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Influence of soil fertility management technologies on phosphorus fractions, sorption characteristics, and use efficiency in humic Nitisols of Upper Eastern Kenya

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ABSTRACT

Fractions of phosphorus (P) and its sorption characteristics are affected by different soil fertility (FM) technologies which ultimately affect crop growth and productivity. However, the response of P fractions and sorption characteristics to soil fertility technologies that integrate diverse amendments is still poorly understood in acidic Nitisols. A randomized complete block design was layout in an acidic Nitisol to determine fractions of P, its sorption characteristics and use efficiencies in acidic Nitisols under various FM technologies in field conditions. The use of minimum tillage + maize residue + inorganic fertilizer + goat manure (MTCrGF) had the highest impact on and significantly increased resin-Pi, $NaHCO_3$-Pi, and maximum P sorption (S_{max}) by 182, 76, and 52 mg P kg^{-1}. Moreover, NaOH-Pi and S_{max} concentrations were higher under conventional tillage + maize residue + inorganic fertilizer + goat manure (CTCrGF) by 216 mg P kg^{-1} and 49 mg P kg^{-1} than the control. MTCrGF and CTCrGF also had the lowest P bonding energy (0.04 L mg^{-1}). CTCrGF had the highest P partial productivity factor (0.093 and 0.140 kg biomass kg^{-1} P) and P agronomic efficiency (0.080 and 0.073 kg biomass kg^{-1} P) during the two cropping seasons. The results demonstrate the positive influence of combining multiple P sources on soil P fractions, sorption characteristics, and use efficiencies. Notably, combining either conventional or minimum tillage with maize straw and applying integrated manure and inorganic fertilizer (MTCrGF or CTCrGF) can increase the labile P concentrations and reduce the potential depletion of the non-renewable rock phosphate and the use of inorganic phosphatic fertilizers for agricultural production.

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1. Introduction

Most agricultural soils have ample total phosphorus (P) reserves but are very low in plant-available fractions for optimal productivity [1]. The low available P fraction is because it is less soluble and also easily fixed in soil exchange sites, especially in highly weathered soils [2]. These soils contain substantial amounts of aluminum (Al^{3+}) and iron (Fe^{3+}) ions which are responsible for P fixation [3,4]. Also, up to 12.3 million tons of P $year^{-1}$ is lost through crop harvesting [5]. Adding P into the soil through inorganic and organic forms and legume intercrops may influence its availability, fractions, and sorption characteristics and reduce phosphate rock depletion [6,7]. Most smallholder farmers use organic materials such as animal manure and *Tithonia diversifolia* as alternatives to inorganic fertilizers and maize residue as soil moisture conservation techniques. Structures and biochemical compositions of these materials vary and can impact P dynamics like fractionations, sorption characteristics phosphorus use efficiency (PUE).

Phosphorus fractionation is necessary to enhance understanding of the P conversion processes [8] under different FM technologies. For instance, Shafqat and Pierzynski, Soltangheisi et al., and Pizzeghello et al. [9–11] found that inorganic P fertilization increased various fractions of P such as; extractable, moderately labile, labile, and residual fractions. However, Tiecher et al. [12] reported a lack of association between inorganic fertilizers and inorganic and residual P fractions. Rock phosphate (RP) has also been reported to improve different P fractions in diverse soil types [13]. Additionally, intercropping maize and legume crops were found to increase or reduce sodium hydroxide-extractable inorganic and hydrochloric acid-extractable inorganic P [14,15]. Nevertheless, there is still a need to understand how integrating fertility amendments influence different P fractions in a P-deficient Nitisol.

Sorption characteristics such as maximum P sorption capacity (S_{max}), bonding energy (k), and degrees of P saturation (DPS) are essential factors that control P release [4]. Amorphous Al^{3+} and Fe^{3+} significantly contribute to P sorption in acidic soils, but the characteristics can also be influenced by the direct or indirect effects of fertilization and cropping systems [16]. Inorganic fertilizers and organic amendments affect P sorption characteristics [17,18], which often differ in their responses to the same fertility amendments. For example, both increases and reductions in S_{max} under organic amendments have been reported in different soils [19,20]. The comparative advantage between inorganic fertilizers and organic amendments' effects on P characteristics is also unclear [16]. Therefore, further investigation is needed on how different P sorption characteristics respond to various FM technologies.

Soil fertility amendments affecting P fractions and their sorption characteristics influence PUE [21]. This parameter can improve

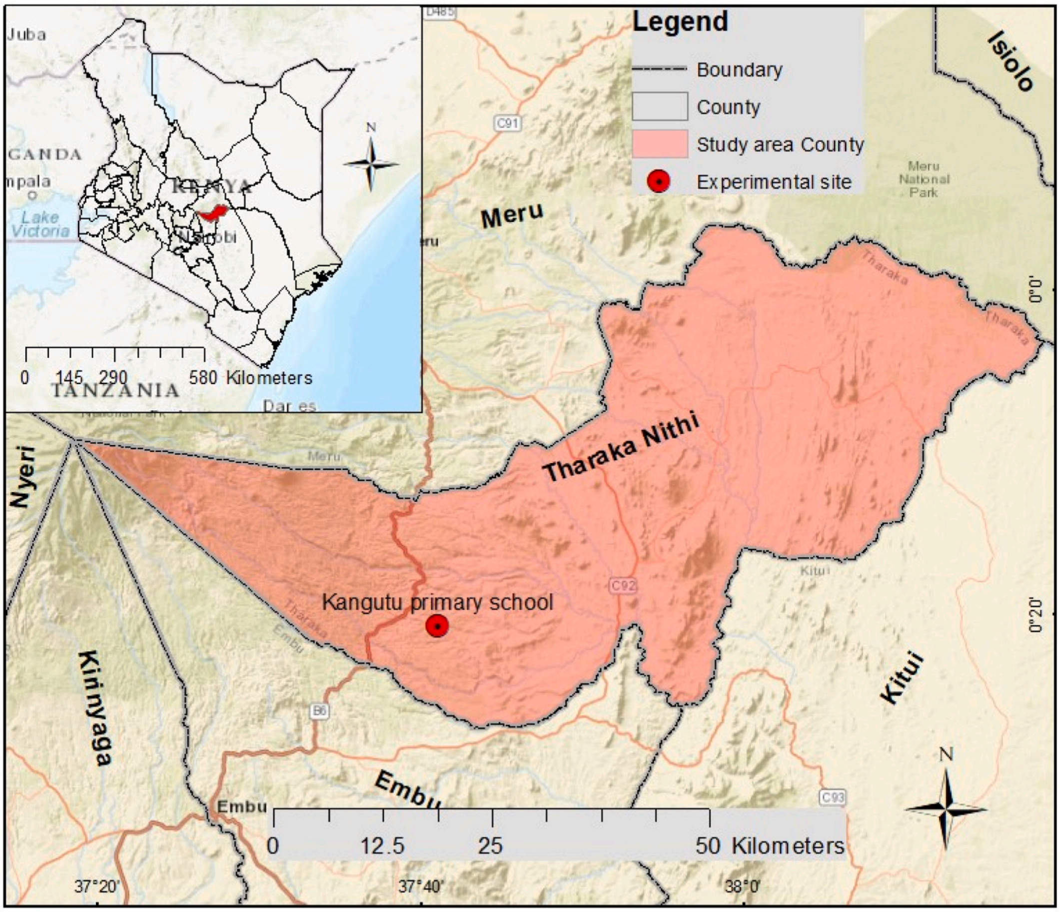

Fig. 1. Study map showing Kenya, Tharaka Nithi county, and study site.

