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Research article

Phosphorus availability and exchangeable aluminum response to phosphate rock and organic inputs in the Central Highlands of Kenya

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ABSTRACT

Soil acidity and phosphorus deficiency are some of the constraints hampering agricultural production in tropical regions. The prevalence of soil acidity is associated with phosphorus (P) insufficiency and aluminum saturation. We conducted a two-seasons experiment to evaluate soil phosphorus availability and exchangeable aluminum in response to phosphate rock and organic inputs in acidic *humic nitisols*. The field experiment was installed in Tharaka Nithi County in the Central Highlands of Kenya. The experimental design was a randomized complete block design with treatments replicated thrice. The treatments were: Green manure (*Tithonia diversifolia* Hemsl.) (60 kg P ha^{-1}), phosphate rock (60 kg P ha^{-1}), goat manure (60 kg P ha^{-1}), *Tithonia diversifolia* (20 kg P ha^{-1}) combined with phosphate rock (40 kg P ha^{-1}), manure (20 kg P ha^{-1}) combined with phosphate rock (40 kg P ha^{-1}), Triple Super Phosphate combined with Calcium Ammonium Nitrate (TSP + CAN) (60 kg P ha^{-1}) and a control (no input). During the long rains of the 2018 season (LR2018), *Tithonia diversifolia* + phosphate rock had a significantly higher reduction (67%) of exchangeable aluminum than the sole use of *Tithonia diversifolia.* Grain yield under TSP + CAN was the highest, followed by the sole organics during the LR2018. *Tithonia diversifolia* + phosphate rock resulted in a 99% and a 90% increase in $NaHCO_3$-Pi compared to sole phosphate rock and sole *Tithonia diversifolia,* respectively. *Tithonia diversifolia* led to 14% and 62% higher resin-Pi and NaOH-Pi, respectively, compared to manure in the short rains of 2017 (SR2017). The increase in NaOH-Po after the two seasons was statistically significant in sole TSP + CAN. Based on the observed reduced exchangeable aluminum and additional nutrients like Ca, Mg, and K in the soil, sole organic inputs or in combination with phosphate rock treatments are feasible alternatives for sustaining soil phosphorus. Our findings underscore an integrated approach utilizing organic amendments combined with phosphate rock in acidic humic nitisols' phosphorus nutrient management.

1. Introduction

Declining soil fertility is one of the major problems faced by smallholder farmers in Sub-Saharan Africa. Besides low levels of inorganic and organic fertilizer use and continuous cultivation (Bationo et al., 2012; Babu et al., 2014), soil acidity and high aluminum concentration can cause soil nutrient imbalance, leading to limited nutrient availability, especially P (Mariano and Keltjens, 2007). Soil P deficiency is common in developing countries. The scenario is worsened under P-fixing acidic soils with high aluminum and iron concentrations (Jaetzold et al., 2007; Muindi et al., 2015). This is due to the high phosphate sorption capacities of acidic soils leading to detrimental effects on crucial physiological and biochemical processes and ultimately curtailing crop growth and development (Kisinyo et al., 2014). Although the inorganic fertilizer application can help overcome the P deficiency, the high market prices limit its use by resource-poor farmers (Basak, 2019). Therefore, it is necessary to find out cheaper and effective alternatives that are locally available, such as organic-based soil fertility ameliorating inputs, such as *Tithonia diversifolia* (Hemsl.) and manure, and phosphate rock into the soil nutrient management of smallholder farming systems.

Manure application has been shown to increase labile and stable P pools. For instance, in a study by He et al. (2005), a single application of animal manure led to an increase in soil inorganic P. According to He et al. (2006), there is a linear relationship between inorganic fertilizer or

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manure application and soil inorganic P, bioavailable P in $NaHCO_3$, and resin-P pools. This indicates that labile P pools directly respond to the added manure P. Therefore, organic inputs have the capacity of supplementing the soil nutrient deficit either solely or in combination with inorganic fertilizer (Ngetich et al., 2012). Also, organic inputs are slow nutrient releasers, reducing leaching of nutrients (Chen, 2006), making them available for the plants. Manure application influences the chemical reaction controlling P sorption and desorption between soil solution and the solid phase (Griffin et al., 2003). Therefore, to develop an environmentally sustainable agricultural system using organic inputs, information on P content and forms is essential.

The biomass of *Tithonia diversifolia* has great nutrient content and is capable of extracting a high amount of nutrients from the soil (Olabode et al., 2007). Its biomass is an effective source of nutrients and has been widely used in annual crops such as rice, maize (Dayo-Olagbende et al., 2020; Kang et al., 2020). Its adaptability to a wide range of agro-ecological conditions, fast growth rate, and very high vegetative turnover make it suitable as a soil organic input (Kiptot, 2008; Partey et al., 2011). For example, according to Chukwuka and Omotayo (2008), *Tithonia diversifolia* can enhance soil physical and chemical properties; therefore, increasing nutrients in the soil. Organic acid released during *Tithonia diversifolia* decomposition can form complex metals with aluminum and iron, leading to reduced P fixation by aluminum and iron, increasing soil P (Parham et al., 2002). Moreover, analysis of foliar *Tithonia diversifolia* biomass shows a greater concentration of macronutrients N (3.5%), P (0.37), and K (4.10%) (Jama et al., 2000). Thus, *Tithonia diversifolia*, as a biomass transfer technique, can replace or complement inorganic fertilizer or manure in improving soil and increasing crop yields (Ngetich et al., 2012; Hafifa, 2016). However, knowledge of *Tithonia diversifolia* interactions with phosphate rock under acidic *humic nitisols* is limited.

