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Effects of different soil management strategies on fertility and crop productivity in acidic nitisols of Central Highlands of Kenya

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ABSTRACT

Managing soil fertility, especially nitrogen (N) and phosphorus (P), to sustain increased crop productivity is a complex challenge, especially in cultivated Nitisols. Experiments were conducted over eleven (11) cropping seasons in the acidic Nitisols to assess the impact of soil management strategies on soil N, P, and crop productivity. Fourteen treatments were laid out in a Randomized Complete Block Design. The treatments include; control (C), conventional tillage + inorganic fertilizer (CTF), conventional tillage + maize residues + inorganic fertilizer (CTCrF), conventional tillage + maize residues + inorganic fertilizer + goat manure (CTCrGF), conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate (CTCrTiR), conventional tillage + maize residues+ goat manure + *Dolichos lablab* (CTCrGL), conventional tillage + maize residues + *Tithonia diversifolia* + goat manure (CTCrTiG), minimum tillage (MT; no amendments), minimum tillage + inorganic fertilizer (MTF), minimum tillage + maize residues + inorganic fertilizer (MTCrF), minimum tillage + maize residues + inorganic fertilizer + goat manure (MTCrGF), minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate (MTCrTiR), minimum tillage + maize residues+ goat manure + *Dolichos lablab* (MTCrGL), and minimum tillage + maize residues + *Tithonia diversifolia* + goat manure (MTCrTiG). Available P was significantly higher by 51, 48, 43, 38, 37, 36 and 27% under MTCrGF, CTCrGF, MTCrF, CTF, CTCrF, MTCrGL, and CTCrTiG than the control. Available soil N was significantly higher (59, 59, 59, 57, 57, 57, 55, 55, 55, 50, and 50%) under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, CTF, MTCrTiG and MTCrGF compared to the control. Grain radiation use efficiency was significantly higher under CTCrGF, MTCrF, CTCrTiR, CTF, MTCrTiG, CTCrF, MTCrGF, CTCrTiG, and MTCrTiR than the control by 95, 93, 93, 93, 92, 92, 92, 91 and 88% during the SR2020 cropping season. In the LR2021 season, it was significantly higher under CTCrGL, MTCrGL, CTCrGF, CTF, MTCrGF, CTCrF, MTF, MTCrF, MTCrTiG, MTCrTiR, CTCrTiG and CTCrTiR than the control by 80, 79, 78, 77, 77, 74, 73, 72, 70, 67, 66 and 62%. Grain yield was significantly higher under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTF, CTCrTiG, and CTCrTiR than the control in the SR2020 season by 95, 93, 93, 93, 92, 92, 92, 92 and 88%. During LR2021, CTCrGF recorded the highest grain yield, which was 74% higher than the control, while CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had higher yields than the control by 73, 71, 70, 69, 69, 66, 65, 64, 58, 55 and 49%. Overall, CTCrGF, CTCrGL, MTCrGF, and MTCrGL had a comparative advantage regarding soil fertility and crop productivity in acidic Nitisols, strongly illustrating the concept of 'complementarity' in integrated soil fertility management.

1. Introduction

Declining soil fertility, primarily nitrogen (N) and phosphorus (P) is the most serious problem facing crop productivity in Kenya and sub-Saharan Africa (SSA) at large. Overreliance on rainfed agriculture by smallholder farmers and degraded soil fertility greatly contribute to the low crop productivity in SSA. As a result, cereal production in SSA is less than 2.0 t ha^{-1} compared to 5.0 and 8.0 t ha^{-1} in Asia and Latin America (Epule & Bryant, 2015). It is estimated that farmers under rainfed agriculture risk a reduction in crop yields by 50% in the next 30-35 years if

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the soil fertility problem is not urgently addressed (Dube et al., 2016). Improving soil fertility through integrated soil management strategies (SMSs) is thus critical to obtaining higher crop yield per unit of land area per raindrop.

Researchers have proposed numerous soil N and P management strategies in different soil types and climatic conditions. For instance, Cao et al. (2021) and Zhang et al. (2021) proposed the integration of residue and inorganic fertilizer, while the sole application of inorganic fertilizer has been promoted in various studies (e.g., Gautam et al., 2020; Jabborova et al., 2021; Phares et al., 2021). Organic amendments such as manure and *Tithonia diversifolia* have also been shown to improve soil N and P (Agbede and Oyewumi, 2022; Bonanomi et al., 2020; Cai et al., 2019; Dubey et al., 2022; Opala, 2020). Other strategies, like the application of rock phosphate and intercropping cereals with legumes, have also been shown to have tremendous potential to improve soil N and P (Biswas et al., 2022; Costa et al., 2021; Husnain et al., 2014; Madembo et al., 2020; Mupangwa et al., 2021). However, smallholder farms are heterogenous, and farmers are endowed with different resources (Tittonell et al., 2005). It is, thus, important to harness and integrate different resources to meet crop nutrient requirements in such farms.

Integration of SMSs offers a great opportunity to adapt to local conditions and improve soil fertility and crop productivity (Mugwe et al., 2019; Vanlauwe et al., 2015). Combined inorganic fertilizers and organic amendments improve soil fertility and nutrient use efficiency leading to high crop productivity (Han et al., 2021; Lian et al., 2022; Qaswar et al., 2020). Recent short-term studies that combined: maize residue, *Tithonia diversifolia,* and rock phosphate (CrTiR); maize residue, goat manure, and maize-*Dolichos lablab* intercrop (CrGL) and, maize residue, *Tithonia diversifolia* and goat manure (CrTiG) reported increased maize yield and improved soil fertility in both on-farm and on-station experiments (Kiboi et al., 2020; Oduor et al., 2021; Otieno et al., 2021). Mupangwa et al., 2012) suggested that the gains of integrating soil fertility amendments on soil fertility are short-term, a claim refuted by Vanlauwe et al. (2010; 2014). Integrating inorganic fertilizers and manure reduces the cost of purchasing inorganic fertilizers and improves nutrient use efficiency (Vandeplas et al., 2010). Combining *Tithonia diversifolia* and rock phosphate aid in solubilizing rock phosphate and making P available to plants (Rusaati et al., 2020). Long-term evaluation of such integrated SMSs provides critical soil fertility improvement information and broadens our understanding of the integrated soil fertility management concept.

Most smallholder farmers practice conventional tillage (CT), which allegedly impacts negatively on soil properties. Consequently, there has been heightened promotion of conservation tillage in the recent past. Nevertheless, Pittelkow et al. (2015) called for increased research on conservation tillage systems before they are recommended to farmers. From past studies, the effect of conservation tillage systems on soil nutrients and crop productivity continues to draw controversies (Ahmed et al., 2020; Chalise et al., 2020; Komissarov & Klik, 2020; Naeem et al., 2021; Zhang et al., 2021). Further, the impact of tillage on soil N, P, and crop productivity is unclear amid the unreliable and highly variable rainfall. Thus, assessing the influence of applying various soil fertility amendments under both CT and minimum tillage (MT) on fertility and crop productivity could provide smallholder farmers with an array of SMSs to cope with climate change and the availability of resources.

The global food demand will increase by more than 70% by 2050 (Mueller et al., 2012). This demand will partially be met through crop intensification (Tilman et al., 2011). However, to maximize agronomic inputs in such a production system, future crop yield increases will have to focus on improving the efficiency with which fertility amendments, rainfall water, and radiation are utilized (Mustafa et al., 2021). Radiation use efficiency (RUE) and water productivity (WP; crop yield per unit water utilized by the crop) are reduced when crop growth is constrained by soil nutrients and water (Teixeira et al., 2014). Inorganic fertilizers, organic amendments, rock phosphate, legumes and/or integrated SMSs could sustain adequate nutrient and crop water demand to improve RUE and WP and achieve high yields (Ali et al., 2018; Him et al., 2019; Teixeira et al., 2014). Oduor et al. (2021) reported high water retention under CrTiR, CrGL, and, CrTiG, which explained the improved WP. Similarly, high water and nutrient retention explained the improved RUE reported in other studies (Bonelli and Andrade, 2020; Gao et al., 2010; Srivastava et al., 2019). Understanding how resource use efficiencies respond to different SMSs is crucial in maximizing crop yields (Teixeira et al., 2014). This understanding could set a benchmark for evaluating and improving future crop production systems that balance crop productivity and resource use efficiencies.

