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Research article

Agronomic and financial benefits of direct Minjingu phosphate rock use in acidic humic nitisols of Upper Eastern Kenya

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ABSTRACT

A major constraint to crop production in Sub-Saharan Africa is nutrient deficiency, especially phosphorus (P) deficiency. Phosphorus plays a crucial role in photosynthesis but is usually deficient in acidic soils since it is converted to less available forms, affecting crop yields. There is a need to improve phosphorus availability to crops for maximum production. This study assessed Minjingu phosphate rock fertilizer's impact on maize yields, soil chemical composition, and cost-effectiveness in acidic humic nitisols of Tharaka Nithi County, Upper Eastern Kenya. A field experiment in a randomized complete block design (RCBD) was set during long rains (SR2017) and Short rains (LR2018) seasons. The treatments were Minjingu phosphate rock, manure, *Tithonia diversifolia,* Minjingu phosphate rock + manure, *Tithonia diversifolia* + Minjingu phosphate rock, Calcium Ammonium Nitrate (CAN) + Triple Superphosphate (TSP), and a control. Soil samples were collected at a depth of 0–20 cm before and at the end of the experiment for pH, P-sorption, and other soil nutrient determinations. Other auxiliary data collected included labor and input costs besides output prices. The CAN+TSP treatment had significantly higher grain yields (6.86 Mg ha^{-1}), while Minjingu phosphate rock on its own had the second-lowest than the control treatment (3.0 Mg ha^{-1}). Also, a similar trend in the stover yields was observed. Minjingu phosphate rock combined with either manure or *Tithonia diversifolia* led to a significant increase (over 100%) in the phosphorous levels. Sole application of Minjingu phosphate rock increased soil iron levels while magnesium, copper, and zinc levels decreased significantly. Other than the control, all treatments significantly lowered the P-sorption levels. However, CAN+TSP had the highest P-sorption (913 mg kg^{-1})while *Tithonia diversifolia* had the lowest (744 mg kg^{-1}). During the LR2018 season, all treatments reached a break-even point, and the net benefit was significantly higher at $P < 0.05$. Conclusively, the use of phosphate rock, either solely or in combination with organic elements, improved yields, soil chemical composition, P-sorption and was very cost-effective.

1. Introduction

Agriculture is a significant source of income, employment, and food security in most developing Countries (Olaoye, 2014). The rural population mainly depends on soils and rain for life-supporting agricultural production (Harrisand Orr, 2014). Food insecurity is a challenge to many African countries in the face of the 21st century (Smith et al., 2017). It is becoming an alarming issue in Sub-Saharan Africa (SSA), where, due to poor yields, a decline in food production of at least 3% per capita has been recorded (Khan et al., 2014). As a result, African countries have resolved to food importation to meet their population's food demand. The decline in soil fertility is a significant factor contributing to SSA's stagnant per capita food production (Tittonell and Giller, 2013). Physical, chemical, and biological deterioration is characterized by loss of natural organic material, increased acidity, increased salinity, and increased alkalinity (Wani et al., 2011). All these factors result in reduced capabilities of soil to produce goods of value to humans (Nkonya and Mirzabaev, 2016).

Land degradation is highest in Sub-Saharan Africa (SSA) compared to anywhere else globally (Nkonya and Mirzabaev, 2016) and with the broadest yield gaps in maize. In the recent past, the central highlands of Kenya have experienced a decrease in crop yields (Kiboi et al., 2017). In Tharaka-Nithi County, a major factor contributing to decreased crop yields for smallholder farmers is Phosphorus (P) deficiency in the soil

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(Nziguheba et al., 2016). It is worsened by poverty and lack of access to credit facilities by most smallholder farmers in the region (Njoroge et al., 2018). Thus, fertilizer is often applied at rates far below the county's recommended levels to replenish depleted P. There is a nexus between fertilizer cost and food supply in SSA (Koussoubé and Nauges, 2017). Also, intensive land use without adequate additions of both organic and inorganic fertilizers leads to soil fertility in the area.

Farmers in Tharaka-Nithi county predominantly use manure to replenish soil fertility (Matusso et al., 2014). Studies show that organic residues and manure, besides improving soil fertility contribute to soil organic matter build-up (Bedada et al., 2014), resulting in increased yields. However, poor cattle feeding management and nutrients lost due to poor handling result in manure with low P levels (Castellanos-Navarrete et al., 2015). Although manure use is of economic benefit to the smallholder farmers of this region, there is still a challenge of not getting enough manure from their farms which can be used as soil fertility inputs. In order to improve soil conditions, increase crop yields, overcome the challenges faced by smallholder farmers and thus positively impact the community economically, P application amounts should be increased substantially.