Therefore, it is essential to establish simple and cost-effective technology for utilizing this low-grade phosphate rock as P fertilizers. One way of improving the bioavailability of phosphate rock is to integrate it with *Tithonia diversifolia* (Basak, 2019). However, knowledge on the P fractions, which is vital in predicting P's bioavailability in soils and monitoring the P fate after applying different organic and inorganic P sources, is still lacking. Hence, this study's objective was to evaluate soil phosphorus availability and exchangeable aluminum in response to phosphate rock and organic inputs in acidic *humic nitisols*. We hypothesized that the application of *Tithonia diversifolia* combined with phosphate rock would reduce exchangeable aluminum in the acidic *humic nitisols*.

2. Materials and methods

2.1. Site description

We established the field experiment in Kigogo Primary School (00° 23′ S, 37° 38′ E) Meru South Sub-county, Tharaka-Nithi County, Kenya. The site is at an altitude of 1500 m above sea level, with average annual rainfall ranging from 1200 to 1400 mm and an annual mean temperature of 20 °C. Rainfall is bimodal, with long rains (LR) falling from March through June and short rains (SR) beginning from October to December. It is in the upper midland zone II (UM2) agro-ecological zone on the eastern slopes of Mount Kenya. The soils are predominantly *humic nitisols*, typically deep and weathered with moderate to high inherent fertility (Jaetzold et al., 2007). The soils are highly fertile, making them good for agricultural production. However, fertility has declined over time due to continuous cultivation. The soil texture is mostly clay (Ngetich et al., 2014). The initial soil characteristics are shown in Table 1.

2.2. Experimental layout and management

The field experiment was laid in a randomized complete block design with seven treatments replicated thrice (Table 2).

The plot size was 6 by 4.5 m with a 1 m wide alley separating plots within a block and 2 m wide alley left between blocks. The test crop was maize (*Zea mays* L.), H516 variety. The field experiment ran for two consecutive cropping seasons; short rains 2017 (SR2017) and long rains 2018 (LR2018). Maize seeds were planted at 0.75 by 0.50m, inter and intra row spacing, respectively. Three maize seeds per hill were planted and later thinned out to two plants per hill two weeks after emergence to achieve the recommended plant density of 53333 plants ha^{-1}. The amount of applied organic inputs were based on their P and N contents as determined through a lab analysis (Table 3). Goat manure and green manure (*Tithonia diversifolia)* were spot-applied into the planting hills during land preparation two weeks before planting. Inorganic fertilizers used were phosphate rock (PR) (12.8 % total P (128 g kg^{-1}), triple superphosphate (TSP) (20 % P) (200 g kg^{-1}), and calcium ammonium nitrate (CAN). Inorganic fertilizer incorporation was done during planting. The experimental plots were maintained weed-free throughout the season by hand-weeding. Best agronomic practices, such as timely control of pest infestations, were applied throughout the season.

The daily rainfall data were obtained from the research stations within the study region. Cumulative rainfall during the experimental period was 608.5 mm during the SR2017 and 1250.5 mm in the LR2018 (Figure 1). A continuous decline in the rainfall amount was observed throughout the cropping seasons. Based on the predictable rainfall dates 15^{th} March and 15^{th} October (Ngetich et al., 2014), the SR2017 season and LR2018 season onset dates were within the reported range. Overall, the SR2017 was a dry season with the earliest cessation dates, making the season shorter (46 days). The LR2018 season was relatively a wet season with early-onset dates and the latest cessation dates making the season the longest with the highest cumulative rainfall (1250.5 mm) with a well-distributed rainfall (Figure 1).

2.3. Soil sampling

Composite soil samples were collected from each plot two weeks before planting, just before land plowing, using a zigzag method at a depth of 0–15 cm using the Edelman soil auger. At the end of each experimental season, soil sampling was done at a depth of 0–15 cm for soil analysis.

2.4. Laboratory analyses

All laboratory analyses followed the standard soil analysis methods; Exchangeable aluminum was determined using McLean's (1982)

Table 1. Initial soil properties of the experimental site (0–15 cm) in Meru South, Kenya.

Parameter	Value
pH water (1:1, soil: water)	5.43
Soil texture	
Clay (%)	78
Silt (%)	14
Sand (%)	8
Exchangeable aluminum (me %)	0.23
Total Organic Carbon (%)	2.53
Phosphorus Mehlich (mg kg^{-1})	5
Potassium (me %)	1.18
Calcium (me %)	2.4
Magnesium (me %)	3.33
Manganese (me %)	1.39
Copper (mg kg^{-1})	1.92
Iron (mg kg^{-1})	14.2
Zinc (mg kg^{-1})	11.8
Sodium (me %)	0.12

Table 2. Treatment description in the study site at Meru South, Kenya.

Treatment	P source	P rate (kg ha^{-1})		
		Organic	Inorganic	Total
TSP + CAN	CAN and TSP	0	60	60
Tithonia diversifolia + phosphate rock	*Tithonia diversifolia* and phosphate rock	20	40	60
Tithonia diversifolia	*Tithonia diversifolia*	60	0	60
Phosphate rock	Phosphate rock	0	60	60
Manure + phosphate rock	Manure and phosphate rock	20	40	60
Manure	Manure	60	0	60
Control	-	0	0	0

Where TSP = triple superphosphate, and CAN = calcium ammonium nitrate.