Table 1
Initial soil physicochemical properties (Kiboi et al., 2018)

Soil chemical parameter*	Value
Total N (%)	0.14
Total carbon, C (%)	1.48
Available P (g kg^{-1})	0.02
Exchangeable Mg^{2+} (cmol^{+} kg^{-1})	1.17
Exchangeable potassium, K^{+} (cmol^{+} kg^{-1})	0.45
Exchangeable calcium, Ca^{2+} (cmol^{+} kg^{-1})	2.53
Iron, Fe^{3+} (ppm)	32.53
Copper, Cu^{2+} (ppm)	4.66
Manganese, Mn^{2+} (ppm)	1.89
pH	4.85
Clay (%)	70
Sand (%)	16
Silt (%)	14
Textural class	Clay

*Soil samples were collected in March 2016 during long rains from 0-20 cm depth using Eijkelkamp Gouge Auger.

Maize is a popular cash and staple food crop for 90% of the population in Kenya (Jaetzold et al., 2007; Ochieng et al., 2016). However, its production is greatly affected by N and P deficiencies and water scarcity (Ngetich et al., 2022). The study hypothesized that integrated SMSs influence soil fertility and maize productivity in acidic Nitisols under the rainfed production system. Therefore, the objective of this study was to determine the impact of selected SMSs on soil N, P, and maize productivity in the acidic Nitisols under a long-term trial established in the Central Highlands of Kenya.

2. Materials and methods

2.1. Site description

The experiment was established at Kangutu Primary School (00° 98′S, 37° 08′E) in Tharaka-Nithi County, located in the Central Highlands of Kenya (Fig. 1). rainfall in the region ranges from 1200-1400 mm annually in a bimodal pattern of long rains (March–June) and short rains (October– December). Daily rainfall and radiation in the site for the experimental period are shown in Fig. 2. The annual mean temperature is 20°C, while the predominant soil type is *Humic Nitisols* (Jaetzold et al., 2006). The soil is typically deep and highly weathered, characterized by moderate to high inherent fertility. Initial soil properties are shown in Table 1.

2.2. Experimental design

The experiment was laid out in a randomized complete block design (RCBD) for 11 cropping seasons. Tillage system and soil fertility amendments were integrated and considered as combined treatments, as shown in Table 2. The treatments were replicated four times in plots measuring 6 m x 4.5 m. Maize (*Zea mays* L.) H516 variety was the test

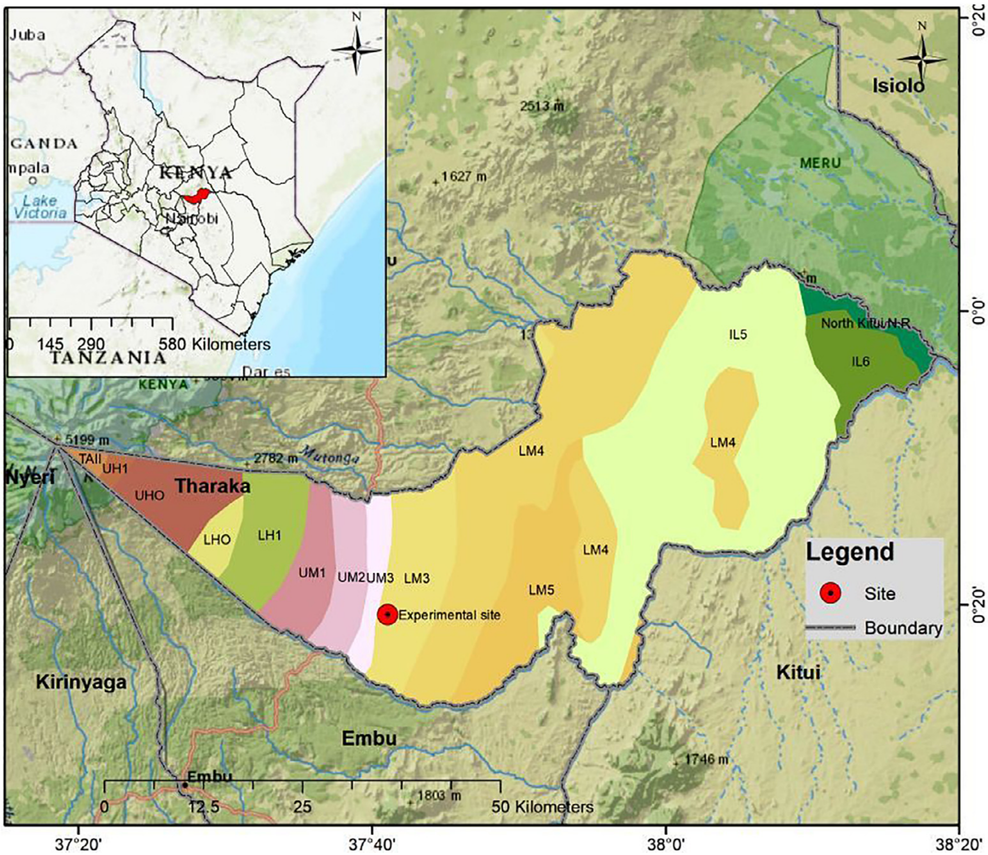

Fig. 1. The study map showing Chuka sub-county, site and agroecological zones

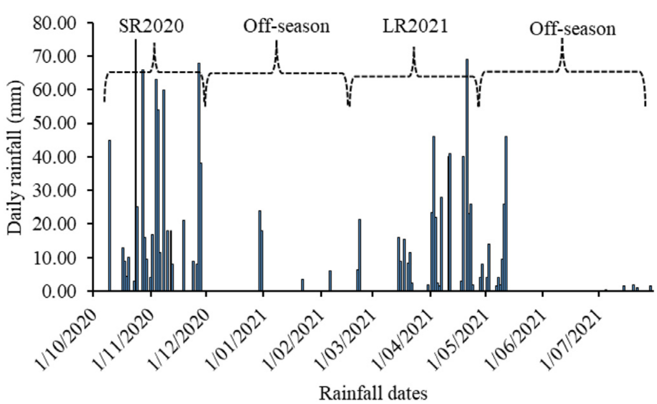

Fig. 2. Daily rainfall amount received during SR2020 and LR2021 seasons

Table 2
Treatment combinations implemented

Tillage system	Soil fertility amendments (SFAs)	Combined treatment
Conventional	No amendments (Control)	C
Conventional	Inorganic fertilizer	CTF
Conventional	Maize residue + inorganic fertilizer	CTCrF
Conventional	Maize residue + inorganic fertilizer + goat manure	CTCrGF
Conventional	Maize residue + *Tithonia diversifolia* + rock phosphate	CTCrTiR
Conventional	Maize residue + goat manure + legume intercrop	CTCrGL
Conventional	Maize residue + *Tithonia diversifolia* + goat manure	CTCrTiG
Minimum	No amendments	MT
Minimum	Inorganic fertilizer	MTF
Minimum	Maize residue + inorganic fertilizer	MTCrF
Minimum	Maize residue + inorganic fertilizer + goat manure	MTCrGF
Minimum	Maize residue + *Tithonia diversifolia* + rock phosphate	MTCrTiR
Minimum	Maize residue + goat manure + legume intercrop	MTCrGL
Minimum	Maize residue + *Tithonia diversifolia* + goat manure	MTCrTiG

crop in the experiment. The experiment was established in March 2016 during the long rains (LR2016) season. The data was collected during the short rains of 2020 (SR2020) and the long rains of 2021 (LR2021).

Seedbed preparation under the MT system involved digging only the planting holes to a depth of 10 cm while the entire plot was tilled using a hand hoe to a depth of 20 cm under the CT system. Two weeks before planting, organics amendments were placed in planting holes under MT but applied uniformly under CT and incorporated into the soil by ploughing. Inorganic fertilizers were applied at planting. Nitrogen was applied at the rate of 120 kg N ha^{-1} annually (Fertilizer Use Recommendation Project (FURP, 1987) through inorganic fertilizers and organic amendments. Inorganic fertilizers were applied as NPK 17:17:17 and rock phosphate. Triple superphosphate (TSP) supplied the additional 60 kg P yearly to all treatments with inorganic fertilizer to ensure P is not limiting. Organic amendments were goat manure and *Tithonia diversifolia*. They were analyzed for N content, and an amount equivalent to 60 kg N ha^{-1} by dry weight was calculated. From the laboratory results, goat manure had 1.75% N and 0.39% P) while *Tithonia diversifolia* had 3.80% N and 0.30% P. *Tithonia diversifolia* aboveground biomass was cut at the active vegetative stage, chopped into smaller pieces, and incorporated into the soil the same day it was cut (biomass transfer). Nutrient application rates were halved in plots that received a combination of inorganic and organic, while full rates were applied in sole inorganic fertilizer and sole organics plots.

