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Enhancing sorghum productivity through integrated nutrient management and water conservation in the sandy loam soil of the semi-arid region of Zimbabwe

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Abstract

Purpose

Low rainfall, water stress, and soil infertility have been one of the major constraints that reduce crop productivity and food security in semi-arid regions. The objective of the study was to evaluate the effects of integrated nutrient management (INM) and water conservation on soil moisture content, nutrient use efficiency, and sorghum grain yield.

Methods

The experiment was laid out in a randomised complete block design with five levels (0, 2.5/25, 5/50, 7.5/75, and 10 t ha^{-1}/100kg ha^{-1}) of INM (Compost-Biochar (CB)/ Nitrogen-Phosphorous-Potassium (NPK) as the main plot factor, two sorghum varieties (Macia and SCXH102) as sub plot factor, and three levels of water conservation (tied ridges, planting pits, and mulching) as the blocking factor.

Results

The results showed that INM significantly ($p < 0.05$) increased the soil moisture content. The highest soil moisture content was 11.97% under $CB_{10}(NPK)_{100}$ + mulching at 20-40cm depth, and it was significantly higher compared with other treatments. The highest grain yield was 2547.3kg ha^{-1} from 10 t ha^{-1} INM +SCXH102 + tied ridges. SCXH102 had the highest nitrogen use efficiency (NUE) of 4.26 kg kg^{-1} at $CB_{7.5}$ $(NPK)_{75}$ + planting pit during the 2024/25 season.

Conclusions

It can be concluded that the application of $CB_{10}(NPK)_{100}$ INM + tied ridge and SCXH102 had the highest grain yield that can sustain smallholder farmers for two years. Smallholder farmers in semi-arid areas of Zimbabwe are recommended to adopt this combination to improve food security and achieve climate-smart agriculture, especially in sandy-loam soils.

1. Introduction

Climate change has affected crop productivity in semi-arid areas to a greater extent over the past three decades. The negative change drastically causes drought, extreme hot temperatures, and heavy downpours that cause soil degradation. The rainfall received in these areas has changed its pattern, and it's now low and erratic, associated with uneven distribution (Cosmas et al. 2026). Additionally, this causes long, frequent mid-season droughts that shorten the cropping season and lead to poor crop yields. Soil fertility issues have been reported to be in an increasing phase in semi-arid areas, especially those occupied by smallholder farmers who are unable to apply adequate quantities of mineral fertiliser (Mwadalu et al. 2022). This calls for the adoption of climate-resilient crops (CRCs) that are drought-tolerant, thrive better under extreme conditions, and have high water and nutrient use efficiency, such as sorghum and millets (Alemu Tolossa et al. 2025; Nahed et al. 2026). There are limited studies in Zimbabwe that evaluated sorghum in sandy-loam soils using a combination of compost-biochar, NPK fertilizer, and water conservation techniques. However, these available studies used other organic and inorganic nutrient sources that have different nutrient contents from compost and biochar, hence the need to evaluate compost-biochar-NPK-water conservation using Macia and SCXH102 sorghum varieties.

Sorghum is a drought-tolerant crop that has the capacity to perform better under low and erratic rainfall in semi-arid areas associated with low fertility. Sorghum is one of the climate-resilient crops that can be grown in sandy-loam soils (Mabasa et al. 2025). Sorghum has better water use efficiency (WUE) that ranges from 2.1-4.8kg ha^{-1} mm^{-1} in sandy loam soils, and it can be increased through water conservation and breeding to meet that of maize and other cereals (Kugedera et al. 2024). Grain yield of sorghum is low in smallholder farming systems, with several farmers realizing 200-350kg $ha^{-1,}$ and has the capacity to go beyond this under better management (Kubiku et al. 2023; Ajeigbe et al. 2024; Loftus et al. 2025). Furthermore, sorghum can yield 2000 to 4500kg ha^{-1} in semi-arid areas with nutrient and water conservation management practices (Kubiku et al. 2025; Kugedera and Kokerai 2025). This has also been reported in West Africa and Central Africa by several authors (Kalema et al. 2022; Ajeigbe et al. 2024; Mwami et al. 2024; Ouédraogo et al. 2024). To enhance sorghum productivity in semi-arid regions, there is a need to adopt integrated nutrient management and water conservation techniques.

Integrated nutrient management (INM) is a soil fertility management that uses various nutrient sources, whether organic or mineral fertilizers, in combination. INM has been used by smallholder farmers, but they were failing to meet the demand by both soil and crops, as plants harvested more nutrients than they added (Walia et al. 2024). However, smallholder farmers have been using cattle manure as the major nutrient source with little or no mineral fertilizer. This was the driving force for soil infertility in these areas since cattle manure alone does not meet crop requirements, as it contains an average of 0.11% nitrogen with adequate potassium and phosphorus (Bai et al. 2025). So, to reduce these effects, there is a need for smallholder farmers to utilize crop residues to form compost and biochar. They can also produce biochar from other animal manure, as this improves nutrient availability and soil fertility (Fei et al. 2026). Furthermore, biochar produced from crop residues and animal manure enhances soil properties, increases nutrient availability, and enhances microbial biomass that will decompose compost and release nutrients in the soil during the season. In addition, there is a need to create a positive synergistic association where the major challenge in semi-arid areas is soil moisture due to low and erratic rainfall that affects nutrient absorption and crop growth. So, there is a need to adopt water conservation techniques.