A good alternative to inorganic P sources is Minjingu phosphate rock (MPR). Research has proved that its use is cost-effective (Qureshi et al., 2014). It is very reactive at pH < 5.5 making it suitable for soils in the study area (Simfukwe and Tindwa, 2018). When used on maize and soya beans, the Marginal Rate of Return (MMR) was above 100%, an acceptable rate for adopting new technology (Savini et al., 2016). Direct application of MPR is an effective approach in restoring P and increasing yields in highly acidic soils in humid regions (Ndungu-Magiroi et al., 2015; Szilas, 2002). However, MPR has low solubility, and it is necessary to identify the best management practices for enhancing its availability to crops. This study evaluated the impact of phosphate rock fertilizer on maize yields and chemical composition in acidic soils.

2. Materials and methods

2.1. Description of the study area

The study was conducted during the Short-rains season (SR) of 2017 and Long-rains season (LR) of 2018 in Kigogo Primary School (S 00°20'07.0"; E 037°36′46.0″) in Meru South Sub-county, Tharaka-Nithi County. The altitude of this area is 1526 m above sea level and is located on the Eastern slopes of Mt. Kenya. The county has a bi-modal rainfall pattern, with the long rains running from March to June, and the short rains start in October and end in December. The area has an annual rainfall of between 1200 mm to 1400 mm (Ngetich et al., 2014) and an average yearly temperature of 20 °C (Nderi et al., 2015). The soil type at the experimental field is humic Nitisol (IUSS WG WRB, 2015). It is well weathered with moderate to high inherent fertility, clay textured (Omenda et al., 2021), and highly acidic with high iron oxide content favoring P-sorption with moderately low cation exchange capacity (CEC). The main economic activities are agriculture; livestock keeping, and farming of food crops such as bananas (*Musa acuminate*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), sweet potatoes (*Ipomoea batatas*), yams (*Dioscorea alata*), cassava (*Manihot esculenta*) and Irish potatoes (*Solanum tuberosum*) while cash crops include tea (*Camellia sinensis),* coffee (*Coffea arabica*), tobacco (*Nicotiana tabacum*) and butternut (*Cucurbita moschata*) (Njue et al., 2020).

2.2. Experimental design

The experiment was laid out in a Randomized Complete Block Design (RCBD) replicated three times. The plot size was 6 m by 4.5 m with a 1 m wide alley separating plots within a block and a 2 m wide alley left between the blocks. The land was plowed before planting using a hoe. The test crop was maize (*Zea mays*), H516 variety suitable for the upper midland agroecological zone (Otieno et al., 2020), has good husk cover, and is very tolerant to lodging ear rot, rust, grey leaf spot, and stem, and leaf blight. Manure and *Tithonia diversifolia* were applied into the planting holes before planting. The source of Minjingu phosphate rock is Tanzania. It occurs as hard (compact phosphates mixed with clay) and soft (white, porous phosphate held in between sand and clay layers) (Szilas et al., 2008) and contains additional nutrients other than P (Husnain et al., 2014). Minjingu phosphate rock was applied one week before planting, while CAN+TSP application was done during planting. Each hole had three maize seeds, with a spacing of 0.75 m between rows and 0.25 m within rows, and thinning was done two weeks after emergence to remain with two plants per hole. The experimental plots were kept weed and pest-free, and disease control was observed. The seven treatments each replicated thrice were: (i) manure, (ii) Minjingu phosphate rock, (iii) Minjingu phosphate rock + manure, (iv) *Tithonia diversifolia*, (v) *Tithonia diversifolia* + Minjingu phosphate rock, (vi) CAN + TSP and (vii) Control (Table 1).

2.3. Data collection

A composite soil sample was collected in each plot for analysis before the experiment using an Edelman Soil Auger at a 0–20 cm depth using a zigzag method. The sample bags were clearly labeled to avoid any mix-up of the samples. This was repeated at the end of the field trial. The samples were taken to the laboratory, where they were air-dried and sieved using a 2 mm sieve before analysis.

