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ENHANCING MAIZE PRODUCTIVITY WITH INFIELD RAINWATER HARVESTING TECHNIQUES AND CATTLE MANURE IN SEMI-ARID AREAS OF ZIMBABWE

Andrew Tapiwa KUGEDERA[1,2*], Ponesai MUTERO[3] and Letticia Kudzai KOKERAI[3]

[1]Department of Agriculture Management, Zimbabwe Open University, P.O Box 1210, Masvingo, Zimbabwe
[2]Department of Mathematics and Science, Morgenster Teachers College, Masvingo, Zimbabwe
[3]Department of Crop and Livestock, Ministry of Lands, Agriculture, Fisheries, Water and Rural Development, Masvingo, Zimbabwe; email: ponesaimutero@gmail.com; kokerailk@gmail.com

*Correspondence: kugederaandrew48@gmail.com

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ABSTRACT. Soil fertility and moisture management can be sustainable ways to improve crop production in low rainfall areas. The aim of this study was to evaluate the effects of infield rainwater harvesting and cattle manure on maize yield, rainwater use efficiency, agronomic efficiency, and the value–cost ratio. The experiment used a split plot design with three in situ rainwater harvesting (IRWH) techniques (planting pits, infiltration pits, and conventional tillage (as a control)) as the main treatment factor and cattle manure as the sub-plot factor at four levels (0, 2.5, 5, and 10 t ha^{-1}). The interactive effects of IRWH, cattle manure, and season were significant among all parameters measured ($p<0.05$). The highest maize grain yield (3990 kg ha^{-1}) was obtained from the planting pits with 10 t ha^{-1} cattle manure in the 2022/23 cropping season. Maize stover yield increased with an increase in cattle manure, with the highest yield of 6450 t ha^{-1} at 10 t ha^{-1} cattle manure. Rainwater use efficiency was significantly ($p<0.05$) increased by an average of 2.5 kg ha^{-1} mm^{-1} from 0 to 2.5 t ha^{-1}. Agronomic use efficiency significantly decreased with the increasing application rate of cattle manure ($p<0.05$). The interaction of planting pits and 2.5 t ha^{-1} cattle manure had the highest cost ratio of 6.66 in the 2022/23 season. The interaction between planting pits and 10 t ha^{-1} cattle manure resulted in higher maize yields and rainwater use efficiency. However, it is recommended that smallholder farmers use planting pits and 2.5 t ha^{-1} cattle manure to obtain higher yield increments and high profits in high-risk climates.

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Keywords: agronomic efficiency; infiltration pits; maize production; planting pits; value–cost ratio.

INTRODUCTION

Crop productivity in semi-arid and arid regions is mainly limited by erratic and low rainfall, which is unreliable and causes scarcity in soil water, leading to poor growth and crop development (Swai *et al*., 2023). Semi-arid areas are associated with long mid-season droughts, which sometimes become frequent during the cropping season, exposing crops to high evapotranspiration rates and reducing nutrient uptake and growth (Enciso *et al*., 2019; Shumba *et al*., 2020; Sileshi *et al*., 2019). Low nutrient uptake is also caused by soil infertility, which is another constraint faced by farmers in semi-arid areas. This has been attributed to inadequate nutrient application since many smallholder farmers are resource poor and unable to procure adequate mineral fertiliser (Kugedera and Kokerai, 2024; Winter-Nelson *et al*., 2016). Soils in semi-arid areas are mainly sandy to sandy loam that are infertile because of the monoculture practiced by smallholder farmers (Kugedera *et al*., 2023a; Sileshi *et al*., 2019). To reduce these constraints, smallholder farmers can adopt infield rainwater harvesting (IRWH) techniques and use different rates of cattle manure to improve the soil water and nutrient content.