Since smallholder farmers are resource-poor, there is a need to adopt economic water conservation techniques such as mulching, tied ridges, and planting pits that are universal and support a variety of crops. Mulching can be done using locally available resources such as grass obtained from farms and crop residues that were left from biochar and compost making. Mulching reduces the effects of surface evaporation, conserves soil moisture, and facilitates nutrient recycling, which also improves soil fertility (Hakeem et al. 2025; Kayusi et al. 2025). Besides moisture conservation, it reduces emission of greenhouse gases and increases soil organic carbon (Wang et al. 2025). Planting pits collect surface runoff, store water, and recharge underground water in the plant root zone that supports crops to survive during dry spells. Since they are produced in large numbers, they conserve a lot of soil water that helps crops mitigate water stress (Marumbi et al. 2020). Additionally, tied ridge is a water conservation technique that maximizes water availability to plants and increases crop productivity, especially in low rainfall areas (Bekele and Chemeda 2022; Wainaina 2023; Mwami et al. 2024). To maximize and enhance sorghum productivity in semi-arid areas, there is a need for integrating INM of biochar, compost, and NPK fertilizer with water conservation techniques. The objective of the study was to evaluate the effects of integrated nutrient management (INM) and water conservation on soil moisture content, sorghum grain yield, and nutrient use efficiency in sandy-loam soils. The study hypothesized that the integration of INM and water conservation significantly improves soil moisture content, grain yield, and nutrient use efficiency of sorghum sandy-loam soils.

2. Materials and methods

2.1 Study area

The study was carried out at Farm 34 ($20^0$15’28.8” S and 30°59’30.8” E, 1117m.a.s.l), ward 4 of Masvingo district. The site is in agroecological Zone IV (AEZ IV) of Zimbabwe that receives rainfall ranging from 350-500mm per annum (Manatsa et al. 2020). The area is composed of old resettlement (OR) that has been following the directive on what to grow and what not to grow. Additionally, the area has been supported by donors in terms of food, hence the need to equip them with small grain production. It is characterized by sandy-loam soils (Nitisols). The soil is moderately fertile but with high leaching levels, which also facilitate the continual loss of nutrients. The common agricultural practices include crop and livestock production. Many smallholder farmers in this area grow maize, but there is a high probability of low grain yields.

2.2 Soil characterisation

Initial soil characterisation was done before land preparation during 2022/23, 2023/24, and 2024/25 cropping seasons. The study used a transverse sampling method to collect soil samples from 20 sampling points. The soil was collected using a spade and an auger from 0-40cm deep, and all areas that had previously had crop rows were avoided. Collected samples were mixed thoroughly in a plastic bucket to produce 1 kilogram as composite sample after shade drying. Soil texture, pH, available phosphorous and soil organic carbon were determined using the Bouyoucos hydrometer, calcium chloride ($CaCl_2$), the Oslen method, and the Walkley-Black method, respectively (Chiturike et al. 2025). Additionally, total nitrogen and exchangeable cations were determined using the Kheldjahl and atomic absorption spectrophotometer method, respectively (Jayanthi and Gokila 2022).

2.3 Rainfall

Rainfall was collected from the experimental site using a standard rain gauge that was fixed at the site. Data was collected every day at 8 am. Total rainfall received was 453mm, 389mm, and 438mm during 2022/23, 2023/24, and 2024/25 cropping seasons, respectively. A long dry spell was experienced from 17 January 2023 to 10 March 2023 during the 2022/23 season, 10 December 2023 to 5 January 2024 during the 2023/24 season, and from 11 January 2025 to 3 February 2025. The seasons were also associated with mid-season dry spells.

2.4 Experimental design and treatments

The experiment was laid out in a 5 x 2 x 3 factorial design with five INM levels (($CB_0(NPK)_0$, $CB_{2.5}(NPK)_{25}$, $CB_5(NPK)_{50}$, $CB_{7.5}(NPK)_{75}$, and $CB_{10}(NPK)_{100}$), (where 0, 2.5, 5, 7.5, and 10t/ha are for compost-biochar, and 0, 25, 50, 75, and 100kg ha^{-1} are for NPK (7%N: 14%P_2O_5: 7% K_2O)), two sorghum varieties (Macia and SCXH102), and three water conservation techniques (tied ridges, planting pits, and mulching). This gives a total of 30 treatments, each replicated three times on the same plots over the experimental period, and nutrient sources were applied each season. Each treatment plot measured 4m x 5m ($20m^2$). Treatment plots were separated by 0.5m and 1m between each block. Land preparation was done using an animal-drawn plough to a depth of 20cm, and a harrow was used to break clods, remove, and level the land. Planting was done on 17 November 2022, 21 November 2023, and 15 November 2024 for 2022/23, 2023/24, and 2024/25 cropping seasons, respectively. Planting was done using 0.75m between rows and 0.2m within the row to achieve a plant population of 66 666plants ha^{-1}. INM was used as a basal dressing. Top dressing was done using ammonium nitrate (34.5%N) at a rate of 100kg ha^{-1} and applied in two splits at a rate of 50kg ha^{-1} at 28 and 56 days after emergence. Weeding was done using Bentazone herbicide at a rate of 3 litres ha^{-1}. Fowl armyworm was controlled four times using Demise 65EC. A bird guard chemical was sprayed to control birds during the flowering to dough stage period.