After harvesting, grain and stover yields (above-ground biomass minus grain) were estimated from the net plot and weighed using a digital scale. Maize cob was separated from the stover, sun-dried, and packed in gunny bags for threshing. After this, the moisture content of grains was determined using the moisture meter and recorded. The grain weight was then standardized by adjusting to a per hectare basis at 12.5% moisture content and expressed in Mg ha^{-1}.

Rainfall measurements were taken daily using an automatic rain gauge with 0.2 mm resolution stationed within the field trials. The rain gauge data was read out using HOBO ware Pro Version 3.2.2 and exported to excel worksheets for further processing.

2.4. Laboratory analysis

Soil pH was determined in a 1:1 (w/V) soil-water suspension with a pH meter following standard laboratory methods outlined in Okalebo et al. (1993). Other laboratory tests such as available nutrient elements, exchangeable acidity, total C and N, and P-sorption were carried out following standard laboratory methods outlined by Okalebo et al. (1993).

2.5. Data analysis

Harvest data was managed in MS excel before analysis and subjected to Analysis of Variance (ANOVA) in SAS 9.4. Mean separation was done using the Least Significant Difference (LSD) test at P $\leq$ 0.05. Data for soil chemical composition analysis before and after treatments were

Table 1. Treatment description in the field trial.

Treatment	P rate (kg ha^{-1})		
	Organic	Inorganic	Total
1. Manure	60	-	60
2. TSP +CAN	-	60	60
3. Control	-	-	-
4. Minjingu Phosphate Rock	-	60	60
5. *Tithonia diversifolia* +Minjingu Phosphate Rock	20	40	60
6. Manure+ Minjingu Phosphate Rock	20	40	60
7. *Tithonia diversifolia*	60	0	60

TSP = triple superphosphate, CAN = calcium ammonium nitrate.

subjected to t-test and analysis of variance (ANOVA) using the general linear model (GLM) in SAS version 9.4 software and mean separation done using Least Significant Difference (LSD) Test at P = 0.05.

For the cost-effectiveness analysis, detailed data on the cost of inputs were collected through a survey of inputs from suppliers in the study area. Time taken for each field operation, including labor cost for land preparation, planting, treatment application, thinning, weeding, pest control, and harvesting, was collected. The average time taken was then calculated and converted into monetary value at 2.49 USD per working day. The partial budget procedure was used for cost-benefit analysis. A rapid market survey was done, and the grain and stover costs were estimated. Maize stovers were used as cattle feed in the area, which was considered as an economic benefit. The net benefit was calculated by subtracting the total variable cost from the gross benefit for each treatment. The benefit to cost ratio was calculated as the ratio of net benefit to total variable cost.

3. Results and discussion

3.1. Rainfall patterns during the experimental period

A meteorological drought was experienced during the SR2017, 38 days after planting for 80 days, which greatly affected crop yields (Figure 1). Meteorological drought is the absence of rainfall for over 28 days during the growing season and is a major challenge in this ecological zone (Kiboi et al., 2017). Dry spells, which are also common in the area, expose crops to water stress, as shown in Figure 1.

3.2. Effects of Minjingu phosphate rock on grains and stover yields

As indicated in Table 2, there was a significant difference in grain yields observed in both seasons, SR2017 (P = 0.005), LR2018 (P < 0.05), while stover yields were only significantly different during the LR2018 season (P < *0.05).* In the SR2017 season, only CAN+TSP increased both grain yields (92%) and stover yields (16%) above the control. During the LR2018 season, CAN+TSP grain yields increased by 188%followed by sole treatment with *Tithonia diversifolia* at 75% above the control. When manure was used alone as a treatment, an increase of 67% was observed, while treatment with Minjingu phosphate rock + *Tithonia diversifolia* increased grain yields by 37%. Minjingu Phosphate rock + manure recorded a grain yield increase of 36% compared to the control (Table 2). Minjingu phosphate rock alone gave an increase of 25% lower than when Minjingu phosphate rock was used in combination with either manure or *Tithonia diversifolia.*

During the LR2018 season, stover yield significantly increased almost three times the control (142%) with CAN+TSP, while *Tithonia diversifolia* alone showed a 43% increase followed by manure with a 30% increase. A notable increase of 22% above the control when manure was combined with Minjingu phosphate rock was observed. *Tithonia diversifolia* and Minjingu phosphate rock increased by 18%, while Minjingu phosphate rock alone gave an increase of 12% (Table 2).