Table 3. Nutrient composition (%) of organic materials applied in the experiment.

Treatment	Parameter					
	N	P	Ca	Mg	K	Ash
Goat manure	1.0	0.3	1.4	0.4	0.9	63.6
Tithonia diversifolia	3.0	0.2	2.2	0.6	2.9	13.2

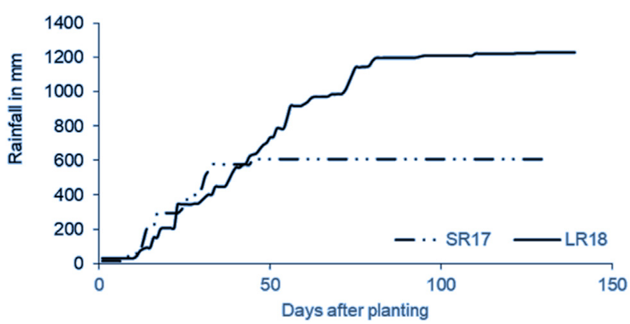

Figure 1. Cumulative rainfall distribution in Meru South during the SR2017 (October to December) and LR2018 (March to June) seasons.

procedure. Available soil P was done using the Brays' 2 P method (Bray and Kurtz, 1945). Soil organic carbon followed the modified Walkley and Black oxidation method (Walkley, 1935). Sequential fractions of soil phosphorus (P) followed the modified Hedley protocol Hedley (1982), as shown in Figure 2. Soil P was calculated using Eq. (1)

$$P1 = \frac{P2 \times dv \times ev}{g \times av} \tag{1}$$

Where P1 is phosphorus in soil (mg kg^{-1}), P2 is phosphorus in solution (mg/L), dv is dilution volume (mL), ev is extraction volume (mL), g is weight of soil (g), av Aliquot volume (mL).

The soil phosphorus was sequentially extracted into seven fractions: The labile inorganic and organic P (resin Pi, $NaHCO_3$-Pi, and $NaHCO_3$-Po), moderately labile P (NaOH-Pi and NaOH-Po), inorganic P associated with Ca (HCl-Pi), and residual P (Figure 2). For the resin Pi, we used the resin strip.

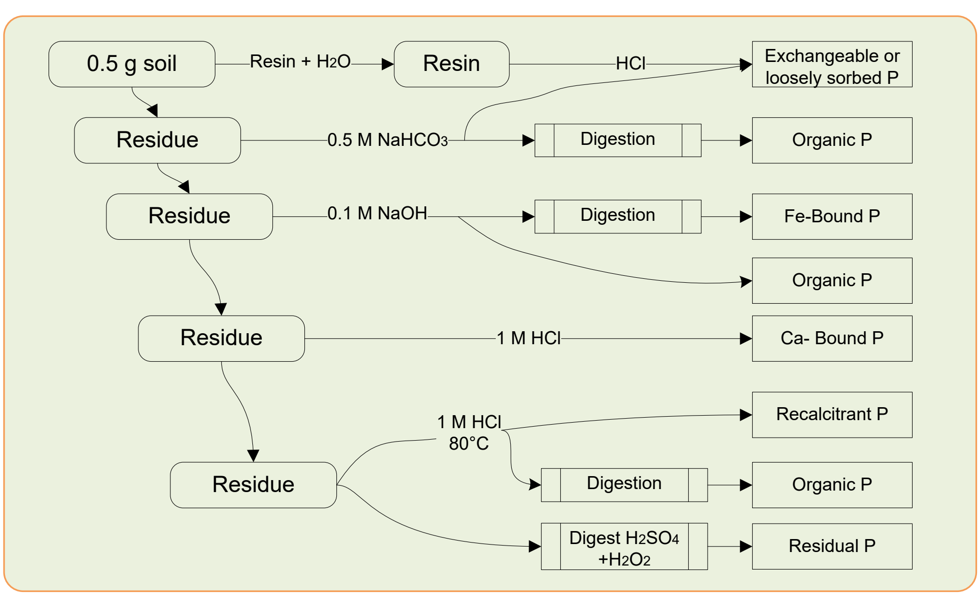

Figure 2. Sequential extraction of different P fractions Hedley (1982).

2.5. Data analysis

As a first step, diagnostic checks on potentially influential and outlying random and residual effects were performed on the data using the studentized residual approach in SAS 9.4 (SAS Institute, 2013). This allowed for quick graphical checks of fitted residuals and assessment of distributional assumptions such as homogeneity/heterogeneity of variance and lack/presence of serial correlation. Diagnostic plots showed normal distribution; hence there was no need to transform the data. We then subjected the data to the analysis of variance (ANOVA). Mean separation was done using the least significant difference (lsd) at $p = 0.05$. All pairwise comparisons of the treatment differences between the start and the end of the experiment's period were carried out using Student's t-tests at $p = 0.05$.

3. Results

3.1. Effects of treatments on soil chemical properties in Meru South, Kenya

Table 4 shows the soil's chemical composition at the beginning of the experiment (SR2017) and at the end of the experiment (LR2018). The highest ($p = 0.002$) soil pH was observed under *Tithonia diversifolia* + phosphate rock (5.63) followed by manure (5.54), manure + phosphate rock (5.52), and sole phosphate rock (5.51). During the SR2017, *Tithonia diversifolia* + phosphate rock significantly ($p < 0.0001$) increased the calcium concentration by 33% and 27%, respectively, compared with sole *Tithonia diversifolia* and sole phosphate rock. During the LR2018, sole manure significantly ($p < 0.0001$) increased calcium by 89% and 53%, respectively, compared to manure + phosphate rock and sole *Tithonia diversifolia*. Soil potassium significantly declined in TSP + CAN, *Tithonia diversifolia* and manure + phosphate rock ($p = 0.02$, 0.03 and 0.03, respectively). Manure + phosphate rock increased magnesium by 42% compared to sole manure (Table 4). During the SR2017, all treatments significantly increased the total soil nitrogen relative to the control. However, during the LR2018 season, only CAN + TSP increased the total nitrogen.