2.5 Data collection

Soil moisture content was determined using the gravimetric method from 0-20cm and 20-40cm deep. Pits were dug using shovels, and samples were collected, where 1 kilogram was used for data determination. Three soil samples were collected per plot, 3 weeks after emergence (WAE), 7WAE, and 11WAE. The following formula was used (Eq. 1).

$$\Theta m\ (\%) = \frac{wet\ soil\ mass - oven\ dry\ soil\ mass}{Oven\ dry\ soil\ mass} \times 100 \quad \text{..... Eq. 1.}$$

Grain yield was determined from the net plot of 3m x 3m, and converted to kg ha^{-1}. Heads were cut from stover using sharp knives per treatment and its replicates. Collected heads were sun-dried for one week and manually threshed, winnowed, and weighed using a digital scale. The formula (Eq. 2) below was used to convert to kg ha^{-1}.

Grain yield (kg ha^{-1}) = $\frac{Grain\ from\ net\ plot\ (kg)}{Net\ plot\ area\ (9m^2)}\ x\ 10000\ m^2$ ..... Eq. 2.

Nitrogen use efficiency (NUE) was determined after harvesting and weighing of grain yield. This was calculated using Eq. 3 below.

NUE = $\frac{\text{Grain yield of fertilised plot (kg)} - \text{grain yield in control plot(kg)}}{Amount\ of\ N\ applied\ (kg)}$ ..... Eq. 3.

2.6 Data analysis

Data was analysed for analysis of variance using GenStat version 14, and means were separated using Fisher's Least Significant Difference at $p < 0.05$. The study used the following full factorial design after testing for normality.

$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \epsilon_{ijkl}$

Where: $\mathbf{Y_{ijk}}$ is the response variable, $\boldsymbol{\mu}$ is the overall mean, $\boldsymbol{\alpha_i}$ is the effect of INM (I = 1–5), $\boldsymbol{\beta_j}$ is the effect of variety (j = 1, 2), and $\boldsymbol{\gamma_k}$ is the effect of water conservation (k = 1, 2, 3). $\boldsymbol{(\alpha\beta)_{ij}}$, $\boldsymbol{(\alpha\gamma)_{ik}}$, and $\boldsymbol{(\beta\gamma)_{jk}}$ are two-way interactions, $\boldsymbol{(\alpha\beta\gamma)_{ijk}}$ is the three-way interaction, and $\boldsymbol{\epsilon_{ijkl}}$ is the error term.

3. Results

3.1 Soil Characterization

The initial soil characterisation was classified as a sandy loam soil according to Zimbabwean classification, and as Nitisols according to the World Reference Base (WRB) classification. The soil had low total nitrogen and soil organic matter. The soil texture had 650g kg^{-1} sand, 280g kg^{-1}silt, and 70g kg^{-1} clay. Soil total nitrogen and organic carbon increased slightly with season. All other soil properties from characterisation are shown in Table 1.

Table 1
Soil properties determined during the experimental period (2022/23 to 2024/25)

Soil property	2022/23	2023/24	2024/25
Total nitrogen (g kg^{-1})	1.4	1.9	2.2
Soil organic carbon (g kg^{-1})	13.4	14.6	15.2
pH	5.6	5.8	5.8
Available phosphorus (g kg^{-1})	0.0348	0.0465	0.0482
Exchangeable cations: potassium (g kg^{-1})	0.02	0.02	0.02
Magnesium (g kg^{-1})	0.037	0.045	0.049
Calcium (g kg^{-1})	0.098	0.13	0.18
Sodium ($cmol_c$ kg^{-1})	0.15	0.092	0.077
Bulk density (g cm^{-3})	1.64	1.47	1.29
Cation exchange capacity ($cmol_c$ kg^{-1})	2.25	2.68	2.98

3.2 Effects of INM and water conservation on soil moisture content

Soil moisture was significant ($p < 0.05$) among all treatment factors. Results showed that soil moisture content was influenced by an increase in application rates of INM due to biochar and compost. Soil moisture content was highest from $CB_{10}NPK_{100,}$ and this was 45.4% above the control treatment (CB_0NPK_0), as shown in Table 2. Water conservation also showed positive effects on soil moisture content, with mulching having the highest content (9.72%) compared with tied ridges and planting pits, and it was significant ($p < 0.05$). Additionally, soil moisture content was also affected by collection period, with the highest content observed from 7WAE, which was 3.7% and 9.2% above the results from 3WAE and 11WAE, respectively. Furthermore, soil moisture content increased with depth, with the highest content observed from 20-40cm deep compared with 0-20cm, and was significant ($p < 0.05$). In addition, the cropping season also affects soil moisture content, with the highest content reported from the 2024/25 cropping season (Table 2).