2.2.1. Planting and crop management

Maize was planted at 0.75 m and 0.50 m, inter-, and intra-spacing, respectively. Three (3) seeds were placed per hole and thinned back to two (2) seedlings after full emergence. *Dolichos lablab* was planted in the middle of the inter-rows of maize on the same day as maize under the intercrop treatments (CTCrGL and MTCrGL). *Dolichos lablab* was mainly used as a source of nutrients rather than a farming system; thus, its yield was not within the scope of this study. Five (5) t ha^{-1} of maize residue was surface-applied after thinning (Kiboi et al., 2019). Topdressing was done in all plots with inorganic fertilizer using calcium ammonium nitrate (CAN) when the crop reached knee-height. Weeding was done twice a season by rogueing and hand hoe under minimum and conventional tillage systems, respectively. The plots were kept free from diseases and pests by constant surveillance and applying pesticides.

2.3. Data collection and laboratory analysis

2.3.1. Soil sampling and laboratory analysis

Soil samples were randomly collected at a depth of 0-20 cm in each plot at the end of the trial period (LR2021 season). Available soil N and P were extracted following Kjeldahl and Bray2 methods, respectively. Both N and P extracted were determined colorimetrically using a spectrophotometer according to Okalebo et al. (2002). Legacy P was calculated as the difference between available soil P at the end of the study and initial soil P at the start of the experiment. Core ring soil samples were collected at the start and end of the cropping season for bulk density determination. Soil moisture content (SMC) was determined at the start and end of each cropping season. Both bulk density and SMC were determined gravimetrically. Gravimetric SMC (%) was converted to volumetric SMC (m^3/m^3) as shown in equation 1;

$$\text{Volumetric SMC (m3/m3)} = \left(\frac{\text{Gravimetric SMC (\%)}}{100}\right) \text{x bulk density x depth (m)} \tag{1}$$

2.3.2. PAR, LAI, and relative chlorophyll content determinations

Plant growth parameters (relative chlorophyll content, leaf area index (LAI), photosynthetically active radiation (PAR), and height) were determined at the 6th leaf stage and 10th leaf stage (Kiboi et al., 2019). Relative chlorophyll content was determined using a SPAD-502Plus® meter (Konica Minolta Optics, Inc., Japan). The readings of relative chlorophyll were taken from the leaves of four (4) middle-tagged plants in the two middle rows (2 plants per row) and averaged. Photosynthetically active radiation and LAI were determined using LP-80 linear ceptometer (Decagon Devices, Pullman, WA). Ceptometer readings were taken from midpoints between rows to the middle of adjacent rows to take into consideration row and inter-row canopy effects (Johnson et al., 2010). Three readings per plot were taken and averaged. The ceptometer was placed above the crop canopy and below the canopy at 10 cm above the ground level and at a 90° angle to the orientation of the plant rows. The measurements were recorded during sunny, cloudless times of the sampling days, and caution was taken to avoid the researcher's shadow covering any part of the ceptometer. Before taking each below-canopy measurement, a calibration factor (cf) was taken (Johnson et al., 2010). The fraction of PAR incepted by the plant was calculated as in equation 2. Plant height was determined using a tape measure.

$$\text{PAR} = \frac{PAR_b}{cf PAR_a} \tag{2}$$

Where PAR is the actual PAR while PAR_a and PAR_b are above and below canopy respectively and *cf* represents the calibration factor.

2.3.3. Maize yield determination

Maize was harvested manually from net plots measuring 21 m^2. Net plots were determined by discarding the first rows to eliminate edge effects. Cobs were separated from the maize stover, and grains were shelled by hand. Grain moisture content was determined at harvest using a Dickey-John MiniGAC® moisture meter. Grains and cobs (separated) were sun-dried for seven days, and moisture content (MC) was determined. Grain weight at the prevailing MC after drying was corrected using a 12.5% equivalence factor and extrapolated to per hectare (ha) basis. Stover yield was determined at harvest, and the total dry matter yield was determined as the summation of grain, cobs weight, and stover weights, and also extrapolated to ha basis.

2.3.4. Calculation of crop water productivity, measurement of rainfall, and solar radiation

Crop water r productivity (WP) was defined as the amount of maize yield produced per unit of water consumed (Cook et al., 2018);

$$\text{WP} = \frac{Maize\ yield\ \left(kg\ ha^{-1}\right)}{Consumptive\ water\ use\ \left(E_t\right)} \tag{3}$$

The water balance equation (4) was used to estimate E_t as adopted by Oduor et al. (2021);

$$E_t = (R + I + C) - \left(S_r + D\right) - \Delta S \tag{4}$$

Where E_t is evapotranspiration; R is cumulative rainfall received in a season; *I* is irrigation water; C is upward flux from the water table; S_r is surface runoff; D is deep percolation and ΔS = soil moisture changes with time within the rooting zone or soil profile.

All the plots were fairly flat; thus, no runoff (S_r) losses were experienced. Moreover, the study was purely under rainfed agriculture; hence no irrigation (*I*) was done. The soils at the site are deep and well-drained, with a deep groundwater table. Therefore, upward fluxes (C) were assumed to be insignificant. Deep percolation (D) out of the rooting zone of the crop/soil profile in question was not observed as per the amount of rainfall received and the frequency of the same during the seasons. Water productivity calculation was therefore reduced to equation 5 (Pereira et al., 2012);

$$WP = \frac{above\ ground\ yield}{E_t = R - \Delta S} \tag{5}$$

Daily rainfall readings were obtained from a manual rain gauge installed approximately 20 m from the experimental site. The rainfall readings were recorded daily at 0900 hours. Daily solar radiation from 1/10/2020 to 30/06/2021 was downloaded from the National Aeronautics and Space Administration (NASA) website (https://power.larc.nasa.gov/data-access-viewer/). Longitude (37.6833) and latitude (-0.33849) coordinates were used to specify the exact location. File named 'All Sky Surface Shortwave Downward' was downloaded from 'Solar fluxes and related' folder.

2.3.5. Radiation use efficiency

Radiation use efficiency was calculated as adopted by Kaur et al. (2012):

$$\text{Fraction of PAR intercepted by plants (fPAR)} = 1 - \left(\frac{PAR_b}{PAR_a}\right) \tag{6}$$

$$\text{Intercepted PAR } (iPAR) = Incident\ PAR\ x\ fPAR \tag{7}$$

$$RUE = \frac{Aboveground\ yield\ \left(Mg\ h^{-1}\right)}{iPAR} \tag{8}$$

Where aboveground yield is grain or stover yield and *i*PAR is the fraction of radiation intercepted by the plant as calculated in equation 6 above. PAR_a and PAR_b represent above and below-ground PAR, respectively

2.4. Data analysis

Soil and maize yield data were subjected to analysis of variance (ANOVA) using R software version 4.1.2 (R Core Team, 2021) to test the model effect. Levene and Shapiro-Wilk tests were used to confirm the homogeneity of variances and normality assumptions. Where the model effect was significant, treatment means were separated using Tukey's honestly significant difference at $\alpha \leq 0.05$ significance level. The mean differences in soil available N at the beginning and the end of the trials were analyzed by the Student paired t-test at $\alpha \leq 0.05$.

