There was therefore no synergistic effect in terms of increased Olsen P, when PRs were applied in combination with organic materials. In general, the combined application of organic and inorganic P sources generally resulted in observed increases in Olsen P intermediate to those of sole applications of the organic or inorganic P sources.

The likely reason why the PRs when combined with tithonia and FYM gave higher Olsen P levels compared to their combination with urea is because both tithonia and FYM were generally more effective in increasing the Olsen P compared to the PRs, and therefore, a portion of the insoluble PRs (20 kg P ha^{-1}) was substituted for by the more available tithonia or FYM in the combinations. However, when combined with urea all the 60 kg P ha^{-1} was from the low soluble PRs and thus the lower Olsen P levels. On the other hand, TSP when combined with urea, gave higher Olsen P levels compared to its combination with tithonia or FYM. In this case, TSP was more effective in increasing the Olsen P compared to tithonia and FYM whose P is mostly in organic forms initially, and hence, substituting a portion of it (20 kg P ha^{-1}) in the combination with tithonia or FYM yielded less Olsen P than when it (TSP) was applied at the full rate of 60 kg P ha^{-1} with urea.

The findings of the present study are in contrast to others (e.g., [2, 4, 36]) who reported synergism when OMs such as manures were combined with PRs. These authors combined PRs with OMs of diverse composition and concluded that due to acidifying effect organic acids produced during the decomposition of the OMs, the solubilization of PRs was enhanced thus leading to the higher extractable P values in treatments where PR was combined with OMs than from application of PR alone. The most probable reason, however, why the combined application of PR and OM gave higher extractable P values compared to sole application of PR in these studies was because the contribution of P by the OM in the OM/PR combination was not considered, thus leading to a higher total P rate in the OM/PR combination than the sole PR application, and hence the higher amounts of available P in the combination. The results reported herein are, however, in agreement with other recent works where total P among the treatments to be compared was the same [1, 3]. The common conclusion in these studies was that combination of PR with OMs does not enhance the dissolution of the PR mainly because OMs can increase the soil pH and Ca levels which are negatively correlated with PR dissolution. If the cost was not a limiting factor, then replenishing soil P

using TSP would be a more appropriate strategy, as it results in more available P than when it is applied in combination with tithonia or FYM (at the same total P rate). Likewise, if availability and cost were not a constraint, then it would be better to apply tithonia or FYM alone at 60 kg P ha⁻¹ than combining them with MPR or BPR because the combination results in a lesser amount of available soil P than if the OMs are applied alone.

4. Conclusion

Tithonia and farmyard manure were more effective in increasing the soil pH and reducing exchangeable acidity and Al than the inorganic P sources (MPR, BPR, and TSP) in the early stages of incubation suggesting that these OMs can substitute for lime. Addition of P from both organic and inorganic sources generally resulted in an increase in the Olsen P, relative to the control, whose magnitude depended on the soil type, time of soil sampling, P source, and rate of P application. The effectiveness of the inorganic P sources in increasing P availability followed the order, TSP > MPR > BPR, while among the OMs, FYM was more effective than tithonia. There was no synergistic effect, in terms of increased Olsen P, when inorganic P sources were applied in combination with OMs. In general, the combined application of organic and inorganic P sources resulted in observed increases in Olsen P intermediate to those of sole applications of the organic or inorganic P sources. The combination of OMs with inorganic P fertilizers may, however, have other benefits associated with integrated soil fertility management.

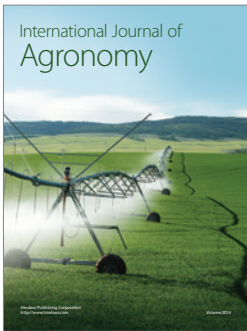
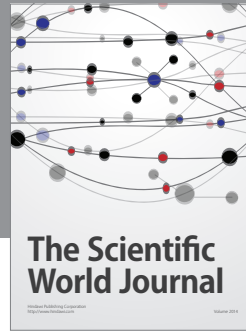
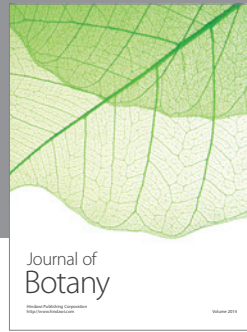
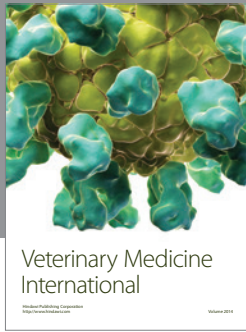
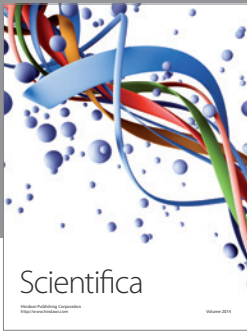
Acknowledgments

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