[22] or decline [23] under inorganic and organic fertilization. Additionally, PUE also varies with the type of cereal-legume intercrop. It is, thus, essential to assess the influence of maize-Dolichos intercrop on PUE. Moreover, it is critical to simultaneously investigate the response of P fractions, its sorption characteristics, and PUE to different FM technologies for enhanced P management to improve crop productivity. No study has assessed the influence of integrating; 1) maize residue, *Tithonia diversifolia,* and RP (CrTiR), 2) maize residue, goat manure, and Dolichos intercrop (CrGL), and, 3) maize residue, *Tithonia diversifolia*, and goat manure (CrTiG) on P fractions, sorption characteristics and PUE executed under conventional (CT) and minimum (MT) tillage systems. Moreover, quantitative information on the effect of; 4) sole inorganic fertilizer (F), 5) integrated maize residue and inorganic fertilizer (CrF), and, 6) combined maize residue, inorganic fertilizer, and goat manure (CrGF) under the two tillage systems in an acidic Nitisol is scanty. The objective of this study was, thus, to determine the influence of these innovative technologies on P fractions, its sorption characteristics, and PUE in an acidic Nitisol.

2. Materials and methods

2.1. Experimental site and soil characterization

A field study was conducted for five consecutive years (from 2016 to 2021) on acidic Nitisols (deep, highly weathered, and high to moderate inherent fertility) in Kangutu Primary School (00° 98′S, 37° 08′E) located in Chuka sub-county, Tharaka-Nithi County, Kenya (Fig. 1). The initial soil characteristics are shown in Table 1. Annual rainfall in the County is bimodal and ranges from 1200 to 1400 mm. The long rains (LR) fall from March to June, and short rains (SR) are experienced between October–December; and hence, two cropping seasons in a calendar year. The mean temperature ranges yearly from 19 to 21 °C [24]. Kangutu is 1458 m above sea level and is situated within Upper Midland 2 (UM 2) agroecological zone (main coffee growing zone) [25]. A pre-visit to the study site revealed goat manure and *Tithonia diversifolia* as the most readily available organic manure that are utilized by farmers to manage soil fertility. Smallholder farmers in the region also retain maize stubble after harvest and mostly practice intercropping of cereals with legumes. These technologies have been recommended as sustainable strategies for improving soil fertility and their availability within the locality makes them easily adaptable by the farmers [26,27].

2.2. Experimental design and management

The experiment was established as a Randomized Complete Block Design with treatments replicated four times. The treatments involved combining conventional (CT) and minimum (MT) tillage systems with soil fertility amendments (SFAs) (Table 2). The trials were conducted for eleven (11) cropping seasons in a maize-based (*Zea mays* L., H516 variety) cropping system. Maize was sown and managed following standard agronomic practices such as weeding, pests, and disease control. A detailed description of amendments application, planting, and crop management are provided by Kiboi et al. [28]. Soil management involved plowing to 20 cm depth using a hand hoe in CT, while MT involved surface scrabbing using a machete to clear the debris and digging 20 cm deep planting holes. Manure and *Tithonia diversifolia* were incorporated into planting holes two weeks before planting, while inorganic fertilizers were applied at planting. Maize residue was surface applied at the rate of 5 t ha^{-1} soon after crop emergence.

Phosphorus was applied at 90 kg P per cropping season as P_2O_5 based on the recommended P rate for a maize crop. Inorganic fertilizer (NPK 17:17:17) was the inorganic P source and was supplemented with Triple Superphosphate (TSP) (0:46:0) to attain a rate of 90 kg P ha^{-1}. Additionally, goat manure (1.75 % N and 0.39 % P) and *Tithonia diversifolia* (0.75 % N and 0.30 % P), and rock phosphate (27:29 % total P_2O_5, 36:38 % CaO) were the organic P sources.

Table 1
Soil physicochemical properties before implementation of the experiment [28].

Soil parameter*	Value
Total N (%)	0.14
Total carbon, C (%)	1.48
Soil organic matter (%)	2.55
Total P (g kg^{-1})	29.35
Available P (g kg^{-1})	0.02
Iron, Fe^{3+} (ppm)	32.53
pH (1:1H_2O)	4.85
Clay (%)	70
Sand (%)	16
Silt (%)	14
Textural class	Clay

pH (1:1, soil: H2O), and texture were determined using Kjeldahl, modified Walkley and Black wet oxidation, Mehlich 3, atomic absorption spectrophotometry, pH meter, and hydrometer methods, respectively.
*Soil samples were collected from 0 to 20 cm depth using Eijkelkamp Gouge Auger. Total N, C, available P, Fe2+.

Table 2
Fertility management technologies implemented during the trial.

Tillage system	Soil fertility amendments (SFAs)	Combined treatment	kg P ha^{-1}	P source(s)
Conventional	No amendments (Control)	C	0 kg	None
Conventional	Inorganic fertilizer	CTF	90 kg	NPK 17:17:17
Conventional	Maize residue + Inorganic fertilizer	CTCrF	90 kg	NPK 17:17:17
Conventional	Maize residue + Inorganic fertilizer + Goat manure	CTCrGF	45 kg + 45 kg	Manure + NPK 17:17:17
Conventional	Maize residue + *Tithonia diversifolia* + Rock phosphate (RP)	CTCrTiR	45 kg + 45 kg	*Tithonia diversifolia* + RP
Conventional	Maize residue + Goat manure + Dolichos intercrop	CTCrGL	90 kg	Manure
Conventional	Maize residue + *Tithonia diversifolia* + Goat manure	CTCrTiG	45 kg + 45 kg	*Tithonia diversifolia* + manure
Minimum	No fertility amendments	MT	0 kg	None
Minimum	Inorganic fertilizer	MTF	90 kg	NPK 17:17:17
Minimum	Maize residue + Inorganic fertilizer	MTCrF	90 kg	NPK 17:17:17
Minimum	Maize residue + Inorganic fertilizer + Goat manure	MTCrGF	45 kg + 45 kg	Manure + NPK 17:17:17
Minimum	Maize residue + *Tithonia diversifolia* + Rock phosphate (RP)	MTCrTiR	45 kg + 45 kg	*Tithonia diversifolia* + RP
Minimum	Maize residue + Goat manure + Dolichos intercrop	MTCrGL	90 kg	Manure
Minimum	Maize residue + *Tithonia diversifolia* + Goat manure	MTCrTiG	45 kg + 45 kg	*Tithonia diversifolia* + manure

2.3. Soil sampling, P fractionation, and P efficiencies determination

Approximately 50 g of soil samples were randomly collected at 0–20 cm depth immediately after maize harvesting and processed for laboratory analyses. Organic (Po) and inorganic (Pi) fractions were sequentially determined based on the sequestration method [29]. One gram (1 g) of soil was emptied into 50-ml centrifuge tubes containing 30 ml of distilled water. One resin strip was added to each tube and shaken overnight for 16 h on an end-to-end shaker. The strips were removed after shaking and gently submerged in distilled water thrice to wash the soil off. The strips were then immersed into centrifuge tubes containing 20 ml of 0.5 M HCl and shaken for 1 h. After Resin-Pi extraction, the soil suspensions were centrifuged at 2500 rpm for 10–15 min, and phosphates were then sequentially extracted using the following extractants; (a) 30 ml of 0.5 M $NaHCO_3$ at pH 8.5 for Pi, (b) 30 ml of 0.1 M NaOH for Fe.Al–P extraction, (c) 20 ml 0.1 M NaOH for NaOH-sonic Pi, and (d) 30 ml of 1 M HCl for Mg.Ca–P extraction. The soil suspensions were shaken overnight for 16 h after extraction of each P fraction. Organic P fractions were calculated as the difference between each extract's total phosphorus (TP) and inorganic P (Pi). Residual P was determined according to Brookes and Powlson's [29] method by H_2SO_4 + H_2O_2 + $MgCl_2$ digestion. The P concentration in each extract was determined by the molybdenum blue method at the wavelength of 882 nm.