Table 2
Sole effects of INM, water conservation, and variety on soil moisture content over the 2022/23 to 2024/25 cropping season

Treatment	Soil moisture content (%)
INM (Compost-Biochar/NPK) (t ha^{-1}/kg ha^{-1})	
CB_0NPK_0	6.87^{e}
$CB_{2.5}NPK_{25}$	7.45^{d}
CB_5NPK_{50}	8.97^{c}
$CB_{7.5}NPK_{75}$	9.24^{b}
$CB_{10}NPK_{100}$	9.99^{a}
LSD (5%)	0.0925
P-value	< 0.001
Water conservation	
Planting pits	8.63^{c}
Tied ridge	8.12^{b}
Mulching	9.72^{a}
LSD (5%)	0.0925
P-value	< 0.001
Week after emergency (WAE)	
3WAE	8.82^{b}
7WAE	9.15^{a}
11WAE	8.38^{c}
LSD (5%)	0.0623
P-value	< 0.001
Collection depth (cm)	
0–20	8.24^{b}
20–40	9.77^{a}
LSD (5%)	0.0623
P-value	< 0.001
Season	
2022/23	8.19^{b}
2023/24	7.46^{c}
2024/25	10.23^{a}
LSD (5%)	0.0623
P-value	< 0.001

The interactive effects of INM with water conservation, and water conservation with season, were significant ($p < 0.05$) regardless of WAE and collection depth. However, the interaction between INM and water conservation techniques increased soil moisture across all depths and treatments, overriding the effects of either factor alone. The highest soil moisture content (13.92%) was obtained with Mulching + 10 t/ha INM at 20-40cm depth during the 2024/25 cropping season at 11WAE, and this was significantly different ($p < 0.05$) from the other treatments (Table 3). Soil moisture content also varied due to the period of collection and the season. Although soil moisture content increased with an increase in application rates, it differed according to water conservation techniques, depth of collection, season, and WAE. During 2022/23, soil moisture content was better at 11WAE, which interacted with all water conservation techniques and INM. Specifically, the highest soil moisture content (12.89% and 13.92%) was observed from Mulching + $CB_{10}(NPK)_{100}$ + 2024/25 at 11WAE for 0-20cm and 20-40cm. In 2022/23, soil moisture content was high during the first 3WAE, and showed a decline during 7WAE but increased at 11WAE across water conservation, INM application rates, and collection depth (Table 3). The same trend was observed during 2023/24, where

soil moisture ranges from 6.89% to 10.02% regardless of water conservation technique and INM application rate. Additionally, soil moisture content increased during the 2024/25 cropping season at all water conservation techniques, collection depths, and WAE. Specifically, mulching + $CB_{10}(NPK)_{100}$ +11WAE had the highest increase in soil moisture content, which was 14.1% and 16.3% above the same treatment at 7WAE and 3WAE, respectively, at 20-40cm.

Table 3
Interactive effects of INM and water conservation on soil moisture content (%)

3WAE										**7WAE**			
Treatment combinations		**2022/23**		**2023/24**		**2024/25**		**2022/23**		**2023/24**		**2024/25**	
Water conservation	**INM (t ha^{-1})**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
Planting pits	$CB_0(NPK)_0$	6.92^{b}	9.22^{d}	6.89^{b}	7.31^{c}	6.92^{b}	7.99^{b}	6.23^{b}	8.15^{c}	6.1^{b}	7.1^{b}	7.97^{b}	8.67^{b}
	$CB_{2.5}(NPK)_{25}$	8.13^{b}	9.36^{g}	7.13^{e}	7.85^{e}	7.39^{c}	8.56^{d}	7.89^{f}	8.9^{d}	6.78^{d}	7.45^{d}	8.35^{d}	9.48^{d}
	$CB_5(NPK)_{50}$	8.99^{c}	10.15^{g}	7.97^{g}	8.14^{f}	8.05^{e}	9.21^{f}	8.11^{g}	9.09^{e}	7.35^{g}	8.2^{g}	8.88^{g}	10.1^{g}
	$CB_{7.5}(NPK)_{75}$	9.88^{e}	10.67^{ij}	8.33^{i}	8.99^{g}	8.65^{g}	10.45^{h}	8.67^{i}	9.8^{h}	8.2^{j}	8.78^{i}	9.26^{h}	10.8^{i}
	$CB_{10}(NPK)_{100}$	10.21^{h}	11.15^{j}	8.88^{k}	9.16^{h}	9.11^{h}	10.97^{j}	9.16^{j}	10.4^{k}	8.72^{l}	9.05^{k}	9.87^{j}	11.1^{j}
Mulching	$CB_0(NPK)_0$	6.97^{b}	8.43^{e}	6.99^{c}	8.48^{d}	7.66^{ab}	8.69^{b}	6.89^{c}	8.01^{b}	6.47^{c}	8.11^{f}	8.45^{e}	9.8^{f}
	$CB_{2.5}(NPK)_{25}$	9.46^{c}	9.98^{g}	8.35^{e}	8.97^{e}	8.52^{c}	9.99^{d}	7.67^{e}	9.15^{e}	7.21^{f}	8.48^{h}	9.25^{h}	10.22^{h}
	$CB_5(NPK)_{50}$	10.07^{f}	10.42^{h}	8.89^{g}	9.45^{gh}	9.29^{e}	10.67^{f}	8.33^{h}	9.72^{g}	8.55^{k}	8.97^{j}	9.89^{j}	10.89^{j}
	$CB_{7.5}(NPK)_{75}$	10.48^{h}	11.23^{i}	9.28^{i}	9.77^{g}	9.98^{f}	11.38^{h}	9.21^{j}	10.5^{l}	9.09^{m}	9.45^{g}	10.1^{k}	11.46^{k}
	$CB_{10}(NPK)_{100}$	10.94^{j}	11.86^{j}	9.84^{l}	10.02^{h}	10.26^{h}	11.97^{ij}	9.95^{h}	10.91^{m}	9.34^{n}	9.9^{l}	10.62^{l}	12.2^{l}
Tied ridges	$CB_0(NPK)_0$	6.48^{a}	8.75^{a}	6.72^{a}	7.15^{a}	6.82^{a}	7.33^{a}	5.88^{a}	7.25^{a}	5.97^{a}	6.75^{a}	7.75^{a}	8.38^{a}
	$CB_{2.5}(NPK)_{25}$	6.78^{b}	9.01^{b}	6.94^{d}	7.69^{b}	7.08^{c}	7.89^{c}	6.15^{b}	8.14^{c}	6.12^{b}	7.2^{c}	8.23^{c}	8.86^{c}
	$CB_5(NPK)_{50}$	7.13^{d}	9.68^{c}	7.23^{f}	8.01^{d}	7.95^{d}	8.52^{e}	6.88^{c}	9.26^{f}	6.99^{e}	7.9^{e}	8.71^{f}	9.72^{e}
	$CB_{7.5}(NPK)_{75}$	7.98^{g}	9.96^{d}	7.98^{h}	8.57^{f}	8.27^{f}	9.13^{g}	7.08^{d}	9.9^{i}	7.45^{h}	8.17^{fg}	9.2^{h}	10.2^{h}
	$CB_{10}(NPK)_{100}$	8.23^{i}	10.06^{f}	8.38^{j}	9.02^{g}	8.91^{h}	9.81^{i}	7.77^{e}	10.1^{j}	8.1^{i}	8.99^{jk}	9.71^{i}	10.9^{i}
	P-value	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*0.001*	*0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*0.001*	*0.001*
	LSD (0.05)	*0.0949*	*0.0723*	*0.0949*	*0.0723*	*0.0949*	*0.0723*	*0.0949*	*0.0723*	*0.0949*	*0.0723*	*0.0949*	*0.0723*
	CV (%)	*1.5*	*2.7*	*1.5*	*2.7*	*1.5*	*2.7*	*1.5*	*2.7*	*1.5*	*2.7*	*1.5*	*2.7*