Maize (*Zea mays L*) is ranked first in Zimbabwe in terms of staple crops (Tapiwa *et al*., 2020). Maize is used as the main staple food in many sub-Saharan African (SSA) countries, including Zimbabwe (Ayanlade *et al*., 2018; Tapiwa *et al*., 2020). Many smallholder farmers in semi-arid areas of SSA harvest maize grain yields below 500 kg ha^{-1} with only a few achieving yields above 1000 kg ha^{-1} (Kugedera and Kokerai, 2024). This means that many people in semi-arid areas that depend on maize are food insecure. Maize productivity is highly different from small grain production, which is drought tolerant and performs better under low rainfall. Farmers growing small grains, especially sorghum, harvest 200–500 kg ha^{-1} of grain yield, which improves food security (Enciso *et al*., 2019). To improve maize grain yield, farmers can use cattle manure and IRWH techniques, such as planting pit (PP) and infiltration pit (IP), which harvest and store rainwater, allowing its later use in crops (Kubiku *et al*., 2022; Kugedera and Kokerai, 2024).

Planting pits are holes dug by farmers to a depth of 15 cm and width of 20 cm so that they collect enough water to sustain crop growth for 3 weeks during dry spell (Kugedera *et al*., 2023b). Farmers can apply cattle manure and mix it with soil before rain, allowing for the decomposition of cattle manure. A maximum of three seeds can be placed in each pit and thinned to two (Kokerai and Kugedera, 2019). Planting pits have been reported to increase crop yield, although they are labour intensive because they need to be dug every cropping season (Kugedera and Kokerai, 2024).

Infiltration pits are dug either in the field or on the field edge to collect rainwater during rainfall, reduce excess water loss from the field, and recharge the soil water in the rooting zone during dry spells (Chilagane *et al*., 2020; Nyagumbo *et al*., 2019). Infiltration pits holding 1.25 m^3 per pit have the following dimensions:

0.5 m long × 0.5 m wide × 0.5 m deep. Infiltration pits can be used to make compost during the off-season, which makes soil nutrient sources readily available. Infiltration pits have been reported to increase maize yield (Nyagumbo *et al*., 2019; Nyakudya *et al*., 2014; Nyamadzawo *et al*., 2015) and sorghum grain yield (Kubiku *et al*., 2022; Kugedera *et al*., 2023a). Rainwater harvested by IPs laterally moves into the soil, reducing soil moisture stress and improving crop growth and development, especially when crops are in the physiological stages, such as grain filling, which is highly correlated with grain yield.

Cattle manure application by smallholder farmers has been the norm in Zimbabwe, with many farmers applying it as a basal fertiliser during ploughing. Many farmers apply inadequate quantities of cattle manure that do not meet the recommended rates of 20–40 t ha^{-1} (Mucheru-Muna *et al*., 2014; Nyamangara *et al*., 2005, 2013). Cattle manure contains all the required minerals, including trace elements, that are not supplied by mineral fertilisers. Cattle manure improves the soil structure, regulates soil pH, and improves soil health (Kimaru-Muchai *et al*., 2021; Mamuye *et al*., 2021). Furthermore, cattle manure reduces mesopores and macropores to micropores, thereby increasing the water retention capacity of the soil and supplying more water in the rooting zone (Eleduma *et al*., 2020). Therefore, integrating IRWH techniques with cattle manure can be a major solution for smallholder farmers to reduce soil water scarcity and nutrient stress and to improve maize grain yield. Combining these two factors has the potential to increase maize grain yield above 1500 kg ha^{-1} for many smallholder farmers in semi-arid areas of Zimbabwe. Smallholder farmers in semi-arid areas of Zimbabwe have been using less decomposed cattle manure and apply it late in October, when rain is to be expected. This reduces the quality of manure and affects the rate of decomposition and, thus, yield. Farmers in the study area have low adoption of IRWH and have failed to implement them properly, leading to low yield and abandonment of the technique. Therefore, the objectives of this study were to: (i) determine the effects of IRWH and cattle manure on maize grain and stover yield; (ii) evaluate the effects of IRWH and cattle manure on rainwater use efficiency, agronomic efficiency, and the value–cost ratio (VCR) of maize in a semi-arid region of Zimbabwe. The study was based on the following hypotheses: (i) the use of IRWH and cattle manure significantly increases maize grain and stover yield in the semi-arid region of Zimbabwe and (ii) the VCR, agronomic efficiency, and rainwater use efficiency of maize can significantly increase with the use of IRWH and cattle manure in the semi-arid region of Zimbabwe.