3.2. Effects of treatments on exchangeable aluminum, Bray's 2 P, soil organic carbon (SOC) & iron during the SR2017 and LR2018 season in Meru South

Treatments under *Tithonia diversifolia* alone significantly ($p = 0.002$) reduced (57%) exchangeable aluminum, followed by manure (43%), manure + phosphate rock (29%) and sole phosphate rock (29%) compared to *Tithonia diversifolia* + phosphate rock (Table 5). In the LR2018 season, sole *Tithonia diversifolia* + phosphate rock application reduced (67%) the exchangeable aluminum compared to sole *Tithonia diversifolia*. Sole manure significantly ($p < 0.0001$) led to a reduction in exchangeable aluminum by a difference of 58% relative to sole *Tithonia diversifolia*. Sole phosphate rock reduced exchangeable aluminum by 27% and 38% compared to *Tithonia diversifolia* + phosphate rock and manure + phosphate rock, respectively. TSP + CAN performed the least in reducing ($p = 0.0001$) exchangeable aluminum (15%) compared to *Tithonia diversifolia* alone (Table 5).

The soil organic carbon was significantly ($p < 0.0001$) different (Table 5). Manure + phosphate rock significantly ($p = 0.0001$) increased soil organic carbon by 74% and 32%, respectively, compared to the sole manure and sole phosphate rock (Table 5). The application of sole phosphate rock and sole *Tithonia diversifolia* increased SOC by 44% and 28%, respectively, compared to *Tithonia diversifolia* + phosphate rock (Table 5). During SR17, the Bray's 2 P under TSP + CAN was significantly ($p = 0.0001$) the highest, followed by sole manure and then *Tithonia diversifolia* + phosphate rock. The control gave the lowest Brays'2 P (Table 5). Compared with the sole *Tithonia diversifolia* treatment, *Tithonia diversifolia* + phosphate rock led to a 47% increase in iron concentration (Table 5).

3.3. Effects of treatments on different P fractions during the SR2017 and LR2018 season in Meru South, Kenya

3.3.1. Labile P (resin Pi and sodium bicarbonate inorganic and organic P)

Treatment under *Tithonia diversifolia* increased resin-Pi by 14% and 26%, respectively, compared to sole manure and *Tithonia diversifolia* + phosphate rock. The application of sole manure increased resin-Pi by 22% compared to manure + phosphate rock. Resin-Pi increased by 48 and 12%, respectively, in manure + phosphate rock and sole *Tithonia diversifolia* compared to sole manure. $NaHCO_3$-Pi increased by 99% and 40% under *Tithonia diversifolia* + phosphate rock and sole manure compared to sole *Tithonia diversifolia*. TSP + CAN increased the $NaHCO_3$-Pi by 54% relative to phosphate rock during the first season (SR2017). On average sole manure and *Tithonia diversifolia* + phosphate rock increased $NaHCO_3$-Pi by 51% relative to phosphate rock + manure. The soil $NaHCO_3$-Po significantly increased in sole phosphate rock (*t*-test $p = 0.0004$) after the two seasons (Table 6).

3.3.2. Moderately labile P (NaOH-Pi and NaOH-Po)

During the SR2017 season, NaOH-Pi varied significantly ($p < 0.001$) across treatments; *Tithonia diversifolia*, manure + phosphate rock, sole phosphate rock, *Tithonia diversifolia* + phosphate rock, CAN + TSP increased NaOH-Pi by 63, 55, 46, 35, and 32%, respectively compared to sole manure. In LR2018, *Tithonia diversifolia* + phosphate rock led to a 26% and 18% increase in NaOH-Pi compared to sole *Tithonia diversifolia* and phosphate rock. The increase in NaOH-Po was statistically significant in sole TSP + CAN after the two cropping seasons (*t*-test; $p = 0.001$) (Table 6).

Table 4. Effects of treatments on soil chemical properties after two seasons in Meru South, Kenya.