Phosphorus adsorption isotherms were determined based on the method by Graetz & Nair [30] and Yan et al. [4] where 3.0 g air-dried soil samples were equilibrated in 50-ml centrifuge tubes filled with 30 ml of 0.01 M $CaCl_2$ solution containing H_2PO_4–P concentrations of 0, 10, 20, 30, 40, 50 and 60 P mg L^{-1}. Two to three drops of chloroform were added to every centrifuge tube to impede microbial activity. After this, the tubes were shaken for 30 min daily for six days. On the 6th day, the solutions were filtered using Whatman No. 542 filters, and the P contained in the solution was determined colorimetrically using a spectrophotometer at 880 nm.

The sorbed P (S') removed from the solution was calculated as the difference between the concentration of soluble P added in the original solution and the concentration of P in the solution at equilibrium. The Langmuir equation was used to describe soil P adsorption because the equation provides vital information about the constant k (related to the P bonding energy) and the maximum P sorption capacity. The linearized Langmuir model was determined using Equation (1).

$$\frac{C_e}{S}=\frac{C_e}{S_{max}}+\frac{1}{KS_{max}} \tag{1}$$

Where C_e and S denote the concentration of P in the equilibrium solution (mg L^{-1}) and the total quantity of sorbed P (mg kg^{-1}), respectively, in which $S = S' + So$; S' denotes the sorbed P (mg kg^{-1}) obtained by subtracting final P concentration from the initial P concentration; So is the oxalate-extractable P as an estimate of the initially sorbed P (mg kg^{-1}) P; k (L mg^{-1} P) is a constant associated to the bonding energy [4].

Each treatment's degree of P saturation (DPS) was calculated using Equation (2).

$$DPS=\frac{P_{ox}}{S_{max}}\ x\ 100\% \tag{2}$$

Where P_{ox} denotes oxalate-extractable P concentration (mg kg^{-1}) while S_{max} refers to the maximum P sorption capacity (mg kg^{-1}) derived from equation (1).

Phosphorus partial productivity factor (PPF) and agronomic efficiency (PAE) were determined according to equations (3) and (4), respectively [16].

$$PPF\left(kg\ biomass\ kg^{-1}\ P\right)=\frac{Y_C+\Delta Y_P}{P_{input}} \tag{3}$$

Table 3
Quantitative distributions of soil P fractions among different fertility management technologies.

Treatments[a]	Labile			Moderate labile-P		Less labile		None labile HCl-Pi	Residual P
	Resin-Pi	$NaHCO_3$-Pi	$NaHCO_3$-Po	NaOH-Pi	NaOH-Po	Sonic NaOH-Pi	Sonic NaOH-Po		
	mg P kg^{-1}								
MTCrGF	206.26^{a}	89.74^{a}	23.62^{ab}	417.84^{a}	79.60^{abc}	108.32^{ab}	84.03^{a}	33.81^{ab}	10936.50^{a}
CTCrGF	124.65^{bc}	61.25^{bc}	29.19^{ab}	450.80^{a}	74.20^{abc}	113.76^{a}	44.30^{abcd}	28.36^{abc}	8057.00^{ab}
MTCrF	139.46^{b}	66.74^{b}	28.82^{ab}	449.25^{a}	53.45^{bc}	87.26^{bcde}	52.35^{ab}	24.78^{bcd}	8638.50^{ab}
MTCrGL	$61.89d^{ef}$	17.64^{e}	21.14^{ab}	246.84^{c}	72.15^{abc}	70.99^{e}	47.86^{abc}	23.82^{bcd}	9603.20^{ab}
CTF	107.17^{bcd}	58.75^{bc}	17.14^{ab}	444.66^{a}	38.39^{c}	99.35^{abc}	31.36^{bcd}	14.69^{d}	9259.60^{ab}
CTCrF	124.74^{bc}	56.13^{bc}	19.54^{ab}	421.52^{a}	45.51^{bc}	96.71^{abcd}	44.27^{abcd}	17.87^{cd}	9321.30^{ab}
CTCrTiG	46.05^{ef}	14.11^{e}	14.20^{ab}	240.54^{c}	106.20^{ab}	71.09^{e}	13.33^{bcd}	15.35^{cd}	7642.90^{b}
CTCrGL	75.25^{cdef}	20.67^{e}	13.41^{ab}	259.52^{bc}	55.89^{bc}	75.25^{de}	40.55^{bcd}	18.41^{cd}	8902.80^{ab}
CTCrTiR	77.45^{cdef}	30.11^{de}	43.67^{a}	270.53^{bc}	46.80^{bc}	75.48^{de}	26.74^{bcd}	18.83^{cd}	7766.20^{b}
MTCrTiR	93.23^{bcde}	27.83^{de}	14.74^{ab}	304.03^{bc}	63.16^{bc}	80.08^{cde}	53.12^{ab}	38.61^{a}	9415.20^{ab}
MTF	66.71^{def}	44.55^{cd}	16.73^{ab}	358.36^{ab}	30.95^{c}	71.92^{e}	15.21^{bcd}	14.69^{d}	7616.50^{b}
MTCrTiG	50.73^{ef}	20.59^{e}	17.81^{ab}	239.16^{c}	129.78^{a}	71.37^{e}	12.25^{bcd}	18.53^{cd}	10096.60^{ab}
MT	26.20^{f}	13.66^{e}	7.07^{b}	229.54^{c}	18.99^{c}	69.59^{e}	7.45^{cd}	12.77^{d}	8215.60^{ab}
C	24.35^{f}	13.74^{e}	11.61^{b}	235.16^{c}	29.13^{c}	68.61^{e}	4.52^{d}	14.63^{d}	7465.20^{b}
hsd	*54.79*	*22.07*	*31.38*	*102.40*	*62.61*	*23.83*	*41.56*	*13.42*	*3045.20*
p value	***	***	*	***	***	***	***	***	**

Mean values followed with the same letter(s) within the same column do not differ at $p \leq 0.05$. *$p < 0.0285$, **$p < 0.0035$, ***$p < 0.0001$.