MATERIALS AND METHODS

Study area

This study was conducted at Rudzana Farm (19°52’52” S and 31°14’51” E, 890 m above sea level) in Gutu District, Masvingo Province. The study area is characterised by semi-arid climatic conditions and lies in agroecological zone IV, which receives

450–650 mm per annum of rainfall in a single season between October and April (Manatsa *et al.*, 2020). This region is subjected to frequent seasonal droughts and extended dry spells during the rainy season, and the probability of receiving annual rainfall above 600 mm is only 45–65% (Manatsa *et al.*, 2020).

The experimental site is characterised by sandy loam soils with a low nitrogen content, which can be improved by soil fertility management. The soil belongs to the Fersiallitic 5G group and is regarded as nitisol/luvisol. Maize accounts for more than half of the total crop area (Twomlow *et al.*, 2008). Minor crops grown in this area include cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea L*), Bambara nut (*Vigna subterranean*), and sorghum (*Sorghum bicolor*).

Soil characterisation

Soil characterisation was performed using zigzag soil sampling to collect soil samples before land preparation. Fifteen sampling points were randomly allocated, and samples were collected. All collected samples were thoroughly mixed and dried in the shade, and a composite sample (1 kg) was prepared after sieving using a 2 mm sieve. The pH was measured using the chloride ($CaCl_2$) method (Mamuye *et al.*, 2021), and the Bouyoucos hydrometer method was used to determine the soil texture (Kubiku *et al.*, 2022). The Kjeldahl method was used to determine the total nitrogen content (Kugedera *et al.*, 2023b), and wet digestion and Olsen methods were used to determine the soil organic carbon and available phosphorous content, respectively (Mamuye *et al.*, 2021). The exchangeable cations (potassium, magnesium, and calcium) were determined using ammonium acetate at pH 7. The soil characteristics are presented in *Table 1*.

Table 1 – Physiochemical properties of soil in the study area during the 2022/23 cropping season

Parameter	Composition
pH ($CaCl_2$)	5.7
SOC (g kg^{-1})	11.2
Total nitrogen (g kg^{-1})	1.2
P_2O_5 (mg kg^{-1})	3.36
K_2O (cmol $_{(+)}$ kg^{-1})	0.34
Calcium (cmol $_{(+)}$ kg^{-1})	0.95
Magnesium (cmol $_{(+)}$ kg^{-1})	0.46
Bulk density (Mg m^{-3})	1.66
Sand (%)	73.2
Clay (%)	6.1
Silt (%)	20.7
Texture	Sandy loam (Nitisol/Luvisol)

Rainfall

A standard rain gauge installed at the experimental site was used to measure daily rainfall. The total rainfall received during the 2021/22 and 2022/23 cropping seasons was associated with long mid-season droughts. Furthermore, the total rainfall received was low compared to the 30-year average of 450 mm for agroecological zone IV (Manatsa *et al.*, 2020). More rainfall was received from the end of February to mid-March, totalling 225 mm in 2022/23, which supported the plants' maturity.

The rainfall received, totalling 405 and 424 mm during the 2021/22 and 2022/23 seasons, respectively, is shown in *Figure 1*.