Soil parameter	pH (H_2O)		Ca (C mol/kg)		Mg (C mol/kg)		K (C mol/kg)		Total N (%)	
Treatment	Start	End	Start	End	Start	End	Start	End	Start	End
TSP + CAN	5.80^{a}	5.12^{c} (-0.1)	2.40^{b}	2.2^{cd} (-1.0)	2.34^{a}	1.13^{d} (6.0*)	0.76^{ab}	0.32^{d} (6.7*)	0.16^{a}	0.95^{a} (1.31)
Tithonia diversifolia	5.83^{a}	5.28^{bc} (3.9)	2.13^{bc}	2.60^{bc} (-0.7)	2.46^{a}	1.53^{b} (4.5)	0.86^{a}	0.40^{bc} (4.9*)	0.16^{a}	0.14^{b} (-2.65)
Tithonia diversifolia + phosphate rock	5.53^{a}	5.63^{a} (0.8)	2.80^{a}	2.10^{d} (-0.8)	2.43^{a}	1.51^{b} (2.9)	0.74^{ab}	0.30^{d} (1.4)	0.16^{a}	0.14^{b} (1.22)
Phosphate rock	5.51^{a}	5.51^{a} (0.2)	2.20^{bc}	2.90^{b} (-1.0)	1.79^{a}	1.23^{cd} (1.6)	0.92^{a}	0.51^{a} (1.3)	0.15^{a}	0.16^{b} (0.46)
Manure	5.56^{a}	5.54^{a} (0.3)	1.40^{d}	3.97^{a} (-0.3)	2.23^{a}	1.30^{c} (2.7)	0.71^{ab}	0.31^{d} (2.5)	0.15^{a}	0.16^{b} (-1.01)
Manure + phosphate rock	5.61^{a}	5.52^{a} (0.4)	2.00^{c}	2.10^{d} (-1.7)	1.86^{a}	1.85^{a} (1.0)	0.62^{b}	0.48^{ab} (5.7*)	0.15^{a}	0.12^{b} (0.49)
Control (no input)	5.54^{a}	5.49^{ab} (1.2)	2.00^{c}	2.10^{d} (-0.8)	2.39^{a}	1.58^{b} (5.4*)	0.58^{b}	0.36^{cd} (2.2)	0.13^{b}	0.19^{b} (-0.87)
P-value	0.22	0.002	0.0001	0.0001	0.19	0.0001	0.04	0.0001	0.0001	0.01

TSP = Triple Super Phosphate, CAN = Calcium Ammonium Nitrate. Means with the same letter(s) within a column are not statistically different at $p = 0.05$. NS not significant. Values in the parentheses are *t* values of soil chemical properties during 2017–2018. Start-start of experiment SR17, End-end of experiment LR18, * significant at $p = 0.05$.

Table 5. Effects of treatments on exchangeable aluminum, Bray's 2 P, Soil organic carbon (SOC), and iron during the SR2017 and LR2018 season in Meru South, Kenya.

Soil parameter	Exchangeable Al (cmol Al kg^{-1})		Bray's 2 P (mg P kg^{-1})		SOC (mg C kg^{-1} soil)		Fe (mg C kg^{-1} soil)	
Treatment	Start	End	Start	End	Start	End	Start	End
TSP + CAN	0.05[b]	0.28[b] (-13.4*)	13.84[a]	20.56[a] (-0.8)	1.80[e]	2.19[c] (-8.5*)	17.60[a]	33.45[a] (-2.3)
Tithonia diversifolia	0.03[b]	0.33[a] (-13.0*)	4.13[cd]	5.99[a] (-2.2)	1.86[e]	2.58[b] (-20.8*)	19.03[a]	22.57[b] (-1.6)
Tithonia diversifolia + Phosphate rock	0.07[a]	0.11[c] (-3.5)	9.84[b]	15.10[a] (0.9)	4.26[a]	2.01[c] (43.3*)	26.30[a]	33.07[a] (-1.6)
Phosphate rock	0.05[b]	0.08[d] (-20*)	5.78[c]	8.28[a] (-1.2)	2.52[c]	2.97[a] (-7.2*)	17.53[a]	22.57[b] (-5.0*)
Manure	0.04[b]	0.14[c] (-6.0*)	11.25[ab]	4.05[a] (8.7*)	2.16[d]	3.15[a] (-8.2*)	17.4[a]	20.40[b] (-2.6)
Manure + Phosphate rock	0.05[b]	0.13[c] (-8.0*)	3.26[cd]	11.35[a] (-4.0)	3.75[b]	2.88[ab] (2.4)	18.70[a]	23.15[b] (-1.6)
Control (no input)	0.07[a]	0.13[c] (-10.4*)	1.10[d]	4.55[a] (-6.4*)	1.26[f]	1.34[d] (-0.7)	17.27[a]	24.23[b] (-2.5)
P-value	0.002	0.0001	0.0001	*NS*	0.0001	0.0001	0.49	0.0001

TSP = triple superphosphate, CAN = Calcium Ammonium Nitrate. Means with the same letter(s) within a column are not statistically different at p = 0.05. NS not significant. Values in the parentheses are *t* values of exchangeable aluminum, Bray's 2 P, Soil organic carbon (SOC) & iron during 2017–2018. Start-start of experiment SR17, End-end of experiment LR18, * significant at p = 0.05.

3.3.3. Non-labile P fractions (HCl-Pi and residual-P)

Treatments significantly ($p < 0.0001$) influenced the HCl-Pi fractions during the first season (SR2017). Treatments under sole *Tithonia diversifolia* led to a 2.6-fold increase in HCl-Pi relative to the sole use of manure and 2.4 fold compared to *Tithonia diversifolia* + phosphate rock and 3.6% compared to phosphate rock alone (Table 7). Manure + phosphate rock led to a 185% and 59% increase in HCl-Pi compared to sole manure and sole phosphate rock during LR2018. Treatments significantly ($p < 0.03$) affected the residual-P with the highest P-value under sole phosphate rock and lowest under control.

3.4. Grain yield in different treatments during the SR2017 and LR2018 in Meru South, Kenya

Comparative grain yield performance showed that there was a better performance of grain yield at the end of the experimental trial (LR18) while the SR17 was the worst season. During the LR18, grain yield under TSP + CAN was the highest ($p = 0.0001$), followed by the sole organics. Treatments with sole phosphate rock, *Tithonia diversifolia* + phosphate rock, and manure + phosphate rock were low without significant difference between them (Figure 3). Correlation analysis showed that resin-Pi, $NaHCO_3$-Po, $NaHCO_3$-Pi, NaOH-Po NaOH-Pi, and residual P significantly correlated ($p = 0.01$) with grain yield and exchangeable aluminum. HCl-Pi correlated significantly ($p = 0.05$) with exchangeable aluminum and with grain yield ($p = 0.01$).