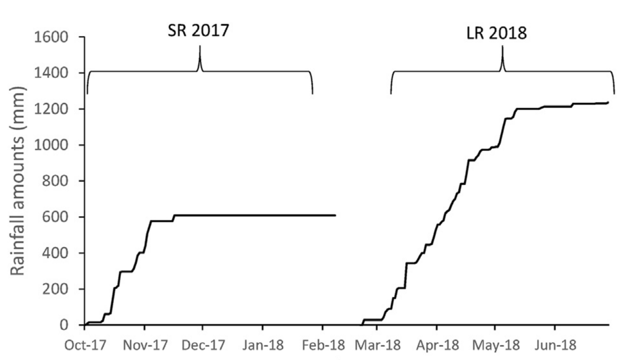

Figure 1. Rainfall characteristics of Tharaka-Nithi County during SR2017 and LR2018 Seasons.

Table 2. Maize grain and stover yields during SR2017 and LR2018 in Kigogo, Tharaka-Nithi County.

	Grain (Mg ha^{-1})		Stover (Mg ha^{-1})	
	SR2017	LR2018	SR2017	LR2018
CAN + TSP	0.65^{a}	6.86^{a}	2.14^{a}	7.78^{a}
Manure+MinjinguPhosphate rock	0.14^{b}	3.23^{bc}	1.52^{a}	3.93^{b}
Manure	0.15^{b}	4.1^{b}	1.19^{a}	4.20^{b}
Minjingu Phosphate rock	0.19^{b}	3.0^{bc}	1.27^{a}	3.61^{b}
Tithonia diversifolia + Phosphate rock	0.1^{b}	3.35^{bc}	1.60^{a}	3.78^{b}
Tithonia diversifolia diversifolia	0.17^{b}	4.17^{b}	1.40^{a}	4.60^{b}
Control	0.34^{b}	2.39^{c}	1.85^{a}	3.21^{b}
P-value	<0.05	<0.05	0.3623	<0.05
SED	0.119	0.676	0.436	1.016

TSP = triple superphosphate, CAN = calcium ammonium nitrate.
Superscripts show mean groupings with the same letter indicating mean is not significantly at 0.05 level.

The low grain yields (ranging between 0.1 to 0.65 Mg ha^{-1}) during the SR2017 season could be due to the meteorological drought and dry spells experienced during the flowering, grain formation, and grain filling stage. Water is a major constituent of plants' physiological activities, i.e., as a reagent in photosynthesis, affecting plants' productivity (Shittu et al., 2017). Precipitation is a factor that affects agronomic effectiveness by enhancing the plant's ability to utilize available P optimally. Good precipitation is required for organic matter (*Tithonia diversifolia* and manure) to decompose and provide N for plants during the growing season (Nyambati and Opala, 2014). As a result, the crop did not respond well to *diversifolia* and manure treatments either solely or combined with phosphate rock during the SR2017 season. Whereas during the LR2018 season, the good rainfalls experience had a positive impact on the organic manure. There was a significant increase in both stover and grain yield compared to the control. The organic inputs (*Tithonia diversifolia* and manure) could retain soil moisture, increasing yields during the LR2018 season. The addition of organic inputs contributes to the build-up of SOM, which directly supplies the nutrients necessary for plant growth and indirectly modifies soil physical-chemical characteristics (Adugna and Abegaz, 2016). This is in line with studies carried out by Song et al. (2015), who observed that organic inputs increased grain yields.

The highest increase of grain yields with CAN+TSP treatments in both seasons could be attributed to the inorganic fertilizer's readily available nitrogen and phosphorus. Maize yield doubles when nitrogen fertilizer is applied (Ichami et al., 2019) as in treatments with CAN+TSP, where P from TSP was utilized similarly to P from organic matters. The placement of P fertilizer during the growing season affects P uptake by plants (Arruda *et al.*, 2019).

Tithonia diversifolia alone gave a significant high grain increase (75%) associated with its ability to provide nutrient elements such as N, P, and K hence being a good source of plant nutrients (Endris and Dawid, 2015). The high improved soil status leading to increased grain yield can also be due to the ability of the *Tithonia diversifolia* biomass to reduce soil pH and improve biological activities in the acidic soils of Tharaka-Nithi County (Endris, 2019). During the LR2018 season, enough moisture contributed to the rapid decomposing of the biomass, thus improving soil organic matter and other nutrients such as Ca and Mg. This agrees with Mucheru-Muna et al. (2014), who reported that the sole *Tithonia diversifolia* realized high grain yields.