[a] Fertility management technologies; C = Control (no amendments), CTF = Conventional tillage + inorganic fertilizer, CTCrF = Conventional tillage + maize residue + inorganic fertilizer, CTCrGF = Conventional tillage + maize residue + inorganic fertilizer + goat manure, CTCrTiR = Conventional tillage + maize residue + *Tithonia diversifolia* + rock phosphate, CTCrGL = Conventional tillage + maize residue + goat manure + legume intercrop, CTCrTiG = Conventional tillage + maize residue + *Tithonia diversifolia* + goat manure, MT = Minimum tillage + no amendments, MTF = Minimum tillage + inorganic fertilizer, MTCrF = Minimum tillage + maize residue + inorganic fertilizer, MTCrGF = Minimum tillage + maize residue + inorganic fertilizer + goat manure, MTCrTiR = Minimum tillage + maize residue + *Tithonia diversifolia* + rock phosphate, MTCrGL = Minimum tillage + maize residue + goat manure + legume intercrop, MTCrTiG = Minimum tillage + maize residue + *Tithonia diversifolia* + goat manure. $NaHCO_3$-Pi = sodium bicarbonate-extractable inorganic P, $NaHCO_3$-Po = sodium bicarbonate-extractable organic P, NaOH–P = sodium hydroxide-extractable Fe.Al–P, and HCl-Pi = hydrochloric acid-extractable Mg.Ca–P.

$$P\ agronomic\ effieciency\ (PAE)(kg\ biomass\ kg^{-1}\ P) = \frac{(Y_{P\_trt} - Y_C)}{P_{input}} \tag{4}$$

Where Y_C denotes crop yield biomass in control plots; ΔY_P is the increment in biomass yield as a result of P application; P_{input} is the amount of P applied (kg P ha^{-1}); Y_{P_trt} is the crop yield biomass in P-treated plots.

2.4. Statistical analysis

All statistical analyses were performed using R software version 4.1.2 (R Core Team 2021) and subjected to one-way analysis of variance (ANOVA) to determine treatment effect and significant differences between treatments separated using the Tukey post hoc test at $p \leq 0.05$.

3. Results

3.1. Response of P fractions to fertility management technologies

Fertility management (FM) technologies significantly influenced the pattern of P fraction distributions after five years (Table 3). Generally, most P fractions were higher under MTCrGF and CTCrGF, with a few exceptions. Sequential fractionation showed residual P as the largest P fraction, followed by NaOH-Pi, while the lowest was $NaHCO_3$-Po. The residual P was significantly ($p < 0.0035$) higher by 3471 mg kg^{-1} under MTCrGF than under control. Conversely, resin-Pi was the most dominant fraction under the labile P fractions and was significantly ($p < 0.0001$) higher under MTCrGF, MTCrF, CTCrF, CTCrGF, CTF, and MTCrTiR by 182, 115, 100, 100, 83, and 69 mg kg^{-1} than the control. The remaining technologies had a similar impact on Resin-Pi as the control. The second prominent labile P fraction was $NaHCO_3$-Pi which was significantly ($p < 0.0001$) higher under MTCrGF, MTCrF, CTCrGF, CTF, CTCrF, and MTF by 76, 53, 48, 45, 42, and 31 mg kg^{-1} relative to the control. The rest of the technologies were comparable to the control. The lowest labile P fraction was $NaHCO_3$-Po and was only significantly ($p = 0.0285$) impacted by CTCrTiR, causing a 32 mg kg^{-1} increment than the control. Plots under CTCrGF, MTCrF, CTF, CTCrF, MTCrGF, and MTF treatments had the highest (216, 214, 210, 186, 183, and 123 mg kg^{-1}) concentrations of NaOH-Pi than the control. Conversely, only MTCrTiG and CTCrTiG performed exceedingly well, leading to 101 and 77 mg kg^{-1} higher NaOH-Po than the control.

The greatest contributor to a recalcitrant fraction (less labile and none labile P) was sonic NaOH-Pi. It was significantly ($p < 0.0001$) higher by 45, 40, 31, and 28 mg kg^{-1} under CTCrGF, MTCrGF, CTF, and CTCrF than the control. Though the remaining technologies had higher sonic NaOH-Pi, the variations were insignificant compared to the control. Additionally, sonic NaOH-Po was significantly ($p < 0.0001$) higher under MTCrGF, MTCrTiR, MTCrF, and MTCrGL (80, 49, 48, and 43 mg kg^{-1}) than in control. The

Table 4
Mean maximum P sorption capacity (S_{max}), bonding energy (ƙ), and degrees of P saturation (DPS) as influenced by different fertility management technologies.

Treatments[a]	S_{max}	ƙ	DPS
	mg P kg^{-1}	L mg^{-1}	%
MTCrGF	304.94^{a}	0.04^{c}	78.00^{ab}
CTCrGF	301.95^{a}	0.04^{c}	24.62^{gh}
MTCrF	266.71^{b}	0.16^{c}	44.35^{ef}
MTCrGL	276.68^{ab}	0.15^{c}	69.29^{bc}
CTF	259.78^{b}	0.47^{c}	61.38^{cd}
CTCrF	266.71^{b}	0.19^{c}	33.42^{fg}
CTCrTiG	258.10^{b}	0.36^{c}	52.26^{de}
CTCrGL	266.81^{b}	0.17^{c}	41.98^{ef}
MTCrTiR	261.47^{b}	0.25^{c}	46.95^{ef}
CTCrTiR	265.03^{b}	0.20$_{c}$	76.62^{ab}
MTF	258.10^{b}	0.66^{c}	39.00^{ef}
MTCrTiG	266.71^{b}	0.20^{c}	85.74^{a}
MT	255.07^{b}	4.59^{a}	18.40^{h}
C	253.21^{b}	2.57^{b}	19.74^{gh}
hsd	29.71	1.07	13.93
p value	***	***	***

***$p < 0.0001$.

[a] Fertility management technologies; C = Control (no amendments), CTF = Conventional tillage + inorganic fertilizer, CTCrF = Conventional tillage + maize residue + inorganic fertilizer, CTCrGF = Conventional tillage + maize residue + inorganic fertilizer + goat manure, CTCrTiR = Conventional tillage + maize residue + *Tithonia diversifolia* + rock phosphate, CTCrGL = Conventional tillage + maize residue + goat manure + legume intercrop, CTCrTiG = Conventional tillage + maize residue + *Tithonia diversifolia* + goat manure, MT = Minimum tillage + no amendments, MTF = Minimum tillage + inorganic fertilizer, MTCrF = Minimum tillage + maize residue + inorganic fertilizer, MTCrGF = Minimum tillage + maize residue + inorganic fertilizer + goat manure, MTCrTiR = Minimum tillage + maize residue + *Tithonia diversifolia* + rock phosphate, MTCrGL = Minimum tillage + maize residue + goat manure + legume intercrop, MTCrTiG = Minimum tillage + maize residue + *Tithonia diversifolia* + goat manure.

other FM had higher sonic NaOH-Po, but the differences were insignificant to the control. On the other hand, none labile HCl-Pi was greater under MTCrTiR, MTCrGF, and CTCrGF by 24, 19, and 14 mg kg^{-1} relative to the control. Despite recording appreciably high none labile HCl-Pi, exempt MT, the remaining FM had statistically the same labile HCl-Pi as the control.