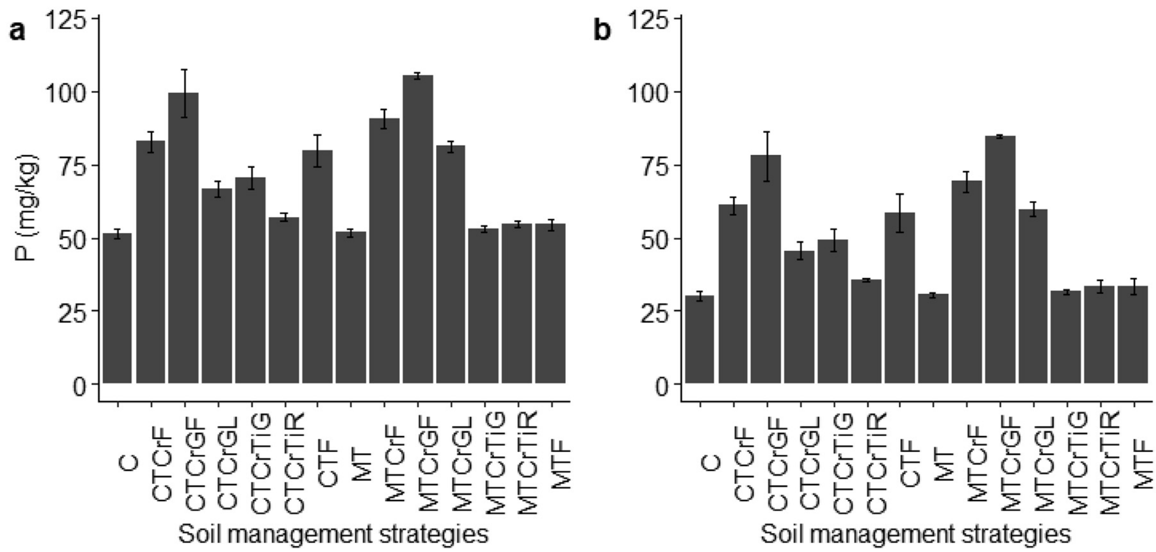

Fig. 3. a) Available P and b) legacy P under SMSs after 11 cropping seasons

3. Results and discussions

3.1. Legacy phosphorus and available phosphorus

The SMSs had significant ($p < 0.0001$) effects on available and legacy P (Fig. 3). Available P was the highest under MTCrGF. Generally, it was significantly higher by 64, 61, 56, 51, 50, 48 and 39% under MTCrGF, CTCrGF, MTCrF, CTCrF, MTCrGL, CTF, and CTCrTiG compared with the control (Fig. 3a). Similar amounts of available P were observed under MTCrGF, CTCrGF, and MTCrF. Also, differences in available P under MTCrGL, CTF, and CTCrTiG were insignificant. The other six SMSs had comparable available P to the control. Similarly, legacy P was the highest under MTCrGF. Also, significantly higher legacy P by 51, 48, 43, 38, 37, 36, and 27% under MTCrGF, CTCrGF, MTCrF, CTF, CTCrF, MTCrGL, and CTCrTiG relative to the control (Fig. 3b) was observed. However, it showed no variations under MTCrGF, CTCrGF, and MTCrF. No significant differences in legacy P were observed among CTF, CTCrF, MTCrGL, and CTCrTiG. Conversely, legacy P under MTCrGF and CTCrGF varied significantly from amounts recorded by CTF, CTCrF, MTCrGL, and CTCrTiG. The remaining SMSs had similar available P to the control.

The significant increase in available and legacy P under MTCrF, MTCrGF, CTCrF, CTCrGF, and CTF (Fig. 3) was explained by P addition from both inorganic fertilizers, residue retention and organic inputs (Asrade et al., 2022; Otieno et al., 2021). Legacy P was enhanced by the application of inorganic P from NPK and TSP, as was also reported by Somavilla et al. (2021). Also, inorganic P fertilization could have increased the mineralization of P from goat manure (Kiboi et al., 2020) by lowering the carbon (C) to P (C:P) ratio and promoting activities of litter-decomposing microorganisms (Jia et al., 2022). Similarly, Shafqat & Pierzynski (2013) reported significantly higher residual P in soil treated with animal manure. Similar to the observation by Musyoka et al. (2017), goat manure used in this study contained high P content (0.39%), which could have explained the high legacy and available P. Residue retention under the strategies could have additionally activated P-related enzymes leading to increased available P (Cao et al., 2022). Improved soil N and P under combined inorganic fertilizer and manure have also been reported by other researchers (Ahmad et al., 2018; Blanchet et al., 2016; Brunetti et al., 2019).

Low soil pH is a primary problem in the current study site which is associated with low P due to fixation. Increased soluble organic substances under organic inputs (MTCrGL and CTCrTiG) could have raised soil pH, chelated exchangeable acidity, and increased desorption of phosphates hence improving the concentration of available P in the soil solution (Zhang et al., 2021). Furthermore, *Dolichos lablab* has an extensive rooting system that can capture and redistribute N to topsoil (Arruda et al., 2021) hence the significantly higher legacy and available P under MTCrGL. Similarly, the legume crop probably responded to low soil P by enhancing mycorrhizal associations and phosphatase activity, thereby increasing available P (Arruda et al., 2021; Hallama et al., 2019).

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 (no amendments), 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. The error bars are standard error bars.

The low P status under CTCrTiR, MTCrTiG, and CTCrGL could be explained by the release of organic acids from the organic amendments (residues, *T. diversifolia,* and manure) that promoted solubility of phosphorus and the subsequent P uptake by maize evidenced by the higher yield (Table 7). Nutrient mining through crop harvest contributes to low soil P (Asrade et al., 2022). Moreover, Nitisols are acidic and contain hydroxides and oxides of aluminum and iron, which strongly fix P (Werner et al., 2017), which could explain the low available P under MTF.

3.2. Available soil N

There was a significant treatment effect on available soil N at the end of the experiment (Table 3). The highest available N was observed under CTCrF, which was 65% higher than the control and differed significantly from the other SMSs. Significantly higher N (59, 59, 59, 57, 57, 57, 55, 55, 55, 50, and 50%) than the control was also recorded under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, CTF, MTCrTiG and MTCrGF. The differences in N among MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, and CTF were insignificant. However, it did not vary significantly among CTCr-

Table 3
Available and change in N under various SMSs at the end of experimentation

SMSs [(1)]	N (%)	Change	t value	Pr > |t|
MTCrF	0.21[bc] [(2)]	0.07[bc]	7.67	0.0046
MTCrGF	0.18[d]	0.04[c]	8.08	0.0040
MTCrGL	0.22[b]	0.08[b]	11.97	0.0013
MTCrTiG	0.18[cd]	0.04[c]	13.66	0.0008
MTCrTiR	0.21[b]	0.07[b]	8.72	0.0032
MT	0.11[e]	-0.03[d]	-5.65	0.0110
MTF	0.20[bcd]	0.06[bc]	13.35	0.0009
CTCrF	0.26[a]	0.12[a]	26.59	0.0001
CTCrGF	0.20[bcd]	0.06[bc]	9.03	0.0029
CTCrGL	0.22[b]	0.08[b]	25.31	0.0001
CTCrTiG	0.21[bcd]	0.07[bc]	6.54	0.0073
CTCrTiR	0.22[b]	0.08[b]	9.24	0.0027
C	0.09[e]	-0.06[d]	-11.1	0.0016
CTF	0.20[bcd]	0.05[bc]	13.17	0.0009
hsd [(3)]	0.03	0.03	na [(4)]	na
p values	***	***	na	na

[(1)] SMSs = soil management strategies; 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 (no amendments), 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,

[(2)] values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,

[(3)] hsd = honestly significant difference

[(4)] not applicable, *** $p < 0.0001$.

TiG, MTF, CTCrGF, CTF, MTCrTiG, and MTCrGF. Though MT did not differ from the control, the variation between it and other SMSs was significant.

The SMSs resulted in a significant change in available N (Table 3). Apart from MT, changes in available N under the SMSs at the end of the experiment were significantly greater than the change in the control. The greatest positive change in N was observed under CTCrF, which was 300% greater than the change showed under the control. On average, SMSs recorded a positive change in N by 214%. The changes under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, and CTF were not significantly different but were higher than the changes under MTCrGF and MTCrTiG. Nitrogen declined by 160% under MT but did not differ with the reduction of 183% under the control.

Goat manure and *T. diversifolia* applied contained substantially high mineralizable N concentrations (1.7% and 3.80% N, respectively), which could be associated with the recorded increase in N under CTCrGL, CTCrTiG, CTCrGF, CTCrTiR, MTCrGL, and MTCrTiR. Cattle manure has been reported to be rich in mineral and organic elements that can improve soil nutrients (Zhang et al., 2021). Therefore, the application of manure-containing SMSs may explain the improved available soil N in the intra- and inter-treatments at the end of the experiment (Table 3). Application of inorganic fertilizer (NPK at planting and top-dressing using CAN) could be the cause of the high available N and the resultant changes under CTF, CTCrGF, MTF, MTCrF, and MTCrGF. This finding agrees with the previous study by Uwah & Eyo (2014). The low C: N ratio of *T. diversifolia* promotes rapid decomposition of the organic input to release N into the soil solution (Nchuaji & Ajebesone, 2022) whereas goat manure combined with residue retention could have induced N-related enzyme activity leading to the release of available N as was also reported by Tayyab et al. (2018).