Sole manure also showed a significant grain increase of 67%. Studies have shown that treatment with manure as a soil amendment improves soil organic matter, reduces soil bulk density, increases soil porosity, helps maintain soil nutrient balance, improves soil nutrient structure and water holding capacity (Wen et al., 2016; Wang et al., 2017). These factors improve soil's biological and physical properties, thus increasing plant yields (Mucheru-Muna et al., 2014).

3.3. Effects of Minjingu phosphate rock on soil chemical composition

Phosphorus levels were observed to increase over 100% with CAN+TSP, Minjingu phosphate rock + manure, and Minjingu phosphate rock +*Tithonia diversifolia.* Sole *Tithonia diversifolia* recorded a significant increase of P by 80% (Table 3). *Tithonia diversifolia* showed a significant decrease in nitrogen (19%) and carbon (25%) (Table 3). Levels of K decreased significantly with CAN+TSP(62%), *Tithonia diversifolia* +Minjingu phosphate rock (32%), and Manure+ Minjingu phosphate rock (23%). A notable decrease in Mg was also observed with CAN+TSP (59%), Sole Minjingu phosphate rock (37%), and *Tithonia diversifolia* + Minjingu phosphate rock (36%), as shown in Table 3.

A significant decrease in Cu levels was observed with *Tithonia diversifolia* + Minjingu phosphate rock (55%), followed by sole *Tithonia diversifolia* (47%), *Tithonia diversifolia* + manure (42%), CAN+TSP (34%), and sole Minjingu phosphate rock (32%) (Table 4). A notable increase in Fe was observed with CAN+TSP (104%), manure+Minjingu phosphate rock (35%), Minjingu phosphate rock (29%), and *Tithonia diversifolia* (19%). Zinc decreased significantly with the sole Minjingu phosphate rock (32%) as well as Na when sole manure was used (43%) and with CAN+TSP (33%). Table 4 A substantial decrease in p-sorption was observed across all the treatments with a sole application of *Tithonia diversifolia* showing the highest decrease (32%),manure+ Minjingu phosphate rock, sole use of manure, and Minjingu phosphate rock+ *Tithonia diversifolia* as treatments all showed a reduction of 22%, sole application of Minjingu phosphate rock (21%). In comparison, CAN+TSP gave the lowest p-sorption at 17%.

Increased levels of total P in the soil reported in CAN+TSP treatment could be related to the soluble nature of TSP, allowing it to be fixed and transformed into NaOH-Pi pool, a sink for soluble P, which is unavailable to plants thus large quantities in the soil (Nyambati and Opala, 2014). An increase in total P in the soil by sole manure and *Tithonia diversifolia* could be attributed to the fact that organics improves soil biological activities and reduces soil P adsorption capacities, thus making it available to the plant (Endris, 2019). The general decrease in nitrogen due to *Tithonia diversifolia* could be associated with increased uptake of the nutrients by plants by removing them from the soil hence low nutrient availability. This is in line with other studies (Savini et al., 2016; Ademba et al., 2015; Mucheru-Muna et al., 2014), indicating that organic fertilizers increase recovery of applied nutrients. Low soil organic carbon observed could be attributed to high SOM decomposition rates resulting in subsequent SOC losses (Ghosh et al., 2016). This is due to high temperatures in the tropics increasing microbial activities in the soil (Luambano et al., 2015). Soil organic carbon decomposition depends mainly on temperature (Zhang et al., 2015).

AAA decrease in Mg levels in soil can result from the nutrient uptake by plants leading to accumulation in plant tissues (Szczepaniak et al., 2016). The decrease in K observed could be associated with acidic soils being inherently low in K or being removed during harvest without any replenishment (Zörb et al., 2014). The decrease in Na levels with sole manure as a treatment agrees with (Demir, 2020) that organic matter reduces salt levels in the soil by improving soil aggregation and water holding capacity. The decrease in Na with CAN+TSP can be associated with salts leaching to the nearby plot. Reduced levels of Cu and Zn can be related to heavy metal immobilization with the use of Minjingu phosphate rock and organics (Zhao et al., 2014), while a decrease in Cu is observed with CAN+TSP could be associated with the nutrient leaching to the nearest field trial. High iron levels could be due to the acidic nature of the soil favoring high concentrations of Fe^{2+} (Tandzi et al., 2018).