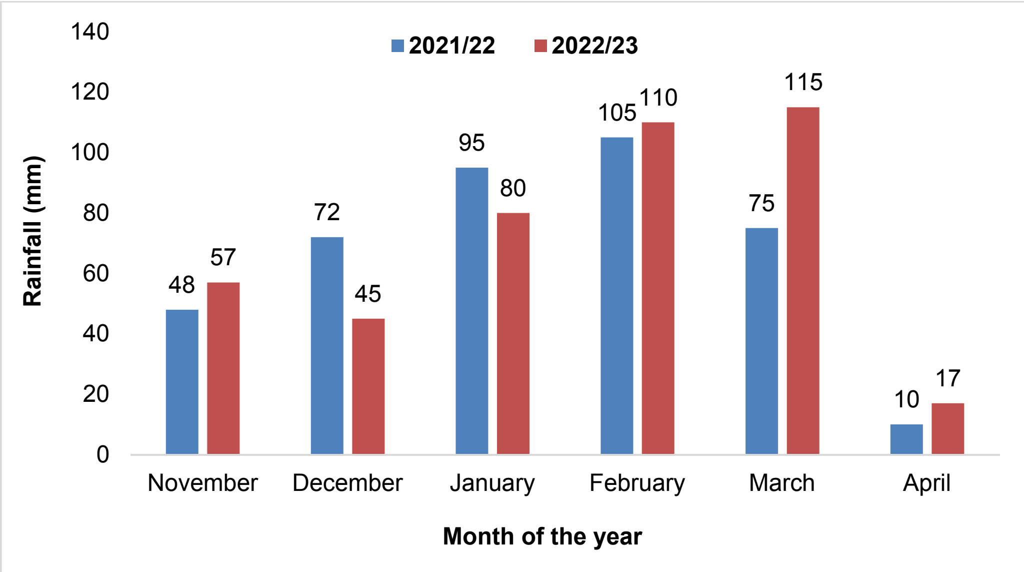

Figure 1 – Rainfall received during the 2021/22 and 2022/23 cropping seasons at the experimental site

Experimental materials

The maize variety used for this experiment was SC419, a short-season variety that requires an average of 110 d to reach maturity. This is a new hybrid seed with an average yield of 13,800 kg ha^{-1} under proper agronomic practices and good rain, particularly in agroecological zones 1 and 2 in Zimbabwe. This variety matures early, making it suitable for smallholder farmers in semi-arid areas who receive rainfall for an average of four months. Decomposed cattle manure was obtained from a local farmer who had already removed it from the kraal. The nutritional chemical composition of cattle manure was analysed, and the results are shown in *Table 2*. Ammonium nitrate (34.5%) and nemesis were obtained using a presidential input scheme. Nemesis (containing chlorfluazuron as an active ingredient) was used to control the fall armyworm. This chemical is manufactured by Philagro South Africa and the AGRICURA company in Zimbabwe for insect control.

Experimental design and treatments

The experiment was laid out in a split plot design, with water management used as the main treatment factor at three levels (planting pit (PP), infiltration pit (IP), and conventional tillage (CT) as a control) and cattle manure as a sub-plot factor at four levels (0, 2.5, 5, and 10 t ha^{-1}). Blocking was performed using water management and randomised using the application levels of cattle manure. Planting pits were dug using a hand hoe to a depth of 20 cm and a width of 15 cm. The pits were spaced at 75 cm between rows and 30 cm within each row. IPs were constructed using a pick and shovel along the standard contour to a depth of 50 cm, length of 3 m, and width of 100 cm. Conventional tillage was characterised by ploughing, using an animal-drawn mouldboard plough to a depth of 20 cm. The costs incurred during construction of IRWH and for CT are shown in Table 3. The main plot measured 100 m × 6 m, and treatment plots measured 3 m × 5 m within the main plot and were spaced 0.5 m apart and replicated three times. Cattle manure was applied as basal manure in November 2022. Two seeds were placed in each planting station using a plant spacing of 75 cm × 30 cm to achieve a plant population of 44,444 plants per hectare. Thinning was performed on two plants per station at three weeks after emergence. Weeding was performed using a hand hoe 28 days after emergence and repeated on day 56. Top dressing was performed using ammonium nitrate at a rate of 300 kg ha^{-1} (103.5 kg N ha^{-1}) as a double-split application at a rate of 150 kg ha^{-1} (51.75 kg N ha^{-1}) per split.