Moreover, the significant increase in N recorded under *Dolichos lablab* SMSs (MTCrGL and CTCrGL) was attributed to biological fixation (Palmero et al., 2022). Also, the experimental site was affected by high soil acidity and low inorganic N; hence the legume crop could have responded to the N stress by recycling and remobilizing N, partially altering root distribution and nodulation capacity (Zheng et al., 2022), resulting to increased N in the topsoil.

3.3. Maize growth parameters

The treatments recorded significant variations in relative chlorophyll and LAI in all phenological stages (Table 4). During SR2020 season, the highest chlorophyll was recorded under CTCrF and was 38% to 61% significantly higher under SMSs compared to the control at the 6th leaf stage. Apart from CTCrF and CTF, chlorophyll differences under the remaining SMSs were insignificant. At the 10th leaf stage, MTCrF, CTCrF, CTCrGF, CTF, CTCrTiG, and CTCrGL had significantly higher chlorophyll than the control by 37, 36, 33, 32, 31, and 30%. The highest chlorophyll was recorded under MTCrF, which also performed exceedingly well than MTCrTiR and MT. High chlorophyll was also recorded under MTCrTiG, MTCrGF, MTF, CTCrTiR, MTCrGL, MTCrTiR and MT, though it did not vary significantly to chlorophyll in the control. The leaf area index at the 6th leaf stage was the highest under CTCrGL (68%) and also significantly higher under MTCrGL, CTCrF, MTCrGF, and CTCrGF by 67, 60, 49, and 48% relative to the control. However, the leaf area index under MTCrGL and CTCrF was comparable to CTCrGL. It was also high under MTF, CTF, MTCrF, CTCrTiG, MTCrTiG, MTCrTiR, and CTCrTiR but was similar to LAI under the control. At the 10th leaf, LAI was greater by 59% and 49% under CTCrGF and MTCrGF compared to the control. The remaining SMSs had a similar LAI as the control.

The treatments also significantly affected chlorophyll content and LAI during LR2021 season (Table 4). At the 6th leaf stage, the highest chlorophyll was recorded under MTF, which was 31% more than under the control. Chlorophyll was also significantly higher under CTF and MTCrGL than the control by 25 and 23%. However, there was no significant increase in chlorophyll under the remaining strategies compared to the control. The highest chlorophyll at the 10th leaf stage was under CTF, which was also a 31% improvement from the control. Also, CTCrGF, MTF, CTCrF, and MTCrGL had significantly higher chlorophyll than the control by 28, 27, 27, and 21% at the same growth stage. The differences in chlorophyll under the remaining strategies and the control were insignificant. At the 6th leaf stage, the highest LAI was recorded under MTCrGL and CTCrGL, representing a 66% and 65% increase from the control. The leaf area index was also significantly higher under MTCrGF, MTCrF, and MTCrTiR than the control by 46, 44 and 39%. Conversely, insignificant differences in LAI under the other strategies compared to the control were recorded. At the 10th leaf stage, the greatest LAI resulted from CTCrGL and MTCrGL, which was 72 and 69% higher than the control. Significantly higher LAI was also observed under MTCrGF, MTCrF, MTF, CTCrGF, MTCrTiG, CTCrF, and CTCrTiG (51, 51, 50, 48, 41, 39, and 38%) compared to the control. However, it was significantly lower under CTF, CTCrTiR, MTCrTiR, and MT compared to CTCrGL and MTCrGL but was comparable to the control.

The high chlorophyll recorded under the various SMSs was partly attributed to N fertilization from inorganic (NPK and CAN) under CTF, CTCrGF, MTF, MTCrF and MTCrGF, and organic (manure and *Tithonia diversifolia*) amendments under CTCrGL, CTCrTiG, CTCrGF, CTCrTiR, MTCrGL and MTCrTiR. Consistent to the current findings, Skudra & Ruza (2017) reported higher chlorophyll content of Winter wheat fertilized with NPK. Moreover, Kiboi et al. (2019) reported significantly higher chlorophyll at the 6th leaf stage under N inputs. However, the low relative chlorophyll under MTCrGL at 10th leaf during SR2020 and CTCrGL at the 6th and 10th leaf during LR2021 could be attributed to interspecific competition for the biologically fixed N between maize and

Table 4
Relative chlorophyll content and LAI at 6th and 10th leaf stages under different SMSs during the SR2020 and LR2021 seasons

SFM [(1)]	SR2020				LR2021			
	Relative chlorophyll		LAI		Relative chlorophyll		LAI	
	6th leaf	10th leaf	6th leaf	10th leaf	6th leaf	10th leaf	6th leaf	10th leaf
	SPAD values		m^{2} m^{-2}		SPAD values		m^{2} m^{-2}	
MTCrF	34.97^{bcd}	44.57^{a} [(2)]	1.34^{bcd}	2.10^{c}	35.98^{abcd}	41.25^{abcde}	1.37^{bc}	2.82^{bc}
MTCrGF	32.00^{cd}	39.08^{abcd}	1.46^{bc}	2.18^{c}	35.65^{abcd}	39.85^{abcde}	1.42^{b}	2.84^{b}
MTCrGL	33.60^{bcd}	33.87^{abcd}	2.24^{a}	4.12^{b}	37.73^{abc}	42.25^{abcd}	2.27^{a}	4.49^{a}
MTCrTiG	34.50^{bcd}	39.13^{abcd}	1.12^{cd}	2.59^{c}	32.73^{bcd}	36.90^{def}	1.25^{bcd}	2.35^{bcde}
MTCrTiR	31.03^{cd}	32.70^{bcd}	1.01^{cd}	2.35^{c}	34.18^{abcd}	35.00^{def}	1.26^{bc}	1.92^{def}
MT	30.28^{d}	29.80^{cd}	0.72^{d}	2.58^{c}	29.30^{d}	30.93^{f}	0.94^{cd}	1.86^{ef}
MTF	37.73^{bcd}	38.13^{abcd}	1.38^{bcd}	2.43^{c}	42.07^{a}	45.90^{abc}	1.25^{bcd}	2.77^{bc}
CTCrF	47.97^{a}	43.63^{ab}	1.84^{ab}	2.28^{c}	35.70^{abcd}	45.63^{abc}	1.08^{bcd}	2.29^{bcde}
CTCrGF	38.37^{bc}	41.93^{ab}	1.42^{bc}	2.49^{c}	36.77^{abcd}	46.25^{ab}	1.11^{bcd}	2.69^{bcd}
CTCrGL	33.75^{bcd}	40.23^{abc}	2.29^{a}	5.10^{a}	32.25^{bcd}	41.08^{abcde}	2.20^{a}	5.00^{a}
CTCrTiG	34.83^{bcd}	40.63^{abc}	1.14^{cd}	2.63^{c}	35.40^{abcd}	37.47^{cdef}	1.06^{bcd}	2.26^{bcde}
CTCrTiR	32.68^{cd}	36.60^{abcd}	1.00^{cd}	2.11^{c}	30.05^{cd}	38.08^{abcde}	1.08^{bcd}	2.03^{cdef}
C	18.73^{e}	28.10^{d}	0.74^{d}	2.10^{c}	29.23^{d}	33.47^{ef}	0.77^{d}	1.39^{f}
CTF	40.80^{ab}	41.58^{ab}	1.35^{bcd}	2.12^{c}	38.95^{ab}	48.28^{a}	1.06^{bcd}	2.07^{bcdef}
hsd [(3)]	7.49	11.67	0.68	0.90	8.13	8.46	0.48	0.80
p value	***	***	***	***	***	***	***	***

(1) SMSs = soil management strategies; 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 (no amendments), 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,

(2) values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,

(3) hsd = honestly significant difference, *** $p < 0.0001$.

the legume (Gong et al., 2021). Leaf area index is a consequence and determinant of critical vegetation canopy processes (Parker, 2020) regulated by N. Therefore, the higher LAI under this study could be attributed to N input through CTF, CTCrF, CTCrGF, CTCrGL, CTCrTiG, CTCrTiR, MTF, MTCrF, MTCrGF, MTCrGL, MTCrTiG, and MTCrTiR. This finding vindicates Villa et al. (2017) and Zhang et al. (2018), who reported significantly improved LAI in various crops at different phenological stages, e.g., in *Solanum tuberosum* L. under N and P deposition from manure, NPK and TSP.