3.2. Phosphorus sorption characteristics under different FM technologies

Phosphorus sorption parameters were significantly ($p < 0.0001$) impacted by the FM technologies (Table 4). Maximum P sorption (S_{max}) was significantly higher under MTCrGF and CTCrGF by 52 and 49 mg P kg^{-1}, respectively, than under the control. As revealed by the greater ƙ values (the bonding energy), P is highly fixed under the control than in all the other FM technologies, except under MT. Fixation of P was twice higher under MT than under the control. The lowest ƙ was recorded under CTCrGF and MTCrGF, 98 % lower than the control. Compared to the control, ƙ was also significantly lower by 2.42, 2.41, 2.40, 2.38, 2.37, 2.37, 2.32, 2.21, 2.10, and 1.91 L mg^{-1} under MTCrGL, MTCrF, CTCrGL, CTCrF, CTCrTiR, MTCrTiG, MTCrTiR, CTCrTiG, CTF, and MTF. In addition, FM technologies had significantly higher DPS with a 40 % increment on average from the control, apart from CTCrF, CTCrGF, and MT, which did not significantly vary DPS. The highest DPS was recorded under MTCrTiG, which was substantially higher than the control by 66 %.

3.3. Response of aboveground P use efficiencies to FM technologies

Phosphorus use efficiency parameters significantly ($p < 0.0001$) varied among the FM technologies during the two seasons (Fig. 2). The effect of the technologies on PPF (Fig. 2 a and c) and PAE (Fig. 2 b and d) was consistent across the two seasons. The highest P use efficiencies, as indicated by PPF (0.093 and 0.140 kg biomass kg^{-1} P) and PAE (0.080 and 0.073 kg biomass kg^{-1} P) during SR20 and LR21, were observed under CTCrGF. However, PPF (0.043 and 0.078 kg biomass kg^{-1} P) and PAE (0.030 and 0.008 kg biomass kg^{-1} P) were the lowest under MTCrTiR during the two seasons. The lowest PPF (0.045 kg biomass kg^{-1} P) was also recorded under MTCrGL during the SR20 season.

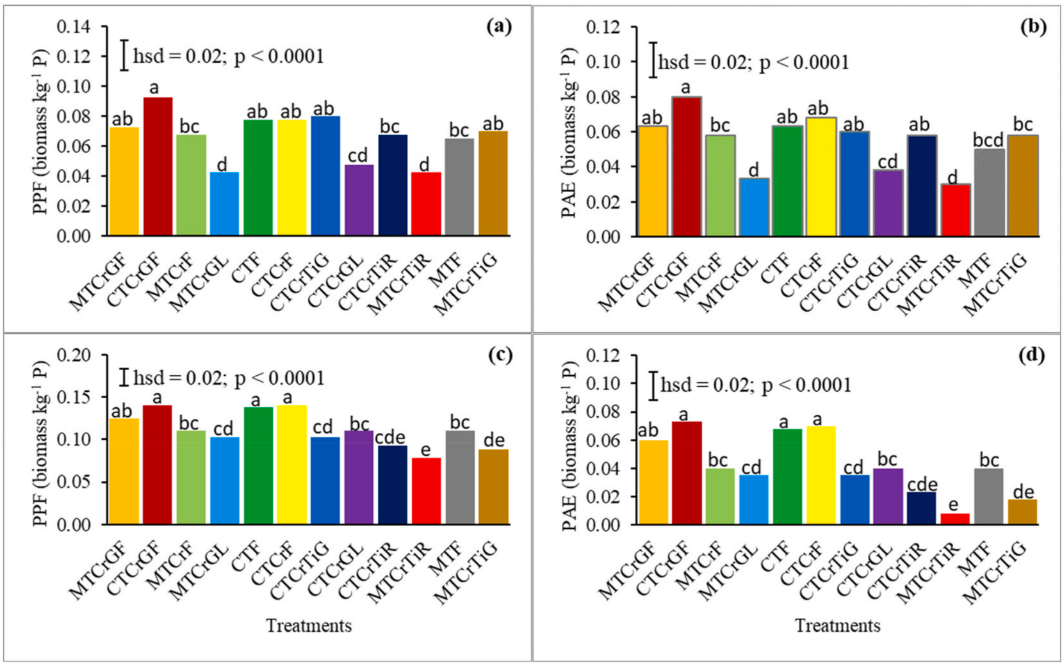

Fig. 2. Mean phosphorus PPF (kg biomass kg^{-1} P) and PAE (kg biomass kg^{-1} P) under different treatments during SR20 (a and b) and LR21 (c and d) cropping seasons, respectively. Means with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues + goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues + goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

3.4. Effect of soil fertility amendments on P fractions and sorption characteristics

Soil fertility amendments (SFAs) significantly ($p < 0.0001$) influenced different P fractions (Table 5) after five years. Different P fractions were higher under the co-application of inorganic fertilizer and goat manure (GF) except for NaOH-Pi and GTi treatment. However, sole inorganic fertilizer (F) application had the highest $NaHCO_3$-Po and NaOH-Pi fractions. On the labile P fractions, GF, F, RTi, and GDi had significantly higher resin-P (155, 123, 67, and 62 mg P kg^{-1}) than the control (Table 5). Also, $NaHCO_3$-Pi was markedly higher under GF, F, and RTi by 62, 52, and 17 mg P kg^{-1} than the control. Nevertheless, it did not differ significantly under GTi and GDi relative to the control. Furthermore, $NaHCO_3$-Po was substantially higher under F, GF, GDi, GTi, and RTi by 16, 12, 8, 7, and 5 mg P kg^{-1} than under the control. The impact of GTi was insignificant but F, GF, RTi, and GDi significantly had higher NaOH-Pi by 237, 235, 34, and 26 mg P kg^{-1} than the control. GTi, GF, GDi, RTi, and F also had significantly higher NaOH-Po by 94, 53, 57, 27, and 34 mg P kg^{-1} than the control.

Similarly, recalcitrant P fractions varied significantly among the treatments. Compared to the control, GF, F, GDi, RTi, and GTi had significantly higher sonic NaOH-Pi (55, 33, 16, 14, and 12 mg P kg^{-1}) and HCl-Pi (22, 9, 9, 8, and 5 mg P kg^{-1}). Apart from GTi, the other amendments (GF, F, RTi, and GDi) had significantly higher sonic NaOH-Po by 54, 40, 40, and 18 mg P kg^{-1} than the control. On the other hand, residual P was significantly higher by 2906, 2479, 2041, 1839, and 1538 mg P kg^{-1} under GF, GTi, RTi, F, and GDi than under the control.

Phosphorus sorption parameters varied significantly ($p < 0.0001$) among the treatments after 11 cropping seasons (Table 6). Generally, GF exhibited the most favorable sorption characteristics (the highest S_{max} and DPS and the lowest k) suitable for P management. Significantly higher S_{max} was recorded under GF and RTi, which was 49 and 35 mg P kg^{-1}, higher than under the control. However, S_{max} did not vary significantly under the remaining SFAs and the control. On the other hand, the bonding energy (k) was significantly lower by 3.54, 3.42, 3.41, 3.35, and 3.30 L mg^{-1} under GF, GDi, F, RTi, and GTi than under the control. Phosphorus was least bonded on soil exchangeable sites under GF, as indicated by the lowest k value. Furthermore, DPS was significantly higher under all the SFAs (GF, GDi, GTi, and RTi) except under F by 3.54, 3.42, 3.41, and 3.35 % than under the control. Notably, F had the least DPS among the SFAs.