There was a significant decrease in P-sorption where organic inputs were used solely or combined with phosphate rock, with sole *Tithonia diversifolia* showing the highest reduction (32%). This is in line with Fink

Table 3. Effects of different treatments on pH, total nitrogen, carbon, phosphorus, potassium and magnesium.

Treatments	pH (water)			Total N (%)			Carbon %			P (ppm)			K (%)			Magnesium (%)		
	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test
CAN+TSP	5.51[a]	5.20[a]	0.34	0.18	0.15[ab]	0.46	1.91	1.60	0.39	13.33	229.0[c]	<0.05*	0.76	0.29	<0.05*	2.44	1.01[a]	<0.05*
MAN+MPR	5.48[a]	5.64[b]	0.51	0.16	0.14[ab]	0.21	1.71	1.36	0.14	10.00	122.0[b]	<0.05*	0.62	0.48	0.05*	1.86	1.85[b]	0.06
Manure	5.38[a]	5.38[ab]	1.00	0.17	0.15[ab]	0.40	1.89	1.61	0.21	11.67	36.7[a]	0.01*	0.76	0.41	0.11	2.48	1.53[ab]	0.12
PR	5.51[a]	5.46[ab]	0.38	0.17	0.14[ab]	0.32	1.82	1.44	0.38	22.67	54.3[b]	0.101	0.72	0.42	0.26	2.48	1.56[ab]	0.03*
TITH+MPR	5.34[a]	5.44[ab]	0.77	0.14	0.12[a]	0.41	1.40	1.13	0.39	30.0	227.7[c]	<0.05*	0.41	0.28	0.05*	2.31	1.61[ab]	0.03*
TITH	5.65[a]	5.45[ab]	0.40	0.16	0.13[ab]	0.01*	1.70	1.27	<0.05*	16.67	30.0[a]	0.04*	0.73	0.41	0.06	2.46	1.59[ab]	0.13
Control	5.54[a]	5.49[ab]	0.51	0.16	0.17[b]	0.83	1.71	1.71	0.99	17.33	41.7[a]	0.02*	0.78	0.49	0.31	2.70	1.87[b]	0.99
p-value	0.94	0.45		0.85	0.43		0.80	0.44		0.126	<0.05*		0.48	0.35		0.56	0.14	
SED	0.28	0.19		0.03	0.02		0.34	0.29		6.885	18.9		0.19	0.11		0.40	0.29	

TSP = triple superphosphate, CAN = calcium ammonium nitrate, MAN = Manure MPR = phosphate rock, TITH = *Tithonia diversifolia.*
SED = Standard Error, t-test column shows p-value from t-test.
* Means there is a statistically significant difference in chemical composition between seasons at 0.05 level.
Superscripts show mean groupings with the same letter indicating chemical composition mean between treatments is not significantly at 0.05 level.

Table 4. Effects of different treatments on copper, iron, zinc, sodium, calcium and p-sorption.

Treatment	Copper (ppm)			Iron (ppm)			Zinc (ppm)			Sodium (%)			Calcium (%)			P-sorption (mg kg^{-1})		
	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test	SR2017	LR2018	t-test
CAN + TSP	2.23	1.47	0.05*	17.60	35.97	<0.05*	9.76	10.31	0.86	0.42	0.28^{a}	<0.05*	1.93	1.47^{a}	0.444	1098	913*	0.02
MAN + MPR	2.25	1.30	<0.05*	18.70	25.30	0.04*	9.44	7.78	0.55	0.38	0.40^{ab}	0.78	1.73	2.90^{ab}	0.084	1105	860	<0.05
Manure	2.09	1.26	0.16	17.40	23.67	0.16	10.93	8.10	0.13	0.46	0.26^{a}	<0.05*	1.93	1.60^{ab}	0.673	1091	853	<0.05
MPR	2.16	1.19	0.01*	17.53	22.57	0.01*	11.30	7.74	0.04*	0.34	0.44	0.43	2.07	2.47^{ab}	0.444	1069	848	0.01
TITH + MPR	2.38	1.07	0.01*	19.83	29.53	0.08	12.23	10.84	0.45	0.40	0.48^{b}	0.56	1.80	3.30^{b}	0.29	1087	852	0.01
TITH	2.32	1.23	<0.05*	19.03	22.73	0.02*	11.93	10.32	0.70	0.32	0.28	0.42	2.07	1.80^{ab}	0.561	1089	744*	0.01
Control	2.27	1.47	0.08	17.27	32.30	0.16	11.63	10.25	0.23	0.36	0.30	0.16	2.13	2.27^{ab}	0.422	1027	848	0.07
p-value	*0.976*	*0.66*		*0.73*	*0.19*		*0.75*	*0.74*		*0.33*	*0.10*		*0.97*	*0.26*		*0.93*	*<0.05*	
SED	*0.15*	*0.16*		*0.32*	*0.25*		*1.83*	*5.67*		*2.01*	*2.55*		*0.47*	*0.80*		*70.1*	*18.1*	