There were significant variations in PAR and RUE among the treatments (Table 5). During the SR2020 season, the highest PAR (76%) was recorded under MTCrGF compared to the control at the 6th leaf stage. Similarly, MTCrF, CTF, CTCrTiG, CTCrGF, CTCrGL, CTCrTiR, MTF, CTCrF, MT, MTCrTiR and MTCrTiG had significantly higher PAR by 75, 75, 74, 74, 72, 70, 68, 67, 65, 64 and 57% compared to the control. However, MTF, CTCrF, MT, MTCrTiR, and MTCrTiG significantly differed from the best-performing SMS (MTCrGF) but did not vary significantly under MTCrGL and the control. At the 10th leaf, PAR was significantly higher under MTCrTiR, CTCrTiR, MTCrGL, CTCrGL, CTF, MTCrTiG, MTCrF, MTF, and CTCrTiG by 50, 50, 49, 48, 47, 45, 43, 40 and 40%. Only MTCrGF, CTCrGF, MT, and CTCrF recorded statistically the same PAR as the control. Apart from MT, PAR was between 52% to 73% higher under the other SMSs than under the control during the LR2021 season at the 6th leaf. In the same season, PAR was between 27% to 43% higher under the SMSs, apart from MT, compared to the control at the 10th leaf stage. Significant higher PAR was also recorded under CTCrF, CTF, MTCrGL, and CTCrGL than under MTCrF and MTCrTiR.

Grain RUE was significantly higher under CTCrGF, MTCrF, CTCrTiR, CTF, MTCrTiG, CTCrF, MTCrGF, CTCrTiG, and MTCrTiR than the control by 95, 93, 93, 93, 92, 92, 92, 91 and 88% during SR2020. However, it did not differ under CTCrGL, MTF, MTCrGL, and MT relative to the control. In LR2021, grain RUE was significantly higher under CTCrGL, MTCrGL, CTCrGF, CTF, MTCrGF, CTCrF, MTF, MTCrF, MTCrTiG, MTCrTiR, CTCrTiG, and CTCrTiR than the control by 80, 79, 78, 77, 77, 74, 73, 72, 70, 67, 66 and 62%. Apart from MT, SMSs had between 74% to 88% significantly higher stover RUE relative to the control during SR2020. In LR2021, there was a significant increase in stover RUE by 63, 62, 59, 57, 54, 53, 51, 44, 43, 42, 34, and 33% under CTF, CTCrF, CTCrGF, MTCrGF, CTCrGL, MTCrGL, MTF, CTCrTiG, MTCrF, CTCrTiR, MTCrTiG and MTCrTiR compared to the control.

Photosynthetically active radiation and RUE are closely related and are important in determining crop yields (Shi et al., 2022; Wang et al., 2015). An optimum biomass accumulation, accentuated by soil fertilization, allows maize to intercept and effectively use solar radiation (Yan et al., 2022). Therefore, the observed higher PAR and RUE may be attributed to higher biomass accumulation (Table 7) supported by nutrients addition from CTCrGF, CTCrGL, CTCrTiG, CTCrTiR, MTCrGF, MTCrGL, MTCrTiG and MTCrTiR. Zhang et al. (2021) reported high PAR in rice under high N, P and K fertilization rates in China. Similar to CTF, CTCrF, MTF and MTCrF, Singh et al. (2017) also reported the highest PAR in maize 60 days after planting under NPK application. Radiation use efficiency depends on the intercepting surface (leaf) which is affected by fertilization and water use efficiency. Cosentino et al. (2016) reported high RUE in giant reed (*Arundo donax* L.) under increased water availability and N fertilization in a semi-arid Mediterranean area. Consistent to the impact of CTCrGL and MTCrGL in the current study, maize-soybean intercrop significantly enhanced RUE under Eutric Cambisol in Shangqiu (Gao et al., 2010). Additionally, residue retention and organic inputs under CTCrTiG, CTCrGF, CTCrTiR, MTCrTiG and MTCrTiR in the current study could have conserved soil moisture for a longer duration causing improved resource-use efficiency (Parihar & Nayak 2019) hence the higher RUE. Conversely, the observed insignificant effect of CTCrGL and MTCrGL, and MTF and MT on RUE could also be attributed to interspecific P competition under

Table 5
PAR and RUE under different SMSs during the SR2020 and LR2021 seasons

SFM [(1)]	SR2020				LR2021			
	PAR (μ mol m^{-2})		RUE (kg MJ^{-1})		PAR (μ mol m^{-2})		RUE (kg MJ^{-1})	
	6^{th} leaf	10^{th} leaf	Grain	Stover	6^{th} leaf	10^{th} leaf	Grain	Stover
MTCrF	0.36^{ab} [(2)]	0.63^{ab}	0.43^{ab}	1.19^{ab}	0.33^{b}	0.62^{c}	0.86^{cdef}	2.04^{cde}
MTCrGF	0.38^{a}	0.50^{bcd}	0.36^{bc}	1.14^{b}	0.37^{b}	0.68^{bc}	1.03^{abcd}	2.67^{ab}
MTCrGL	0.15^{ef}	0.71^{a}	0.13^{de}	0.68^{de}	0.45^{ab}	0.74^{ab}	1.15^{ab}	2.49^{bcd}
MTCrTiG	0.21^{de}	0.66^{a}	0.37^{bc}	1.17^{ab}	0.41^{b}	0.66^{bc}	0.79^{def}	1.77^{e}
MTCrTiR	0.25^{cd}	0.72^{a}	0.25^{bcd}	0.73^{cd}	0.60^{a}	0.62^{c}	0.73^{ef}	1.73^{e}
MT	0.26^{cd}	0.46^{cd}	0.06^{de}	0.36^{ef}	0.15^{c}	0.44^{d}	0.15^{g}	0.80^{f}
MTF	0.28^{bcd}	0.60^{abc}	0.16^{de}	1.15^{ab}	0.44^{b}	0.72^{abc}	0.89^{cde}	2.37^{bcd}
CTCrF	0.27^{bcd}	0.43^{d}	0.37^{bc}	1.14^{b}	0.47^{ab}	0.79^{a}	0.92^{bcde}	3.07^{a}
CTCrGF	0.34^{abc}	0.47^{bcd}	0.57^{a}	1.49^{a}	0.37^{b}	0.71^{abc}	1.10^{abc}	2.81^{ab}
CTCrGL	0.32^{abc}	0.69^{a}	0.20^{cde}	1.04^{bc}	0.43^{b}	0.74^{ab}	1.21^{a}	2.52^{bc}
CTCrTiG	0.35^{abc}	0.60^{abc}	0.35^{bc}	1.32^{ab}	0.44^{b}	0.66^{bc}	0.71^{ef}	2.07^{cde}
CTCrTiR	0.30^{abcd}	0.72^{a}	0.43^{ab}	1.37^{ab}	0.46^{ab}	0.71^{abc}	0.63^{f}	2.00^{de}
C	0.09^{f}	0.36^{d}	0.03^{e}	0.18^{f}	0.16^{c}	0.45^{d}	0.24^{g}	1.16^{f}
CTF	0.36^{ab}	0.68^{a}	0.41^{ab}	1.20^{ab}	0.47^{ab}	0.78^{ab}	1.05^{abc}	3.10^{a}
hsd [(3)]	*0.10*	*0.16*	0.19	0.34	0.15	0.12	0.25	0.51
p values	***	***	***	***	***	***	***	***

[(1)] SMSs = soil management strategies; 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 (no amendments), 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,

[(2)] values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,

[(3)] hsd = honestly significant difference, *** $p < 0.0001$.

the intercrop treatment and fixation under sole inorganic fertilizer application. This finding corroborates the results of the study conducted by Salvagiotti et al. (2017).

The strategies significantly affected plant height except at the 6^{th} leaf stage during the SR2020 season (Table 5). In SR2020, the tallest plants resulted from TillCrGF and was similar to MTCrGF and MTCrGL at the 10^{th} leaf stage. Plants under these SMSs were significantly taller than those in the control by 55, 54 and 52%. The heights of plants under CTCrF, CTCrGL, CTCrTiR, CTCrTiG, CTF, MTCrF, MTCrTiG and MTCrTiR similarly increased by 52, 50, 49, 48, 47, 46, 45 and 44% relative to the control. Plants under MTF and MT were not statistically taller compared to the control but they were significantly shorter than under CTCrGF, MTCrGF and MTCrGL. In the LR2021 season, only MTCrF and MTCrGL had significant (30 and 29%) taller maize plants at the 6^{th} leaf relative to the control. Apart from MT, maize height in the other SMSs did not differ with those under MTCrF and MTCrGL, and the control. At the 10^{th} stage during LR2021, maize under MTCrF, CTCrGL, CTCrGL, CTCrGF, MTCrGF, CTCrTiR, CTF, and MTCrTiG at the 10^{th} leaf stage was taller than under the control by 39, 36, 33, 31, 28, 24, 20 and 20%. However, maize height in MTF, CTCrF, MTCrTiR, CTCrTiG and MT did not vary significantly to the control.