Data collection

The collected data included maize grain and stover yields, rainwater use efficiency (RWUE), agronomic use efficiency (AE), and VCR. Maize was harvested at maturity, when grain attained a moisture content of 12.5%. The yield was correlated to kg ha^{-1} using *Equation 1*. The stover yield was determined by cutting the stover closer to the ground using sharp hoes and cutting it into small pieces using machetes for each treatment and its replicates. The stover was placed into sacks of known weight and weighed using a digital scale and correlated to kg ha^{-1} using *Equation 1*. Rainwater use efficiency was determined using *Equation 2*. The AE was determined using *Equation 3*. The VCR was determined using the local market prices of maize determined by the Grain Marketing Board (GMB) and the costs incurred for transport, loading, and offloading cattle manure. Maize was sold at US$340 t^{-1} in the 2021/22 and 2022/23 cropping seasons. Cattle manure was obtained freely. The cost of transporting, loading, and offloading cattle manure was US$50 t^{-1} during the 2021/22 and 2022/23 cropping seasons. The VCR was calculated using *Equation 4*.

$$\text{Yield (kg ha}^{-1}\text{)} = \frac{Yield\ in\ the\ net\ plot \times 10000 m^2}{net\ plot\ area} \quad (1)$$

$$\text{RWUE (kg ha}^{-1}\text{ mm}^{-1}\text{ rainfall)} = \frac{Total\ grain\ yield\ (kg\ ha^{-1})}{Total\ rainfall\ (mm)} \quad (2)$$

$$\text{AE (kg kg}^{-1}\text{)} = \frac{\text{Grain yield of fertilised plot (kg)} - \text{grain yield in control plot(kg)}}{Amount\ of\ ammendment\ applied\ (kg)} \quad (3)$$

$$\text{Value–cost ratio (VCR)} = \frac{Value\ of\ grain\ yield\ obtained}{Cost\ of\ cattle\ manure\ incurred} \quad (4)$$

Table 2 – Nutritional composition of cattle manure used during the experiment

Treatments	N (g kg^{-1})	P (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	K (g kg^{-1})	C (g kg^{-1})
Cattle manure	10.2	2	4	8.9	18	112.3

Table 3 – Labour requirements during land preparation, application of cattle manure, and weeding

IRWH method	Average man days ha^{-1}	Average man hours ha^{-1}	Average cost ha^{-1} (US$)
PP	18	144	90
IP	21	168	105
CT	12	96	60
Other cost			
Seeds			75
Weeding			
PP	8	64	40
IP	13	104	65
CT	13	104	65
Application of cattle manure			
PP	18	144	90
IP	15	120	75
CT	10	80	50

1 man day = 8 hours; 1 man day cost US$5; CT=Conventional tillage; IP=Infiltration pit; PP=Planting pit. 1 tonne was sold at US$340

Data analysis

Data were analysed with analysis of variance (ANOVA) using GenStat 14 at $p \leq 0.05$, and graphs were produced using Microsoft Excel. Means that showed significant differences were separated using Fisher's least significant difference (LSD) test at $p \leq 0.05$. The main effects used were IRWH and cattle manure application rates as random effects during data analysis.

The study used a general statistical model, as follows (*Equation 5*):

$$Y_{ijk} = \mu + ß_i + T_{j(i)} + ßT_{ij} + \varepsilon_{ijk} \quad (5)$$

where Y_{ijk} is the response variable to be analysed (maize yield, stover yield, RWUE, AE, and VCR); μ is the overall mean; $ß_i$ is the effect of the i^{th} RWH technique (block) and i-stands for 1, 2, and 3 (fixed effect), where 1 is PP, 2 is IP, and 3 is CT; $T_{j(i)}$ is the effects of the j^{th} cattle manure within the i^{th} block and j stands for 1, 2, 3, and 4, where 1 stands for 0, 2 stands for 2.5, 3 stands for 5, and 4 stands for 10 t ha^{-1}; $ßT_{ij}$ is the interaction of i^{th} RWH and j^{th} cattle manure; and ε_{ijk} is the whole plot error.

RESULTS

Effects of infield RWH and cattle manure on maize grain yield

The results showed significant effects ($p<0.05$) of IRWH and cattle manure on maize grain yield (*Table 4*). A higher maize grain yield was observed when using PP, which showed a significant difference ($p<0.05$) when compared with IP and CT.