4. Discussion

During the LR18, the soil pH was significantly higher in the treatments with the organics. The pH increase with manure treatments corresponds with the findings by Mucheru-Muna et al. (2007) and could be attributed to the increases in the exchangeable cations in the organics (Table 4). There was an increase in Ca, Mg, and K after applying organic materials, which is consistent with the work of Mucheru-Muna et al. (2014), who reported a significant change in exchangeable cations with organics after four cropping seasons. The reduction in exchangeable aluminum due to manure and *Tithonia diversifolia* corresponds to the findings of Opala et al. (2012). This can be explained by increased soil pH. As the soil pH increases, the organic inputs effectively fix aluminum and iron (Ahmed et al., 2019). This results in the precipitation of soluble aluminum as insoluble Al hydroxide (Tang et al., 2007). The reduction in exchangeable aluminum by the sole use of phosphate rock during the LR2018 season can be ascribed to a high content of CaO (38%) of phosphate rock compared to TSP (19%), slightly reduced the exchangeable aluminum. During the LR2018 season, *Tithonia diversifolia* + phosphate rock had a higher reduction in exchangeable aluminum than the sole use of *Tithonia diversifolia;* this may be attributed to higher pH (5.63) observed in *Tithonia diversifolia* + phosphate rock treatment compared to pH of 5.28 in sole *Tithonia diversifolia*. Decreases in exchangeable aluminum with increases in soil pH during decomposition of organic residues in soils has been cited by Naramabuye and Haynes (2006). This study's findings corroborate with a study conducted in Western Kenya

Table 6. Effects of treatments on different P fractions during the SR2017 and LR2018 season in Meru South, Kenya.

Treatments	Resin-Pi (mg P Kg^{-1})		$NaHCO_3$-Pi (mg P Kg^{-1})		$NaHCO_3$-Po (mg P Kg^{-1})		NaOH-Pi (mg P Kg^{-1})		NaOH-Po (mg P Kg^{-1})	
	Start	End	Start	End	Start	End	Start	End	Start	End
TSP + CAN	33.91[a]	19.22[a] (21.52*)	3.70[c]	1.30[b] (245.6*)	7.04[a]	4.27[b] (24.5*)	2.38[ab]	9.06[ab] (-20.5*)	6.92[a]	27.32[a] (-30.5*)
Tithonia diversifolia	30.13[b]	13.26[c] (5.98*)	3.30[d]	1.13[b] (55.4*)	8.21[a]	4.06[b] (5.5*)	2.93[a]	7.80[bc] (-28.9*)	7.48[a]	28.97[a] (-3.4)
Tithonia diversifolia + phosphate rock	23.94[d]	12.02[cd] (18.67*)	6.26[a]	1.34[ab] (123.3*)	7.02[a]	4.29[b] (11.0*)	2.43[ab]	9.80[a] (-9.2*)	6.22[a]	9.56[b] (-42.8*)
Phosphate rock	22.07[de]	14.39[bc] (8.4*)	3.15[d]	1.09[b] (123.6*)	7.74[a]	5.65[a] (49.1*)	2.63[a]	8.32[bc] (-10.9*)	6.43[a]	13.22[b] (-10.6*)
Manure	26.46[c]	11.80[cd] (11.0*)	4.63[b]	1.65[a] (219.5*)	7.52[a]	4.28[b] (23.9*)	1.8[bc]	8.07[bc] (-28.0*)	6.39[a]	9.83[b] (-3.19*)
Manure + phosphate rock	21.6[e]	17.07[ab] (38.2*)	3.22[d]	1.09[b] (6.7*)	7.19[a]	4.60[b] (56.0*)	2.79[a]	8.54[ab] (-14.4*)	6.92[a]	17.43[b] (-11.8*)
Control (no input)	23.52[de]	10.06[d] (24.7*)	3.22[d]	1.24[b] (75.1*)	6.96[a]	3.94[b] (65.2*)	1.40[c]	7.08[c] (-37.2*)	7.51[a]	9.36[b] (-1.0)
P-value	0.0001	0.0001	0.0001	0.02	*NS*	0.0006	0.001	0.01	*NS*	0.0003
Total P(Sum)	181.63	97.82	27.48	8.84	51.68	31.09	16.36	58.67	47.9	115.69

TSP = Triple Super Phosphate, CAN = Calcium Ammonium Nitrate. Means with the same letter(s) within a column are not statistically different at p = 0.05. NS not significant. Values in the parentheses are *t* values of different P fractions during 2017–2018. Start-start of experiment SR2017, End-end of experiment LR2018, * significant at p = 0.05.

Table 7. Effects of treatments on HCl-Pi and residual-P during the SR2017 and LR2018 season in Meru South, Kenya.