3.5. Response of P use efficiencies to fertility amendments

Phosphorus use efficiencies varied significantly ($p < 0.0001$) among the different SFAs during the SR20 season and LR21 seasons (Fig. 3). Partial productivity factor was significantly higher under GF, GTi, and F (0.08, 0.08, and 0.07 kg biomass kg^{-1}, P, respectively) than under RTi (0.06 kg biomass kg^{-1} P) and GMi (0.05 kg biomass kg^{-1} P) during SR20 season (Fig. 3a). During LR21 season, PPF was significantly higher under GF (0.13 kg biomass kg^{-1} P) and F (0.13 kg biomass kg^{-1} P) than the rest of the SFAs (Fig. 3b). On the other hand, GDi (0.12 kg biomass kg^{-1} P) had significantly higher PPF than RTi (0.09 kg biomass kg^{-1} P) which did not vary significantly with GTi (0.10 kg biomass kg^{-1} P). The PAE was significantly higher under GF, F, and GTi (0.07, 0.06, and 0.06 kg biomass kg^{-1} P, respectively) than GDi (0.04 kg biomass kg^{-1} P), which was comparable to RTi (0.04 kg biomass kg^{-1} P) during SR20 season (Fig. 3c). Similarly, GF (0.06 kg biomass kg^{-1} P) and F (0.06 kg biomass kg^{-1} P) had significantly higher PAE than the other SFAs during the LR21 season (Fig. 3d). Conversely, GDi (0.04 kg biomass kg^{-1} P) had significantly higher PAE than RTi (0.02 kg biomass kg^{-1} P) which had a similar performance to GTi (0.03 kg biomass kg^{-1} P) during the same season.

Table 5
Quantitative distributions of soil P fractions in response to various soil fertility amendments (SFAs).

SFAs[1]	Labile P			Moderate labile-P		Less labile		None labile	Residual P
	Resin-Pi	$NaHCO_3$-Pi	$NaHCO_3$-Po	NaOH-Pi	NaOH-Po	Sonic NaOH-Pi	Sonic NaOH-Po	HCL-Pi	
	mg P kg^{-1}								
C	26.15^{e}	12.45^{d}	9.16^{d}	223.35^{c}	22.68^{d}	61.48^{d}	6.05^{d}	12.20^{d}	7165.40^{e}
GF	155.08^{a}	74.25^{a}	21.15^{b}	458.07^{a}	76.15^{b}	116.04^{a}	60.54^{a}	33.83^{a}	10071.73^{a}
GDi	62.32^{cd}	14.03^{d}	17.27^{bc}	249.43^{b}	79.77^{b}	77.50^{c}	23.95^{c}	21.11^{b}	8702.98^{d}
GTi	45.89^{de}	17.35^{d}	16.00^{c}	243.60^{bc}	116.74^{a}	73.74^{c}	12.79^{d}	16.94^{c}	9644.73^{b}
RTi	66.81^{c}	28.97^{c}	14.32^{c}	257.28^{b}	49.98^{c}	75.28^{c}	46.18^{b}	20.34^{bc}	9205.95^{c}
F	122.96^{b}	64.43^{b}	25.43^{a}	460.38^{a}	56.23^{c}	94.48^{b}	46.31^{b}	21.45^{b}	9004.86^{cd}
hsd	20.85	9.71	4.05	25.78	9.58	6.46	6.46	3.50	386.16
p value	***	***	***	***	***	***	***	***	***

[1] Soil fertility amendments (SFAs); C = Control, GF = Goat manure + inorganic fertilizer, GDi = Maize-*Dolichos lablab* intercrop + goat manure, GTi = Goat manure + *Tithonia diversifolia*, RTi = Rock phosphate + *Tithonia diversifolia*, F = Sole inorganic fertilizer. $NaHCO_3$-Pi = sodium bicarbonate-extractable inorganic P, $NaHCO_3$-Po = sodium bicarbonate-extractable organic P, NaOH–P = sodium hydroxide-extractable Fe.Al–P, and HCl-Pi = hydrochloric acid-extractable Mg.Ca–P. Mean values followed with the same letter(s) within the same column do not differ significantly at $p \leq 0.05$. ***$p < 0.0001$.

Table 6
Mean maximum P sorption capacity (S_{max}), bonding energy (ķ), and degrees of P saturation (DPS) as influenced by soil fertility amendments.

Treatments[1]	S_{max}	k	DPS
	mg P kg^{-1}	L mg^{-1}	%
C	254.14^{c}	3.58^{a}	19.07^{c}
GF	303.44^{a}	0.04^{b}	69.00^{a}
GDi	266.72^{bc}	0.16^{b}	61.79^{ab}
GTi	263.25^{bc}	0.28^{b}	51.31^{ab}
RTi	288.86^{ab}	0.23^{b}	55.64^{ab}
F	271.75^{bc}	0.17^{b}	38.88^{bc}
hsd	28.06	0.91	25.55
p value	***	***	***

[1] Soil fertility Amendments (SFA); C = Control, GF = Goat manure + inorganic fertilizer, GDI = Maize-*Dolichos lablab* intercrop + goat manure, GTi = Goat manure + *Tithonia diversifolia*, RTi = Rock phosphate + *Tithonia diversifolia,* F = Sole inorganic fertilizer. S_{max} = Maximum sorption capacity, ķ = bonding energy, DPS = Degrees of phosphorus saturation. Mean values followed with the same letter(s) within the same column do not differ at $p \leq 0.05$.
***$p < 0.0001$.