3.3 Effects of INM and water conservation techniques on the grain yield of sorghum

Sorghum grain yield was significant ($p < 0.05$) with the use of INM, water conservation, and variety. Results showed that sorghum grain yield from the Macia variety increased by a lower percentage compared with SCXH102. Sorghum variety Macia had an average grain yield of 898.2kg ha^{-1}, which was 37.3kg ha^{-1} lower than the yield obtained from SCXH102. Furthermore, INM showed increases that were significant ($p < 0.05$) on grain yield with a highest of 997.2kg ha^{-1} from 10t ha^{-1}. Water conservation of the tied ridge had the highest (1120.6kg ha^{-1}) compared with mulching and planting pits. Additionally, cropping season 2024/25 had the highest grain yield (1014.7kg ha^{-1}), which was 150.4kg ha^{-1} (17.4%) and 271.8kg ha^{-1} (36.6%) above 2022/23 and 2023/24 cropping seasons, respectively (Table 4).

Table 4
Sole effects of INM, water conservation, and variety on grain yield over the 2022/23 to 2024/25 cropping season

Treatment	Sorghum grain yield (kg ha^{-1})
INM (Compost-Biochar/NPK) (t ha^{-1}/kg ha^{-1})	
CB_0NPK_0	642.7[e]
$CB_{2.5}NPK_{25}$	715.1[d]
CB_5NPK_{50}	787.7[c]
$CB_{7.5}NPK_{75}$	835.8[b]
$CB_{10}NPK_{100}$	997.2[a]
LSD (5%)	61.3
P-value	< 0.001
Water conservation	
Planting pits	860.3[b]
Tied ridge	1120.6[a]
Mulching	645.2[c]
LSD (5%)	61.3
P-value	< 0.001
Variety	
Macia	898.2[b]
SCXH102	935.5[a]
LSD (5%)	72.4
P-value	< 0.001
Season	
2022/23	864.3[b]
2023/24	742.9[c]
2024/25	1014.7[a]
LSD (5%)	72.4
P-value	< 0.001

The interactive effects of INM and water conservation were significant ($p < 0.05$) and override the single-factor effects. Grain yield was higher from the interaction of INM ($CB_{10}NPK_{100}$) and tied ridge (2015.7kg ha^{-1}), which was significant ($p < 0.05$) when compared with other treatments, regardless of season. Additionally, the interaction of variety and INM was significant, with $CB_{10}NPK_{100}$ + SCXH102 having the highest (1950.9kg ha^{-1}) during the 2024/25 cropping season. All other interactive effects performed below the four-way interaction of INM, water conservation, variety, and season (Table 5). Grain yield increased with an increase in INM under tied ridge, and both varieties, with the highest grain yield of 2547.3kg ha^{-1}, were obtained from 10t ha^{-1}INM + tied ridge + SCXH102 variety during the 2024/25 cropping season (Table 5). Furthermore, INM + planting pit had better sorghum grain yield compared to mulching, regardless of variety and season (Table 5). Results were higher from the 2024/25 cropping season and increased with an increase in INM application rates, and also showed significant differences ($p < 0.05$) between variety and cropping season.