Treatment	HCl-Pi (mg P Kg^{-1})		Residual-P (mg P Kg^{-1})	
	Start	End	Start	End
TSP + CAN	6.80[b]	4.92b (2.6)	54.76[a]	68.26[a] (-25.4)
Tithonia diversifolia	21.42[a]	5.33b (14.9*)	60.66[a]	51.07[a] (-0.8*)
Tithonia diversifolia + phosphate rock	8.80[b]	7.12ab (2.9)	59.33[a]	54.97[a] (-3.6*)
Phosphate rock	6.72[b]	6.25b (0.7)	63.59[a]	70.52[a] (-2.3*)
Manure	8.27[b]	5.24b (3.2)	55.75[a]	51.30[a] (-2.3*)
Manure + phosphate rock	7.34[b]	9.93a (-1.6)	54.06[a]	63.05[a] (-4.8)
Control (no input)	6.54[b]	4.78b (9.5*)	41.20[b]	47.57[a] (0.4*)
P-value	0.0001	0.03	0.03	NS
Total P sum	65.89	43.57	389.35	406.74

TSP = Triple Super Phosphate, CAN = Calcium ammonium nitrate. Means with the same letter(s) within a column are not statistically different at p = 0.05. NS not significant. Values in the parentheses are *t* values of HCl-Pi and residual-P during 2017–2018. Start-start of experiment SR2017, End-end of experiment LR2018, * significant at p = 0.05.

that reported that *Tithonia diversifolia*, manure, and phosphate rock use in sole application or combination reduced the exchangeable aluminum (Opala et al., 2012).

The observed increases in Bray's 2 phosphorus under manure compared to sole *Tithonia diversifolia* could be attributed to the manure's high phosphorus content (Table 3). This can also be explained by increased Ca content in the soil under the manure treatment (Table 4). Calcium acts as a filler to maintain the balance among cation nutrients and reduce the effect of acid cations. Increases in *Tithonia diversifolia* + phosphate rock compared to manure + phosphate rock suggest that *Tithonia diversifolia* enhanced phosphate rock dissolution. *Tithonia diversifolia* has been reported with a low C/N ratio, low cellulose, lignin, and polyphenols than animal manure (Kiboi et al., 2020). The low C/N ratio of *Tithonia diversifolia* implies a rapid decomposition rate. Several authors have reported increased soil phosphorus with manure (Gichangi et al., 2009; Yu et al., 2013) and *Tithonia diversifolia* application (Chukwuka and Omatoyo 2008; Utami et al., 2017). TSP + CAN gave higher Bray's 2 P than sole manure, sole *Tithonia diversifolia,* or phosphate rock. This could be ascribed to the high solubility of TSP compared to phosphate rock (Yusdar et al., 2007).

Significantly higher resin-Pi observed under *Tithonia diversifolia* than manure could be attributed to the rapid decomposition of *Tithonia diversifolia* and its high nutrient concentration (Opala et al., 2010). Manure also increased the $NaHCO_3$-Pi compared to *Tithonia diversifolia;* this may be ascribed to manure's high phosphorus content (Table 3). Gichangi et al. (2009) revealed that the use of goat manure increased the resin-Pi and $NaHCO_3$ Pi compared to sole application of mineral fertilizer, implying that the goat manure reduced the fixation of P. Manure application has shown increases in the labile and stable P pools (He et al., 2005). Similarly, inorganic P, bioavailable P in $NaHCO_3$, and resin-P pools showed a linear relationship to applied P with inorganic fertilizer or manure application, indicating that labile P pools directly respond to the added manure P (He et al., 2006). The labile P (Res Pi, $NaHCO_3$-Pi, and $NaHCO_3$-Po) fractions were noticeably reduced during the LR2018 season. The reduction was possibly due to higher P uptake by the plants. Therefore, manure's combined use with modest phosphate rocks rates could be economical and more appropriate alternative for smallholder farmers in terms of increased yield and sustained soil fertility.

Treatments with TSP + CAN gave higher resin-Pi than phosphate rock in both seasons, which can be attributed to CAN and TSP's high solubility. *Tithonia diversifolia* + phosphate rock led to increases in $NaHCO_3$-Pi compared to sole phosphate rock. The increase could be attributed to the higher pH (5.63) under *Tithonia diversifolia* + phosphate rock (Table 4). The pH enhanced the availability of P by reducing the fixation of P by aluminum. The findings corroborate with the study of Audette et al. (2016). The use of *Tithonia diversifolia* increased NaOH-Pi compared to manure in the SR2017 season. This could partly be ascribed to the lower decomposition rate of manure and subsequent nutrient release to the soil. Manure was a lower quality organic resource, as it contained a lower N concentration and high ash than *Tithonia diversifolia* (Table 3). The higher NaOH-Pi under *Tithonia diversifolia* + phosphate rock and manure + phosphate rock in LR2018 season were probably the effects of