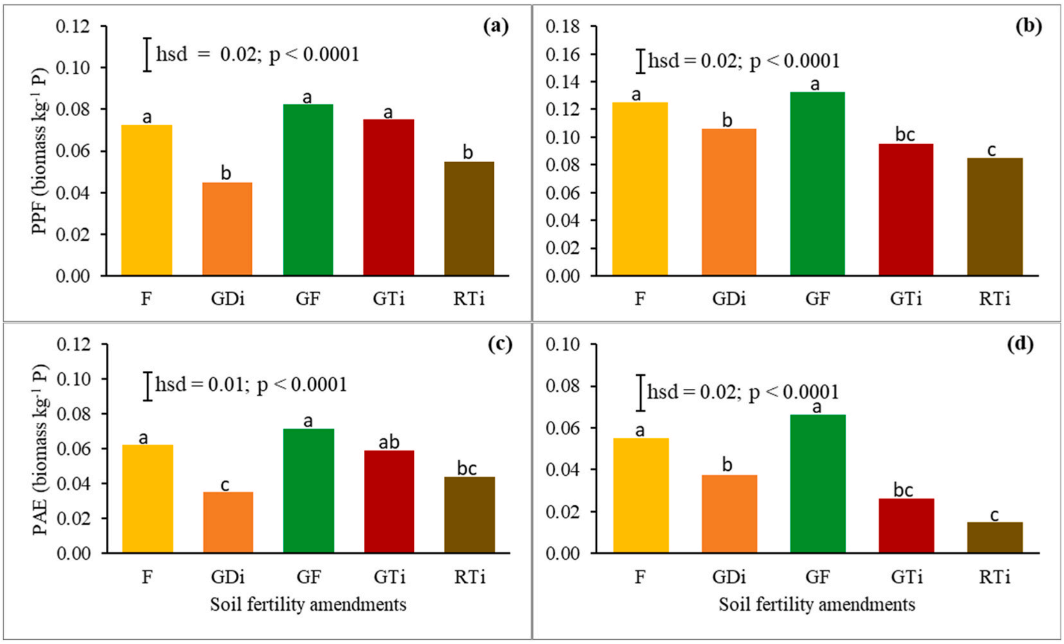

Fig. 3. (a and b) Partial productivity factors (PPF, kg biomass kg^{-1} P) and (c and d) phosphorus agronomic use efficiency (PAE, kg biomass kg^{-1} P) during the SR20 and LR21 seasons, respectively. GF = Goat manure + inorganic fertilizer, GDi = Maize-*Dolichos lablab* intercrop + goat manure, GTi = Goat manure + *Tithonia diversifolia*, RTi = Rock phosphate + *Tithonia diversifolia,* F = Sole inorganic fertilizer. Means with the same superscript letter(s) denote no significant difference at $p < 0.05$; hsd = honestly significant difference pooled error bar.

4. Discussion

4.1. Phosphorus fractions status as influenced by FM technologies

Generally, the distribution of different fractions of P could have been partly influenced by significant relationships between the various fractions (Supplementary Table 1). For instance, sonic NaOH-Po positively correlated with and could have significantly contributed to residual P. Relationships between various fractions have been reported. Mahmood et al. [3] found a positive correlation between residual and NaOH-Pi. Residual P (Table 3) could have also been influenced by long-term fertilization. This finding concurs with the results of Arruda et al. [16], who found residual P to be the largest fraction of total P in Mollisols under long-term cumulative fertilization. The moderately bioavailable NaOH-Pi fraction was equally higher in the studied soil, which could be ascribed to the addition of inorganic P fertilization (NPK and TSP fertilizers) and mineralization from organic amendments [31]. Moreover, the inorganic fertilizer contained substantial amounts of nitrogen (N) and potassium that might have contributed to the moderately bioavailable NaOH-Pi fraction. A similar result was reported by Mahmood et al. [3]. The results of this study support Qiong et al. [32] who found a significant effect of NPK on labile P fractions. The labile $NaHCO_3$-Po could have been mineralized by phosphatase and taken up by the crop explaining the low status of labile $NaHCO_3$-Po in this study. Maize rhizosphere hosts phoC- and phoD-harboring bacterial communities responsible for mineralizing organic P [33]. This could have explained the high NaOH-Pi and low $NaHCO_3$-Po.

Fertility management technologies, MTCrGF and CTCrGF (Table 3), had the highest concentrations of most P fractions. The high concentrations could be ascribed to a high concentration of mineralizable P in goat manure and inorganic fertilizers. This finding agrees with Chen et al. [34], who reported an increased impact of long-term P fertilization on iron and aluminum-bound and soluble P fractions in an orchard. Also, Shi & Ziadi [35] found a similar impact of P fertilization on P fractions under maize-soybean rotation with tillage. Long-term N fertilization could have influenced soil enzymes like acid phosphatase and phosphodiesterase activities, as was also reported by Qaswar et al. [36] under manure and NPK fertilizer co-application, thus, impacting P fractions. In agreement with our findings, Mahmood et al. [3] reported increased different P factions, especially moderate-available P fractions, in response to long-term N fertilization under the Winter wheat cropping system. Still, the co-application of manure and inorganic fertilizer under MTCrGF and CTCrGF could have stimulated synergetic interactions hence the release of P [32], eliciting an increase in some P fractions.

Different P fractions responded indiscriminately under CT and MT systems treated with fertility amendments. This could be attributed to the effects of SFAs on the soil processes, such as biological, physical, and chemical changes that may have triggered the observed positive responses of P fractions in this study. Similar to the findings of this study under CTCrGF, CTF, and CTCrF, Sharma et al. [37] reported significantly higher HCl–P, $NaHCO_3$-Pi, and NaOH-Po fractions under CT and conservation (zero tillage) tillage systems with wheat straw retention. Moreover, inorganic phosphorus fractions (Al–P, Fe–P, Ca–P, and Residual-P) significantly increased under CT treated with biofertilizer for 32 years in a Ferralsol [18], similar to treatments under MT system (MTCrGF, MTCrGL, MTCrTiR, and MTCrTiG) in this study.

4.2. Fractions of P and their distribution in response to FM technologies and SFAs

The higher contents of resin-Pi, $NaHCO_3$-Pi, and NaOH-Pi fractions under amended minimum tillage (MTCrGF, MTCrF, MTCrTiR, and MTF) and conservation tillage (CTCrF, CTCrGF, and CTF) could be explained by the application of SFAs (Table 5) that provided readily available inorganic P (NPK and TSP fertilizers) and easily mineralizable P (goat manure and *Tithonia diversifolia*). These findings vindicate the results of a previous study that found the response of P fractions to inorganic and organic fertilization under contrasting tillage systems [31,32]. The higher resin-Pi under MTCrTiR can be attributed to the nexus between *Tithonia diversifolia* and rock phosphate (slow P-releasing fertilizer) under a minimum tillage system. Similarly, the higher content of the readily mineralizable $NaHCO_3$-Po under CTCrTiR can be ascribed to the interaction of *Tithonia diversifolia* and rock phosphate under the conventional tillage system. This finding may be because *Tithonia diversifolia* could have released organic compounds that hastened the solubilization of rock phosphate [38]. The higher concentration of moderately labile NaOH-Po) under MTCrTiG and CTCrTiG underpins the synergic interaction between organic amendments with different nutrient concentrations in the mineralization processes [39]. Furthermore, co-application of NPK and manure, as was under CTCrGF and MTCrGF, also had significantly higher labile P fractions ($NaHCO_3$-Pi and NaOH-Pi) in a Black soil under continuous maize cropping in a study conducted by Yan et al. [4].

The higher recalcitrant fractions of sonic NaOH-Pi and HCl-Pi could be attributed to the low soil pH (Supplementary Fig. 1). Maharjan et al. [40] and Mahmood et al. [3] attributed increased P sorption to low soil pH due to high concentrations of Al^{3+} and Fe^{3+}. The significant increase in sonic NaOH-Pi under CTCrGF, MTCrGF, CTF, and CTCrF), and HCl-Pi under MTCrTiR, MTCrGF, and CTCrGF (Tables 3 and 5) could be linked to long-term N transformation which probably led to enhanced protonation during nitrification process [41]. These results corroborate the findings of Sun et al. [42], who opined that N fertilization lowered soil pH, leading to low labile Pi but high recalcitrant Pi under the maize cropping system in Mollisols. Moreover, goat manure, *Tithonia diversifolia*, and inorganic fertilizers used in this study supplied P that could have also contributed to the high recalcitrant P fractions. This finding agrees with the results of Yan et al. [4] who also reported a positive response of recalcitrant fractions to P fertilization.