Table 5
Interactive effects of INM and water conservation techniques on sorghum grain yield

Treatment combinations		Macia Grain yield (kg ha^{-1})			SCXH102 Grain yield (kg ha^{-1})		
Water conservation	**Compost +biochar (t ha^{-1}) + NPK (kg ha^{-1})**	**2022/23**	**2023/24**	**2024/25**	**2022/23**	**2023/24**	**2024/25**
Planting pits	$CB_0(NPK)_0$	645.8^{a}	589.6^{a}	688.2^{a}	865.2^{a}	745.8^{a}	894.7^{ab}
	$CB_{2.5}(NPK)_{25}$	818.2^{b}	746.9^{bc}	976.5^{b}	1284.9^{c}	967.2^{c}	1309.3^{d}
	$CB_5(NPK)_{50}$	897.9^{bc}	862.7^{def}	1217.8^{d}	1675.4^{e}	1386.2^{e}	1659.8^{g}
	$CB_{7.5}(NPK)_{75}$	967.3^{cd}	954.1^{fg}	1498.6^{f}	2181.2^{h}	1645.9^{g}	1974.1^{j}
	$CB_{10}(NPK)_{100}$	1210.7^{e}	1119.4^{h}	1509.3^{f}	2498.9^{i}	1969.1^{i}	2224.9^{k}
Mulching	$CB_0(NPK)_0$	638.2^{a}	575.2^{a}	673.2^{a}	837.1^{a}	710.5^{a}	857.9^{a}
	$CB_{2.5}(NPK)_{25}$	809.5^{b}	734.9^{b}	925.6^{b}	997.6^{b}	898.6^{bc}	1242.9^{c}
	$CB_5(NPK)_{50}$	872.9^{b}	855.7^{de}	1135.9^{c}	1394.2^{d}	1159.7^{d}	1523.2^{l}
	$CB_{7.5}(NPK)_{75}$	942.1^{bcd}	938.8^{fg}	1285.2^{d}	1692.4^{e}	1483.9^{f}	1773.7^{h}
	$CB_{10}(NPK)_{100}$	1002.7^{d}	1009.1^{g}	1405.1^{e}	1997.9^{g}	1756.5^{h}	2023.8^{j}
Tied ridges	$CB_0(NPK)_0$	698.3^{a}	630.2^{a}	710.8^{a}	895.4^{a}	862.6^{b}	923.6^{b}
	$CB_{2.5}(NPK)_{25}$	857.9^{b}	821.9^{cd}	1145.7^{c}	1387.1^{d}	1215.8^{d}	1412.6^{e}
	$CB_5(NPK)_{50}$	959.7^{cd}	915.7^{ef}	1483.4^{f}	1845.6^{f}	1655.7^{g}	1862.2^{i}
	$CB_{7.5}(NPK)_{75}$	1215.7^{e}	1109.3^{h}	1689.3^{g}	2210.5^{h}	1987.1^{i}	2247.9^{k}
	$CB_{10}(NPK)_{100}$	1268.1^{e}	1211.9^{i}	1839.9^{h}	2615.9^{j}	2215.3^{j}	2547.3^{l}
P-value		*0.001*	*0.001*	*< 0.001*	*0.001*	*0.001*	*< 0.001*
$LSD_{0.05}$		*90.4*	78.2	60.7	*90.4*	78.2	60.7
CV (%)		*1.9*	*1.1*	0.9	*1.9*	*1.1*	*0.9*

3.4 Effects of INM and water conservation techniques on nitrogen use efficiency (NUE)

Nutrient use efficiency (NUE) was significantly ($p < 0.05$) affected by INM and water conservation techniques. Results indicated that NUE was highest from planting pits for water conservation techniques, and $CB_{7.5}(NPK)_{75}$ for INM, and SCXH102 for the sorghum variety. NUE increased with an increase in application rates of INM up to $CB_{7.5}(NPK)_{75,}$ and an additional increase in 2.5t ha^{-1} compost-biochar + 25kg ha^{-1}NPK showed a significant decline in NUE (Table 6). Additionally, NUE ranged from 0.97 to 1.88kg ha^{-1} from planting pits under Macia and SCXH102, respectively. The planting pit had a significant ($p < 0.05$) NUE that was 9.5% and 43.8% above the tied ridge and mulching, respectively. Furthermore, the 2024/25 cropping season had the highest NUE, which was 28.6% and 50% above the results from 2022/23 and 2023/24 seasons, respectively.

Table 6
Sole effects of INM, water conservation, and variety on NUE over the 2022/23 to 2024/25 cropping season

Treatment	Sorghum grain yield (kg kg^{-1})
INM (Compost-Biochar/NPK) (t ha^{-1}/kg ha^{-1})	
CB_0NPK_0	0.97^{e}
$CB_{2.5}NPK_{25}$	1.1^{d}
CB_5NPK_{50}	1.9^{c}
$CB_{7.5}NPK_{75}$	2.6^{b}
$CB_{10}NPK_{100}$	2.2^{a}
LSD (5%)	0.023
P-value	< 0.001
Water conservation	
Planting pits	2.3^{a}
Tied ridge	2.1^{b}
Mulching	1.6^{c}
LSD (5%)	0.023
P-value	< 0.001
Variety	
Macia	1.1^{b}
SCXH102	2.5^{a}
LSD (5%)	0.037
P-value	< 0.001
Season	
2022/23	2.1^{b}
2023/24	1.8^{c}
2024/25	2.7^{a}
LSD (5%)	0.037
P-value	< 0.001

The interactive effects of INM and water conservation were significant, and the highest NUE was observed from $CB_{7.5}(NPK)_{75}$ + planting pit, which had 2.67kg kg^{-1} regardless of variety and season. Additionally, the interactive effects of INM and variety, and water conservation and variety were also significant ($p < 0.05$) with better performances observed from $CB_{7.5}(NPK)_{75}$ + SCXH102, and planting pit + SCXH102, respectively. The interactive effects of compost-biochar-NPK, water conservation, and variety were significant ($p < 0.05$) on NUE. SCXH102 had the highest NUE of 4.26 kg kg^{-1} at $CB_{7.5}(NPK)_{75}$ + planting pit during the 2024/25 season (Table 7). NUE decreased with an increase in the application rate of INM after $CB_{7.5}(NPK)_{75,}$ except for Planting pit + $CB_{10}(NPK)_{10}$ + Macia + 2022/23, and Mulching + $CB_{10}(NPK)_{10}$ + SCXH102 + 2022/23 and 2023/24 (Table 7).