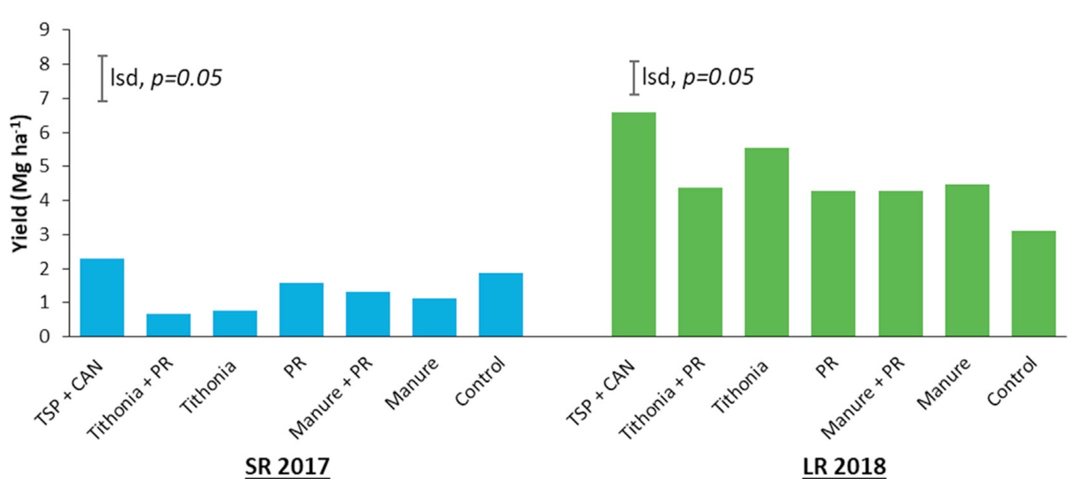

Figure 3. Average maize yields Mg ha^{-1} under different soil management in Tharaka Nithi County (TSP + CAN = Triple Super Phosphate plus Calcium Ammonium Nitrate; PR = phosphate rock; *Tithonia*= *Tithonia diversifolia*). The Error bars denote the least significant difference per season at p = 0.05.

acidification from the organic acid produced during the decomposition process of organic matter that enhanced phosphate rock solubilization. This could have led to a higher extractable P-value under treatments phosphate rock combined with other organic input (Ahmed et al., 2019), suggesting that *Tithonia diversifolia* and manure enhanced the dissolution of phosphate rock. During decomposition, manure discharges exchangeable cation to the soil solution, which exchanges Al^{3+} and H^{+} in the sorption sites and raises the soil pH (Crawford et al., 2008). Manure also gives exchangeable cations through mineralization and nutrient release (Verde et al., 2018). Similarly, Milić et al. (2019) reported that manure augments humic phosphorus fractions showing that manure significantly impacts labile phosphorus.

The sole use of *Tithonia diversifolia* led to a 2.6-fold increase in HCl-Pi relative to the sole use of manure in the SR2017 season. This was possible because the organic amendments increased the soil pH and, at the same time, reduced exchangeable aluminum and exchangeable iron. This could also be credited to increases in organic compounds secreted by the root that stimulated microbial activity and hence P availability (Crème et al., 2016). Additionally, *Tithonia diversifolia* reduces the P sorption sites by blocking the sorption sites by releasing organic compounds during decomposition (Cong and Merckx, 2005). Similarly, Opala et al. (2012) reported that *Tithonia diversifolia* as green manure produced a large amount of organic acids used in the complexion reaction compared to manure.

Manure + phosphate rock led to increases in HCl-Pi compared to sole manure and sole phosphate rock during LR2018. This can be ascribed to the application of phosphate rock. Phosphate rock has a long-lasting residual effect in supplying P (Hussain et al., 2003). Other studies have also highlighted that phosphate rock releases phosphorus slowly under acidic soils (Babana et al., 2016). We observed increases in residual-P with *Tithonia diversifolia* and TSP + CAN. This is not unique to the region alone since others have documented it. For example, Nziguheba et al. (1998) attributed this to the organic anions produced during the high-quality *Tithonia* breakdown. He highlighted that a high-quality organic addition could be comparable to or more effective than inorganic P in enhancing soil P availability.

At the end of the experimental trial, maize grain yield was higher with sole organics than the organics integrated with phosphate rock. The difference in maize performance in the two-season can be attributed to rainfall amounts and patterns experienced during the two seasons (Figure 1). We attributed the high grain yield under *Tithonia diversifolia* and manure to the increased soil organic carbon (Table 5), the high nitrogen content of the *Tithonia diversifolia,* and the manure's high P concentration (Table 3). The increased carbon under *Tithonia diversifolia* and manure in the LR2018 season may have primed the N mineralization from soil organic matter, enhancing N availability for the crop. Studies from other parts of Africa have also reported increased maize yields following incorporation of *Tithonia diversifolia* biomass (Mucheru-Muna et al., 2007, 2014; Opala et al., 2012; Mugwe et al., 2009). Additionally, organic materials also have other benefits such as; improved moisture retention and provision of other additional nutrients, for example, Ca, Mg and K (Ojeniyi et al., 2012). The observed higher grain and stover yield in TSP + CAN treatment is probably because of TSP and CAN's high solubility.

5. Conclusion

Generally, organic and inorganic input use resulted in significant improvement in available soil phosphorus (P) and reduction in exchangeable aluminum. This study showed that the organic amendments could improve P availability in acidic soils, proving the organics' superiority in improving soil P availability. The results suggest that phosphate rock and or a combination of organic input can ameliorate the P fixation of soil to enhance the chemical soil properties. The use of organic input significantly increased the labile P (Res Pi, $NaHCO_3$-Pi, and $NaHCO_3$-Po), NaOH-Pi, HCl-Pi, and residual-P. *Tithonia diversifolia* or manure's sole use increased the grain yields in LR2018 season and reduced exchangeable aluminum in SR2017 season compared to the control. The HCO_3-Pi fraction was significantly influenced by *Tithonia diversifolia* + phosphate rock, while phosphate rock integrated with *Tithonia diversifolia* or manure influenced the NaOH-Pi fractions. The study highlights the importance of improving P availability with phosphate rock combined with the organic amendments for the management of P - deficient acidic soils.

Declarations

Author contribution statement

Omenda, J.A.: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ngetich, K.F.: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kiboi, M.N.: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Mucheru-Muna, M.W.; Mugendi, D.N.: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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