The rapid growth rate observed under the various SMSs in the study was attributed to N, P and K fertilization that promoted active vegetive growth by stimulating growth hormones (Yue et al., 2022). As noted by Liu et al. (2021), plant growth occurs in meristematic cells of the internodes, in which P plays a critical role. In the current study, fertilization by NPK 17:17:17 under CTF, CTCrF, CTCrGF, MTCrF, and MTCrGF probably provided K, which could have promoted the growth of meristematic tissues and key in N metabolism leading to taller maize crops. Furthermore, the enhanced growth under organic-based amendments (CTCrGL, CTCrTiG, MTCrGL, and MTCrTiG) could be attributed to improved soil P (Fig. 3) and N (Table 3). This finding confirms the results of previous studies that recorded rapid crop growth under organic amendments (Abd El-Mageed et al., 2018; Manirakiza and Şeker 2020; Yousaf et al., 2021). Moreover, a similar effect of rock phosphate on maize height as under CTCrTiR and MTCrTiR in the this study, was reported by Kaur and Reddy (2015).

3.3. Maize yield

Grain and stover yields were significantly affected by the SMSs during SR2020 and LR2021 seasons ($p< 0.0001$; Table 7). Grain yield was significantly higher under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTF, CTCrTiG, and CTCrTiR than under the control in SR2020 season by 95, 93, 93, 93, 92, 92, 92, 92 and 88%. However, the yields under MTF, CTCrGL, MTCrGL and MT did not vary significantly with the yield in the control. During LR2021, apart from MT, the SMSs significantly affected grain yield. Similarly, CTCrGF recorded the highest grain yield, which was 74% higher than the control. The other SMSs; CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had higher yields than the control by 73, 71, 70, 69, 69, 66, 65, 64, 58, 55 and 49%. Conversely, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR and CTCrTiR had significantly lower grain yield than the best performing SMS (CTCrGF).

Compared to the control, SMSs had a higher stover yield than the control during SR2020 and LR2021. During SR2020, stover yield was the highest under CTCrGF, which was 88% higher than in the control. Stover yield was also significantly higher under CTCrF, CTF, CTCrTiG, MTCrGF, MTCrF, MTCrTiG, CTCrTiR, MTF, CTCrGL, MTCrGL and MTCrTiR by 85, 85, 85, 84, 84, 84, 83, 83, 76, 73 and 73% relative to the control. However, CTCrGL, MTCrGL and MTCrTiR had significantly lower yields than the best-performing SMSs. Compared to the control, only MTCrTiR and MT did not significantly increase the yield during LR2021. The yield was significantly higher by 51, 51, 50, 46, 38, 37, 37, 34, 32, 25, 23, 39% under CTCrF, CTCrGF, CTF, MTCrGF, MTF, MTCrF, CTCrGL, MTCrGL, CTCrTiG, CTCrTiR, and MTCrTiG compared to the control.

The significant increase in maize yield could be attributed to its response to N and P application through fertilization under the various SMSs to a soil characterized by low N and P (Table 1; Uwah & Eyo, 2014). The increased grain and stover yields under treatments with integrated inorganic fertilizers and organic amendments (CTCrGF and MTCrGF) underpins the importance of integrated soil management strategies in improving crop productivity through complementarity (Vanlauwe et al., 2010; Vanlauwe et al., 2015). A similar finding was reported in rice (Mi et al., 2018) and tomatoes (Brunetti et al., 2019). Combining resources under CTCrTiR, CTCrTiG, MTCrTiG, and MTCrTiR enhanced resource use efficiencies, as shown through the observed improved RUE (Table 5). This finding agrees with a short-term study conducted in the farmers' fields in the Central Highlands of Kenya (Otieno et al., 2021). The finding also corroborates the assertion of Hassen (2018) and reveals the potential of integrated sole organic amendments (CTCrGL, MTCrGL, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR) replacing the use of inorganic fertilizers. Increased yield has been reported in rice under a treatment that combined rock phosphate and *Tithonia diversifolia* (Imani Wa Rusaati et al., 2020), similar to increased maize performance under CTCrTiR and MTCrTiR in this study. The enhanced maize yield under MTF, MTCrF, CTF, and CTCrF is a demonstration of the responsiveness of acidic Nitisols to sole inorganic fertilizer application that regulates crop growth parameters (Table 4 and 5) and yield. This result support the findings of Wu et al. (2017), who reported a positive effect of inorganic P application on maize growth and yield. Positive effects of inorganic fertilizer on the growth and yield of other crops have also been reported in other studies (Ayoola, 2007; Cheptoek et al., 2021). The increased maize yield under the application of inorganic fertilizer and residue retention (CTCrF and MTCrF) agrees with the finding of Zhang et al. (2021), where NPK combined with straw retention increased wheat yield. On the other hand, maize yield under CTCrGL, MTCrGL increased N and P under these treatments (Fig. 3). Other studies have associated increased crop yield under cereal-legume intercrop to the ability of the legume crop to enhance soil N and P within the system (Arruda et al., 2021; Arruda et al., 2019).

Soil management strategies significantly affected grain and stover WP during SR2020 and LR2021 seasons (Table 8). Grain WP was significantly higher by 88, 82, 82, 81, 80, 80, 79, 79, and 70% under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTCrTiG, CTF and MTCrTiR than the control during SR2020. However, MTCrGL, MTF, CTCrGL, and MT recorded similar grain WP to the control during the SR2020. During LR2021, apart from MT, the other SMSs, CTCrGF, CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had significantly higher grain WP than the control by 74, 73, 71, 70, 70, 69, 67, 66, 64, 59, 56 and 50%. Grain WP under CTCrGF, CTCrGL, MTCrGF, MTCrGL, CTF, and MTCrF was significantly higher than WP under TillCrTiG, NoTillCrTiR, and TillCrTiR. Apart from MT during the SR2020, stover WP was 88, 85, 85, 85, 84, 84, 83, 83, 82, 76, 72, and 72% higher under CTCrGF, CTCrF, CTCrTiG, CTF, MTCrGF, MTCrF, MTCrTiG, CTCrTiR, MTF, CTCrGL, MTCrGL and MTCrTiR than under the control. Conversely, stover WP was significantly lower under CTCrGL, MTCrGL, and MTCrTiR compared to the other best-performing SMSs. Except for NoTillCrTiR and MT, stover WP was significantly higher than under the control by 52, 51, 51, 47, 38, 38, 38, 34, 33, 25 and 23% under CTCrF, CTCrGF, CTF, CTCrGF, CTCrF, CTF, CTCrGL, MTCrGL, CTCrTiG, CTCrTiR, and MTCrTiG.

The increased aboveground yield and WP was associated with the addition of N, P and K from inorganic and organic inputs. Nitrogen application affects maize grain yield by regulating; N uptake, radiation, and water use efficiencies, root distribution, photosynthesis, and grain filling (Su et al., 2020; Yue et al., 2022). Applying N through calcium superphosphate, urea, and pig manure significantly increased maize yield in a study conducted by Zhang et al. (2021). Soil fertility amendments improved WP by providing N, P, and K that controls critical bio-physico-chemical functions in crops. For instance, P fertilization from the amendments could have stimulated root hydrotropism during intra-seasonal water shortages (Szulc et al., 2021), leading to higher WP. Strategies that contained organic inputs, CTCrGF, CTCrTiG, MTCrGF, and MTCrTiG could have altered soil hydraulic characteristics and enhanced the soil's physical environment (Parihar & Nayak, 2019), leading to improved water utilization. On the other hand, K from NPK fertilization could have increased water uptake and translocation within the plant resulting in higher WP (Adnan, 2020).