Table 7
Interactive effects of INM and water conservation on NUE

Treatment combinations		Macia NUE (kg kg^{-1})			SC HX102 NUE (kg kg^{-1})		
Water conservation	**Compost +biochar (t ha^{-1}) + NPK (kg ha^{-1})**	**2022/23**	**2023/24**	**2024/25**	**2022/23**	**2023/24**	**2024/25**
Planting pits	$CB_{2.5}(NPK)_{25}$	1.36^{g}	1.24^{bc}	2.27^{b}	3.31^{c}	1.75^{c}	3.27^{d}
	$CB_{5}(NPK)_{50}$	0.99^{e}	1.08^{def}	2.09^{d}	3.2^{e}	2.53^{e}	3.02^{g}
	$CB_{7.5}(NPK)_{75}$	0.85^{c}	0.96^{fg}	2.13^{f}	3.46^{h}	2.37^{g}	4.26^{j}
	$CB_{10}(NPK)_{100}$	1.11^{f}	1.04^{h}	1.62^{f}	3.22^{i}	2.41^{i}	2.62^{k}
Mulching	$CB_{2.5}(NPK)_{25}$	1.35^{g}	1.26^{b}	1.99^{b}	1.27^{b}	1.48^{bc}	3.03^{c}
	$CB_{5}(NPK)_{50}$	0.93^{d}	1.11^{de}	1.83^{c}	2.2^{d}	1.77^{d}	2.62^{l}
	$CB_{7.5}(NPK)_{75}$	0.8^{b}	0.96^{fg}	1.61^{d}	2.25^{e}	2.03^{f}	2.41^{h}
	$CB_{10}(NPK)_{100}$	0.72^{a}	0.86^{g}	1.44^{e}	2.3^{g}	2.06^{h}	2.3^{j}
Tied ridges	$CB_{2.5}(NPK)_{25}$	1.26^{b}	1.51^{cd}	3.43^{c}	3.88^{d}	2.79^{d}	3.86^{e}
	$CB_{5}(NPK)_{50}$	1.03^{e}	1.13^{ef}	3.05^{f}	3.75^{f}	3.13^{g}	3.7^{i}
	$CB_{7.5}(NPK)_{75}$	1.36^{g}	1.26^{h}	2.57^{g}	3.46^{h}	2.96^{i}	3.48^{k}
	$CB_{10}(NPK)_{100}$	1.13^{f}	1.15^{i}	2.23^{h}	3.39^{j}	2.67^{j}	3.2^{l}
P-value		*0.001*	*0.001*	*< 0.001*	*0.001*	*0.001*	*< 0.001*
$LSD_{0.05}$		*0.045*	0.0321	0.015	*0.045*	0.0321	0.015
CV (%)		*0.9*	*1.2*	1.1	*0.9*	*1.2*	1.1

4. Discussion

4.1 Soil moisture content

Soil moisture content increased with an increase in application rates of INM and water conservation techniques. This increase in soil moisture content was based on the increase in soil organic matter caused by the application of a compost-biochar combination and water harvested by planting pits, tied ridges, and mulching material that minimises surface evaporation. This was similar to findings by Madembo & Nyagumbo (2026), Cosmas et al. (2026), Peng et al. (2026), and Su et al. (2026), who reported an increase in soil moisture content with INM and rainwater harvesting techniques in semi-arid areas associated with sandy to sandy loam soils. An increase in soil moisture content with a combination of biochar, mineral fertilizer, and compost manure was also reported by Mwadalu (2023), who indicated that soil moisture content increased in sandy soil by 23 to 191% due to an increase in organic matter that increases soil total porosity and enhances soil structure. Additionally, soil moisture has been reported to increase with the use of water conservation techniques, for example, mulching using crop residues increased soil moisture content with an average of 56% in semi-arid areas (Ayala et al. 2023). The increase in soil moisture content with the use of INM of biochar and compost together with water conservation techniques was because organic manure increases water retention due to improved soil porosity, and water retention by organic manure. Tied ridges collect water and recharge soil moisture in the 0-40cm deep hence increasing soil moisture content (Mandumbu et al. 2021; Swai et al. 2023). Furthermore, combining INM and water conservation improves soil structure, texture, and soil organic matter, that increase water retention (Kubiku et al. 2025). An increase in soil moisture from this study was also reported in Burkina Faso and Tanzania with the use of INM and water conservation techniques (Zougmoré et al. 2003; Mahinda et al. 2018; Mdemu et al. 2025). Additionally, higher soil moisture content at 11WAE during the 2024/25 cropping season was caused by rainfall received during that recharge soil moisture, especially at 20-40cm deep.