The enhanced recalcitrant sonic NaOH-Po under an amended minimum tillage system (MTCrGF, MTCrTiR, MTCrF, and MTCrGL) can be attributed to increased stable soil organic matter (SOM) contributed by organic amendments applied (Table 5). A previous study reported stable SOM reported under a minimum tillage system [43]. Similar to the findings of this study, Cao et al. [44] reported increased recalcitrant NaOH-Po under maize stover retention co-applied with NPK. The higher residual P under MTCrGF probably was due to the transformation of P fractions (from stover residues, goat manure, and inorganic fertilizer), resulting in a build-up of residual P and occluded within soil micro-aggregates. Phosphorus added mainly as soluble Pi often precipitates as Al and Fe phosphate in acidic soils while insoluble P forms, such as from organic amendments, physicochemically stabilize into SOM complexes [43,44].

4.3. Phosphorus sorption characteristics under different FM technologies

The fertility amendments contained multiple nutrients which increased soil organic matter (SOM) through biomass production (Supplementary Fig. 2) and could have influenced P sorption characteristics. This finding corroborates the results of Debicka et al. [45], who reported the importance of SOM on P desorption and sorption processes. The high S_{max} recorded in the soil under the current study indicates that the soil has high sorption surfaces and can retain more P [46].

The S_{max} under MTCrGF and CTCrGF (Table 4) and GF and RTi (Table 6) could be attributed to the direct and indirect effect of inorganic fertilizer and organic amendments that possibly increased SOM. Yang et al. [46] found a positive correlation between SOM and S_{max}. Soil organic matter increases S_{max} by creating extra sorption sites [45]. Also, continuous application of inorganic fertilizers for five years under MTCrGF, CTCrGF, and GF could have stabilized soil pH through the buffering effect of organic amendments resulting in increased P sorption. Consistent with this finding, Nobile et al. [19] found significantly higher S_{max} after a decade of inorganic fertilizer application in an Andosol.

The lowest bonding energy (ķ) under FM technologies and SFAs (Tables 4 and 6) may have resulted from P saturation caused by continuous P application because as DPS increases, soil sorption sites decrease [4]. Thus, additional P may have been loosely held by the lowest binding affinity (ķ). The current study found that k is inversely related to DPS and S_{max} (Supplementary Table 2). Similarly, Debicka et al. [45] reported an inverse relationship between ķ and DPS in sandy soil. Furthermore, the FM technologies (CTCrGF, CTCrGL, CTCrTiR, CTCrTiG, MTCrGF, MTCrGL, MTCrTiR, and MTCrTiG) and SFA (GF, GDi, RTi, and GTi) that contained organic amendments could have exudated carboxylates and low molecular organic compounds blocking adsorption sites, therefore, increasing P availability (Arruda et al., 2019; Maharjan et al., 2018) which could have explained the low ķ and high DPS values in this study. These findings agree with Bhattacharyya et al. [47], who found low ķ and significantly higher DPS under NPK + manure treatment. Similar to treatments with manure (MTCrGF and MTCrTiG), Shafqat & Pierzynski [48] found higher S_{max} and lower k when NT was amended with manure compared to CT. However, improved P sorption characteristics in treatments with conventional tillage system (CTCrGF, CTF, CTCrF, CTCrTiG, CTCrGL, and CTCrTiR) agrees with the findings of Fink et al. [49]. The highest ķ under MT can be ascribed to improved soil aggregates under a minimum tillage system [50] that could have enhanced contact between amorphous Fe and Al with soil P leading to strong fixation [51]. Phosphorus sorption relates with soil proprieties thus, soils with high contents of clay and Al, such as the Nitisols in this study, could experience a low P lixiviation [52].

4.4. *Fertility management technology-induced P use efficiency parameters*

The observed response of PUE to the treatments could have been influenced by P reactions, retention, and mobility [47]. The FM technologies and SFAs that enhanced the retention and mobility of labile P fractions probably were also responsible for the improved PUE [53]. Rainfall variability may have also influenced PUE as it was higher during short rains where maize yield was constrained by low rainfall than during long rains. This finding concurs with a study by Pavinato et al. [54], where maize PUE was greater in a year when low rainfall restricted maize yield. Nevertheless, PAE in this study (Figs. 2 and 3) is slightly below the global average PAE (12.4 %) for cereals [55], indicating a great potential to still improve PUE even after five years of P fertilization.

The recorded high PAE and PPF may be attributed to the labile Pi fractions (Tables 3 and 6) that could have improved P availability for crop uptake and utilization [53], leading to increased biomass production (Supplementary Fig. 2). Also, the P addition could have explained the response of the two PUE parameters. This finding agrees with the results of Caspersen & Bergstrand [56], who reported enhanced PAE of poinsettia and chrysanthemum under P fertilization. Still, N inputs through the application of inorganic and organic amendments may be credited for the significantly higher PAE and PPF, particularly under CTCrGF (Fig. 2) and SFAs (GF, GTi, and F; Fig. 3). Effect of N addition on PAE and PPF has also been reported by Zhang et al. [21]. With a possible abundance of phosphatase within the maize rhizosphere [33], the enzyme could have facilitated the decomposition of organophosphates from organic amendments, thus increasing PAE and PPF. Additionally, there may have been an interactive effect between the released humic acids during the decomposition and P addition (under treatments that combined inorganic fertilizer and organic amendments) that could have enhanced P availability and PUE [57].

The slowly solubilized P under MTCrTiR and RTi could have been quickly immobilized, thus restricting P uptake and utilization by the crop resulting in low PUE [56]. Maize-*Dolichos lablab* under GDi could have improved soil enzyme activity under limited P conditions [58] during adequate rainfall (LR21 season), thus the significantly higher PUE. Pang et al. [59] also elaborated on the importance of legume crops on P acquisition and use efficiency. However, the activity of P-solubilizing enzymes may have been suppressed by low soil moisture [60] relating to low rainfall received during the SR20 season, explaining the low PUE under GDi.

5. Conclusion

The results demonstrate that soil FM technologies and SFAs resulted in large amounts of residual P and NaOH-Pi but low $NaHCO_3$-Po concentrations. The FM technologies influenced P fractionation, sorption characteristics, and use efficiencies. The findings of P fractionation illustrate the differential influence of FM technologies on the P fractions. It was evident that combining inorganic fertilizers and organic amendments (CTCrGF, MTCrGF, and GF) triggered the highest S_{max}, DPS, and the least bonding energies. The positive impact of the technologies and SFAs on P fractions corresponded with improved PUE under the same treatments. The study found strong effects of maize-Dolichos intercrop (under CTCrGL, MTCrGL, and GDi) on P fractions and PUE parameters. However, the intercrop was found to improve PUE under good rainfall conditions. Therefore, this work recommends MTCrGF or CTCrGF as the most suitable soil FM technologies to consider in P management to improve PUE and crop productivity in acidic Nitisols. These technologies can increase the labile P concentrations and reduce the potential depletion of the non-renewable rock phosphate and the use of inorganic phosphatic fertilizers for agricultural production.

Additional information

Supplementary content related to this article has been provided as appendices.

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Data availability statement

The raw data related to this study is available online in Mendeley Data on https://doi.org/10.17632/fkvh3dss72.1.

CRediT authorship contribution statement

Erick O. Otieno: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Florence K. Lenga:** Supervision, Writing - review & editing. **David M. Mburu:** Supervision, Writing - review & editing. **Milka N. Kiboi:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Andreas Fliessbach:** Conceptualization, Methodology, Resources, Supervision, Writing - review & editing. **Felix K. Ngetich:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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