TSP = triple superphosphate, CAN = calcium ammonium nitrate, MAN = Manure MPR = Minjingu phosphate rock, TITH = *Tithonia diversifolia*.
SED = Standard Error.
* Means there is a statistically significant difference in chemical composition between seasons at 0.05 level.
Superscripts show mean groupings with the same letter indicating chemical composition mean between treatments is not significantly at 0.05 level.

et al. (2016a,b), who reported that negatively charged functional groups in organic substances could interact with positively charged minerals like iron oxides altering P-adsorption sites. This interaction can promote anion adsorption via cation bridges (Fe^{3+}), increasing the specific surface area (SSA) by inhibiting mineral crystal growth (Fink et al., 2016a,b); thus, there is increased competition with other anions for adsorption sites, and adsorbed ions are desorbed. As a result, P becomes available in solution form (Nishigaki et al., 2019). Sole Minjingu phosphate rock treatment gave similar results to organic elements such as manure. Phosphorus sorption properties of the soil influence P availability to plants from phosphate rock. Highly acidic soils result in low P-sorption (Matamwa et al., 2018) as Minjingu phosphate rock is reactive in highly acidic conditions even with less than 4.5. The decreased P-sorption with CAN+TSP can be attributed to the movement of some organic treatments to the trial field where CAN+TSP was applied. The presence of other heavy metals associated with Minjungu phosphate rock such as cadmium (Cd), titanium (Ti), Rubidium (Rb), Strontium (Sr), Yttrium (Y), Thorium (Th), and Uranium (U) was not tested. These elements are environmental pollutants with adverse effects on plants and animals (Lema et al., 2014). However, these harmful elements can be extracted from phosphate rock before its application (Fayiga and Nwoke, 2016) or released slowly to the environment by partial acidulation of Minjingu phosphate rock (Ahmad et al., 2019).

3.4. Cost-benefit analysis

Control had a higher net benefit (USD 45.46) than other treatments in SR2017 (Table 5). During the LR2018 season, the net benefit was significantly higher at $P < 0.05$, with the highest net benefit observed with CAN+TSP treatments (USD 1419.8). *Tithonia diversifolia* + Minjingu phosphate rock gave lower benefits (USD 565.3) than sole use of *Tithonia diversifolia* (USD 905.6). This was also observed with sole manure application (USD 712.6) versus manure + Minjingu phosphate rock (USD 574.7).

Sole application of *Tithonia diversifolia* gave a high BCR (USD 3.46) than the rest of the treatments. The lowest BCR was reported in manure + Minjingu phosphate rock (USD 1.66). Sole Minjingu phosphate rock gave low BCR (USD 2.09) as compared to the control (USD2.36) (Table 5). During the LR2018 season, a break-even point was arrived at with all the treatments. A break-even point is arrived at when a BCR of 1 is achieved, determining cost recovery with any new treatment application. During the SR2017 season, there was a significant difference between treatments with Minjingu phosphate rock treatments and when no input was added (control). However, the two did not reach the break-even point due to the low yields this season due to low precipitation.

Generally, all the treatments had a positive return to labor (above 1), with CAN+TSP giving the highest return to labor during the LR2018 (USD 23.14) than other treatments. Sole Minjingu phosphate rock and *Tithonia diversifolia* gave higher returns (USD 10.60 and USD 10.35), respectively, as compared to the control (USD 10.26). Manure and manure+ Minjingu phosphate rock had a low return to labor (USD 8.90 and USD 8.10) than the control.