4.2 Sorghum grain yield

Sorghum grain yield increased with an increase in INM application rates, and this may have been caused by improvements in soil fertility. Soil fertility improvements were due to increased soil organic matter that minimizes leaching of nutrients, increases water retention, and cation exchange capacity (Kantwa et al. 2025; Madembo and Nyagumbo 2026). The availability of nutrients increased sorghum growth and surface area for photosynthesis, leading to higher starch content translocated to seeds, hence heavier seeds were produced. Results from this study were similar to findings by Feyisa & Anbesa (2025) and Dube et al. (2024), who reported an increase in sorghum grain yield with the use of INM in sub-Saharan Africa. INM that includes organic manure and mineral fertiliser has been reported to be one of the best because mineral fertiliser provides ready nutrients and organic manure releases nutrients slowly in the soil, reducing nutrient stress during critical physiological periods. Furthermore, an increase in grain yield from this study was enhanced by biochar, which is a soil conditioner that increases soil organic carbon and minimizes emission of greenhouse gases, hence increasing crop productivity (Jindo et al. 2025; Niaz et al. 2025; Dhakal et al. 2026). Additionally, Jelita et al. (2026) reported an increase in sorghum yield with a compost-biochar combination because of increased soil moisture content that supports crop growth even during a dry spell. The use of water conservation increased sorghum grain yield above 500kg

ha^{-1}, realised by some smallholder farmers. Results from this study concur with Cosmas et al. (2026), who indicated that tied ridges double sorghum grain yield. The same effects were reported by Nahed et al. (2026) using furrow ridges and organic manure coupled with mineral fertiliser. So, combining INM with water conservation played a key role in increasing soil moisture content, making it available to plants even during dry spells, hence causing an increase in grain yield of sorghum. This was also reported by Kugedera et al. (2023) in Zimbabwe, where INM in combination with tied contour increased sorghum grain yield to 1146kg ha^{-1} in sandy loam soils. Furthermore, tied ridges and INM increase water use efficiency, hence higher yields (Kubiku et al. 2023; Kugedera et al. 2024). However, the use of INM and water conservation has also been reported to show no significant changes in crop yields. Planting pits and tied ridges are labour-intensive, and this can affect their adoption since most smallholder farming systems are now characterised with old aged farmers. Legume mulching may be difficult to get due to its competition for fodder.

4.3 Nitrogen use efficiency (NUE)

The increase in NUE was due to improvements in nitrogen availability caused by the application of INM of compost-biochar-NPK combination. Biochar and compost manure increase soil organic matter that minimizes leaching, releases nitrogen in the plant root zone, enhance nitrogen utilisation efficiency (Gezahegn et al. 2025; Guo et al. 2025). Compost-biochar combination improves soil fertility, facilitates an increase in microbial biomass, and increases nitrogen use efficiency, especially in sandy to sandy loam soils (Piash et al. 2025). This was similar to findings reported from this study, where INM of biochar, compost, and NPK fertiliser increased NUE. Similar effects were reported by Kumar et al. (2026), who reported that adding 30% NPK to biochar enhances NUE in sorghum. Combined application can improve physiological NUE due to an increase in total N in the soil (Kabato et al. 2025; Kesamreddy et al. 2025; Kugedera and Naik 2026). The highest NUE obtained from $CB_{7.5}(NPK)_{75}$ + planting pits indicated that this is the sustainable application rate and water conservation technique that has the capacity to enhance NUE by sorghum, and any application above this causes a loss, as more nitrogen in amendments will not be lost through leaching. The availability of water from planting pits increases absorption rates and minimizes nutrient loss. Results from this study also agree with findings by several authors who indicated that NUE is improved with the use of organic manure in combination with mineral fertilisers (Pramanick et al. 2024; Fu et al. 2025; Ndiaye et al. 2025). NUE can only be reduced with the application of poor-quality INM amendments with no water conservation techniques used in semi-arid areas.

5. Conclusion

Climate change has caused frequent droughts in semi-arid areas, increased temperatures, and shortened the cropping season. Heavy downpours received once per season also contributed to soil degradation, which also causes soil infertility. The application of inadequate soil amendments causes soil infertility and contributes to poor crop productivity. This calls for nutrient management and conservation of the low and erratic rainfall received in these areas. The adoption of INM and water conservation techniques together with sorghum has the potential to achieve climate-smart agriculture in semi-arid areas and improve food security in these areas. INM of biochar, compost, and NPK fertiliser proved to be a sustainable solution when combined with the water conservation technique of mulching to increase soil moisture content. The application of $CB_{10}(NPK)_{100}$ INM + tied ridge and SCXH102 had the highest grain yield that can sustain smallholder farmers for two years. Additionally, NUE was highest from $CB_{7.5}(NPK)_{75}$ + planting pit + SCXH102, and this showed that application of this INM is sustainable and has the potential to reduce the burden on smallholder farmers. INM that involves organic manure enhances water retention, which can be coupled with water conservation techniques such as planting pits, mulching, and tied ridges to support efficient utilisation of nutrients.

Declarations

Electronic supplementary information

Not applicable

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Author contribution

ATK carried out the experiments, collected data, analysed data, and wrote the paper. Implement revisions from **LKK** and **NM**. **LKL** managed the experiments, collected data, and read the first and final drafts. **NM** designed the experiments, read the first draft, and corrected it.

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Competing interests

Authors declare no conflict of interest

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