Table 6
Mean maize height (cm) at different phenological stages under different SMSs during SR2020 and LR2021 seasons

SFM [(1)]	SR2020		LR2021	
	6th leaf	10th leaf	6th leaf	10th leaf
MTCrF	24.44	66.31[ab] [(2)]	27.19[a]	100.94[a]
MTCrGF	21.19	76.88[a]	22.375[abc]	85.31[abcd]
MTCrGL	22.19	74.88[a]	26.31[a]	92.75[abc]
MTCrTiG	19.97	64.38[ab]	24.00[abc]	76.94[cde]
MTCrTiR	20.88	63.88[ab]	23.06[abc]	73.19[cdef]
MT	16.938	49.75[bc]	17.69[c]	56.06[f]
MTF	21.25	50.31[bc]	21.25[abc]	75.13[cdef]
CTCrF	20.94	73.94[ab]	21.00[abc]	74.19[cdef]
CTCrGF	23.56	78.88[a]	23.38[abc]	88.81[abcd]
CTCrGL	20.35	71.56[ab]	26.13[ab]	96.63[ab]
CTCrTiG	25.63	68.88[ab]	20.88[abc]	73.00[def]
CTCrTiR	20.38	69.75[ab]	20.63[abc]	81.13[bcde]
C	13.44	35.63[c]	18.94[bc]	61.69[ef]
CTF	19.69	67.06[ab]	21.31[abc]	77.25[bcde]
hsd [(3)]	15.85	24.49	7.20	19.57
p value	ns [(4)]	***	**	***

[(1)] SMSs = soil management strategies; 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 (no amendments), 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,

[(2)] values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,

[(3)] hsd = honestly significant difference at $p \leq 0.05$,

[(4)] ns = not significant at p = 0.5454, ** p= 0.001, *** $p < 0.0001$.

Stover yield declined under MT during LR2021 season, which coincided with low WP (Table 6). A previous study also reported a reduced maize yield grown under conservation tillage in adequate rainfall conditions (Parihar & Nayak, 2019). The low maize grain yield observed under CTCrGL, and MTCrGL was attributed to water stress caused by legume-cereal soil moisture competition during periods of moisture scarcity (Teixeira et al., 2014) at the grain filling stage during SR2020 season.

3.4. Tillage effect

Tillage system modifies the environment for the parameters measured in this study. For instance, previous studies have reported high distribution of nutrients at the topsoil layer under MT (Naeem et al., 2021; Sombrero and de Benito 2010). The higher P and N reported under MTCrF, MTCrGF, and MTCrGL in this study could, therefore,

Table 7
Maize grain and stover yields under different SMSs during SR2020 and LR2021 season

SFM strategies [1]	Grain yield (t ha^{-1})		Stover yield (t ha^{-1})	
	SR2020	LR2021	SR2020	LR2021
MTCrF	2.25^{b} [2]	4.13^{abc}	6.27^{b}	9.87^{bc}
MTCrGF	2.02^{b}	4.41^{abc}	6.48^{b}	11.43^{ab}
MTCrGL	0.75^{de}	4.31^{abc}	3.78^{c}	9.35^{cd}
MTCrTiG	1.99^{b}	3.55^{cd}	6.26^{b}	7.97^{de}
MTCrTiR	1.29^{cd}	2.90^{de}	3.78^{c}	6.85^{ef}
MT	0.36^{e}	0.82^{f}	2.17^{d}	4.33^{g}
MTF	0.82^{de}	3.74^{bcd}	5.84^{b}	9.97^{bc}
CTCrF	2.24^{b}	3.86^{bcd}	6.90^{ab}	12.66^{a}
CTCrGF	3.20^{a}	4.90^{a}	8.41^{a}	12.55^{a}
CTCrGL	0.82^{de}	4.72^{ab}	4.20^{c}	9.84^{bc}
CTCrTiG	1.81^{bc}	3.12^{de}	6.83^{b}	9.11^{cd}
CTCrTiR	1.87^{bc}	2.54^{e}	6.05^{b}	8.20^{de}
C	0.15^{e}	1.30^{f}	1.02^{d}	6.18^{f}
CTF	1.87^{bc}	4.20^{abc}	6.84^{b}	12.39^{a}
hsd [3]	0.69	0.99	1.53	1.62
p value	***	***	***	***

[1] SMSs = soil management strategies; 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 (no amendments), 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,
[2] values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,
[3] hsd = honestly significant difference, *** $p < 0.0001$.

Table 8
Maize grain and stover water productivity under different during SR2020 and LR2021 seasons

SFM strategies [1]	SR2020 Season		LR2021 Season	
	Grain	Stover	Grain	Stover
	kg ha^{-1} m^{-3}		kg ha^{-1} m^{-3}	
MTCrF	0.17^{b} [2]	0.49^{b}	0.52^{abc}	1.25^{bc}
MTCrGF	0.16^{b}	0.51^{b}	0.56^{abc}	1.44^{ab}
MTCrGL	0.06^{de}	0.29^{c}	0.54^{abc}	1.17^{cd}
MTCrTiG	0.15^{bc}	0.48^{b}	0.45^{cd}	1.00^{de}
MTCrTiR	0.10^{cd}	0.29^{cd}	0.36^{de}	0.86^{ef}
MT	0.03^{e}	0.17^{de}	0.10^{f}	0.55^{g}
MTF	0.06^{de}	0.45^{b}	0.47^{cd}	1.25^{bc}
CTCrF	0.17^{b}	0.53^{ab}	0.49^{bcd}	1.59^{a}
CTCrGF	0.25^{a}	0.65^{a}	0.62^{a}	1.58^{a}
CTCrGL	0.06^{de}	0.33^{c}	0.60^{ab}	1.24^{bc}
CTCrTiG	0.14^{bc}	0.53^{ab}	0.39^{de}	1.15^{cd}
CTCrTiR	0.15^{bc}	0.47^{b}	0.32^{e}	1.03^{cde}
C	0.01^{e}	0.08^{e}	0.16^{f}	0.77^{fg}
CTF	0.14^{bc}	0.53^{ab}	0.54^{abc}	1.58^{a}
hsd [3]	0.05	0.12	0.12	0.23
p values	***	***	***	***

[1] SMSs = soil management strategies; 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 (no amendments), 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,
[2] values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$,
[3] hsd = honestly significant difference, *** $p < 0.0001$.

be partly attributed to the effectiveness of minimum tillage to store the nutrients at the 0-20 cm depth (Vazquez et al., 2019). Minimum tillage could have enhanced soil microbe diversity and population size (Li et al., 2020), which may have accelerated the mineralization of P and N from the organic materials. Improved aeration and water infiltration under MT (Fonseca et al., 2021) is suitable for rhizobia root infection and consequent N fixation, partly explaining the observed high N under CTCrGL. Conventional tillage promotes root development; hence the plant could have obtained P under CTCrF, CTCrGF, and CTF and N under CTCrGL and deposited on the first top soil layers (Chen et al., 2022).

The observed higher maize performance under the different SMSs was due to a combined effect of tillage and soil fertility amendments. The improved performance under CT could be ascribed to better root development due to improved soil porosity (Cosentino et al., 2016) and rapid mineralization of plant nutrients. Kiboi et al. (2019) attributed the significant high maize yield to quick nutrient release under conservation tillage. On the other hand, MT could have contributed to better maize performance by regulating plant photosynthetic capacity, hormonal changes and grain filling (Yue et al., 2022). Other studies have linked high crop performance under MT to increased water retention and fertilizer responsiveness (Lamptey et al., 2020; Vazquez et al., 2019).

Conclusions

The findings of this study strongly demonstrate the importance of integrated approaches to improving soil fertility (N and P) and crop productivity in acidic Nitisols. Combining inorganic fertilizers and organic amendments (CTCrGF and MTCrGF) and integrating sole organic amendments (CTCrTiR, CTCrTiG, MTCrTiG and MTCrTiR) resulted in significantly higher soil N and P, and maize growth (LAI, PAR and height), resource use efficiencies (RUE and WP) and yield parameters. These results clearly shows that soil fertility and crop productivity can be enhanced by either integrating inorganic fertilizer with organic amendments, or integrating sole organic amendments. Moreover, the great performance of CTCrGF and MTCrGF in regard to soil fertility and crop performance illustrates the complementarity between inorganic and organic resources when the application rates of the two amendments are halved. Additionally, the high N, P and crop performances under sole inorganic fertilizer (CTF, CTCrF, MTF and MTCrF) are indications of the responsiveness of acidic Nitisols to inorganic fertilizer application that cannot be overlooked in soil fertility management options. However, the findings of this study also reveal that nearly identical effect on soil fertility and crop performance can be attained through CTCrTiR, CTCrTiG, MTCrTiG, and MTCrTiR in the absence of inorganic fertilizers, further illustrating the concept of 'substitutability' in soil fertility management. The study further shows that, though CTCrGL and MTCrGL improved soil fertility, they are better crop yield performers during adequate rainfall seasons.

Declaration of Competing Interests

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.

Data Availability

We have attached the data as a zipped folder

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