The high net benefit with control in SR2017 could be attributed to the poor yields experienced from the poor rains, while low benefits in LR2018 agree with Mucheru-Muna et al. (2007), who reported that no benefits were realized when there were no inputs added to the soil. The high net benefits with sole treatments with organics versus combined with phosphate rock can be associated with the Minjingu phosphate rock's insoluble nature, which could have hindered the immediate release of nutrients. The highest return to labor with CAN+TSP could result from nutrients in this fertilizer being readily available for uptake by plants. The process of acquiring and application of the treatment is less laborious as compared to organic inputs. Much time and human effort was needed from sourcing, transportation to the application of manure, thus increasing the cost of production. To determine the profitable use of any fertilizer, one needs to understand fertilizer agronomics, the yield

Table 5. Cost-benefit analysis.

Treatment	Net Benefit (USD)		BCR (USD)		Return to labour (USD)	
	SR2017	LR2018	SR2017	LR2018	SR2017	LR2018
CAN+TSP	-138.2^{ab}	1419.79^{a}	-0.33^{ab}	2.81^{b}	-2.27^{ab}	23.14^{b}
Manure + Minjingu Phosphate Rock	-133.2^{ab}	574.66^{b}	-0.63^{a}	1.66^{a}	-2.33^{ab}	8.1^{a}
Manure	-167.5^{a}	712.63^{b}	-0.7^{a}	1.83^{b}	-2.7^{a}	8.89^{a}
Minjingu Phosphate Rock	-64.33^{bc}	572.4^{b}	-0.43^{ab}	2.09^{b}	-1.43^{ab}	10.6^{a}
Tithonia diversifolia + Minjingu Phosphate Rock	-128.47^{ab}	565.33^{b}	-0.67^{a}	1.67^{a}	-2.17^{ab}	7.45^{a}
Tithonia diversifolia	-27.9^{cd}	905.56^{b}	-0.23^{ab}	3.46^{b}	-0.43^{bc}	10.34^{a}
Control	45.47^{d}	510.69^{b}	0.47^{b}	2.36^{b}	0.93^{c}	10.26^{a}
p-value	$<$0.05	0.01	0.12	0.28	0.01	0.07
SED	41.96	200.99	0.40	0.80	0.86	4.74

Superscripts show mean groupings with the same letter indicating mean is not significantly at 0.05 level.

response, and fertilizer economics, which is the cost of inputs versus output (Liverpool-Tasie et al., 2017). This is necessary since the decision by farmers to adapt to the nutrient inputs depends on its profitability.

4. Conclusion

The study shows that combining phosphate rock with organic nutrients potentially impacts the yields, soil chemical properties, and P-sorption. It is worth noting that treatments with CAN+TSP were observed to give better yields; however, the high cost of these fertilizers affects food production since there is a nexus between the cost of fertilizers and food production. When Minjingu phosphate rock was combined with organics in SR2018, there was an increase in yields (manure 22% and *Tithonia diversifolia* 18%) while sole Minjingu phosphate rock had a 12% increase. Due to insufficient rains, low yields experienced in SR2017 indicate that soil moisture affects organic matter decomposition and soil nutrients release. It is, therefore, necessary to ensure an adequate supply of moisture for the successful performance of the treatments.

The combination also improved the soil nutrient composition and decreased P-sorption making phosphorus available to the maize crop. The results indicate that Minjingu phosphate rock combined with organic nutrients can enhance available P in acidic soils. An increase in P levels over 100% was observed while P-sorption reduced by 22%. Copper levels reduced with combination organics (Minjingu phosphate rock +*Tithonia diversifolia* 55% and Minjingu phosphate rock + manure 42% while sole Minjingu phosphate rock had a 32% decrease. A high return to labor was realized when Minjingu phosphate rock was used solely than when combined with organics (8.1 USD). Sound knowledge of the interaction between Minjingu phosphate rock and organic inputs in acidic soils is important in combating the challenge of P deficiency in acidic soils. To ensure rational use of MPR with organic inputs, there is a need to consider the soil's condition in terms of soil pH and P-sorption capacities and soil moisture content.

Declarations

Author contribution statement

Ndeleko-Barasa, E.M.: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Mucheru-Muna, M.W.; Ngetich, K.F.: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data associated with this study has been deposited at Figshare: https://doi.org/10.6084/m9.figshare.16850209.v1.

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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