Maize grain yield increased with increasing application rates of cattle manure (*Table 4*). Application of 2.5 t ha^{-1} had the highest increment in grain yield, which was 117% above that of 0 t ha^{-1}. The application rate of 10 t ha^{-1} did not show a rapid increase in maize grain yield compared with a 100% increase in cattle manure level at 5 t ha^{-1}.

There was a positive correlation (r^2=0.91–0.94) between the application rates of cattle manure and maize grain yield. Increasing application rates of cattle manure resulted in a linear increase in maize grain yield, with the highest correlation between cattle manure and grain yield observed in the 2021/22 cropping season (*Figure 2*).

The interactive effects of IRWH and cattle manure had significant effects ($p<0.05$) on maize grain yield (*Figure 3*). Treatments with PP and any application rate of cattle manure had the highest maize grain yield and showed a significant increase ($p<0.05$) compared with other treatments. Conventional tillage had the lowest maize grain yield at each application rate of cattle manure, which was also significantly lower ($p<0.05$) than that of the IP treatments. PP treatments had better increments in maize grain yield (1140 kg ha^{-1}) when an application rate of 2.5 t ha^{-1} was used compared with 0 t ha^{-1} (*Figure 3*). The increment produced a yield that could sustain one family for a period of 12 months.

Effects of infield RWH and cattle manure on maize stover yield

Maize stover yield was significantly influenced ($p<0.05$) by infield RWH, cattle manure, and season. The maize stover yield was significantly higher ($p<0.05$) in PP than in the CT and IP treatments. The cattle manure application rate had a significant effect on stover yield ($p<0.05$), with a higher yield observed at 10 t ha^{-1}. The increment in stover yield showed a trend of 2.5>5>10 t ha^{-1}, indicating that increasing cattle manure by 2.5 t ha^{-1} resulted in a better increment that was significantly different ($p<0.05$) from any other level. The stover yield was significant ($p<0.05$) due to infield RWH, cattle manure, and season. The interaction between infield RWH and cattle manure significantly increased maize stover yield ($p<0.05$). The integration of PP and cattle manure resulted in the highest stover yield (6450 kg ha^{-1}) at 10 t ha^{-1} of cattle manure, which was significantly different ($p<0.05$) from IP and CT under the same treatments (*Figure 4*). The application of 0 t ha^{-1} cattle manure showed no significant difference ($p>0.05$) between PP and IP (*Figure 4*). The stover yield was significantly higher in the 2022/23 cropping season than in the 2021/22 cropping season. All treatments under CT had significantly lower maize stover yields than those under PP and IP (*Figure 4*). Maize stover yield increased linearly with season and cattle manure application under different infield RWH techniques.

Interactive effects of infield RWH and cattle manure on rainwater use efficiency (RWUE)

The RWUE was significantly influenced ($p<0.05$) by infield RWH, season, and cattle manure. Increasing the application rate of cattle manure from 0 to 10 t ha^{-1} increased RWUE by more than 100%. Infield RWH techniques showed a trend of PP>IP>CT, with CT having the lowest RWUE over the two seasons. RWUE was highest (9.43 kg ha^{-1} mm^{-1}) with PP and 10 t ha^{-1} cattle manure during the 2021/22 cropping season (*Figure 5*). Rainwater use efficiency increased with an increase in the application rate of cattle manure, regardless of the season and infield RWH techniques. On average, RWUE was better in the 2021/22 cropping season compared with the 2022/23 cropping season, regardless of the treatment used.

Table 4 – Effects of tillage and cattle manure on maize grain yield

Treatment	Maize grain yield kg ha^{-1}	
	2021/22	**2022/23**
Planting pits	1295[a]	1305[a]
Infiltration pit	1118[b]	1130[b]
Conventional tillage	945[c]	968[c]
LSD (0.05)	155.6	155.6
P-value	<0.001	<0.001
Cattle manure (t ha^{-1})		
0	689[d]	727[d]
2.5	1437[c]	1575[c]
5	1845[b]	1962[b]
10	2398[a]	2452[a]
LSD (0.05)	168.1	168.1
P-value	<0.001	<0.001

Different lowercase letters within a column indicate significant differences between values, according to Fisher's test ($p \leq 0.05$). LSD means least significant different

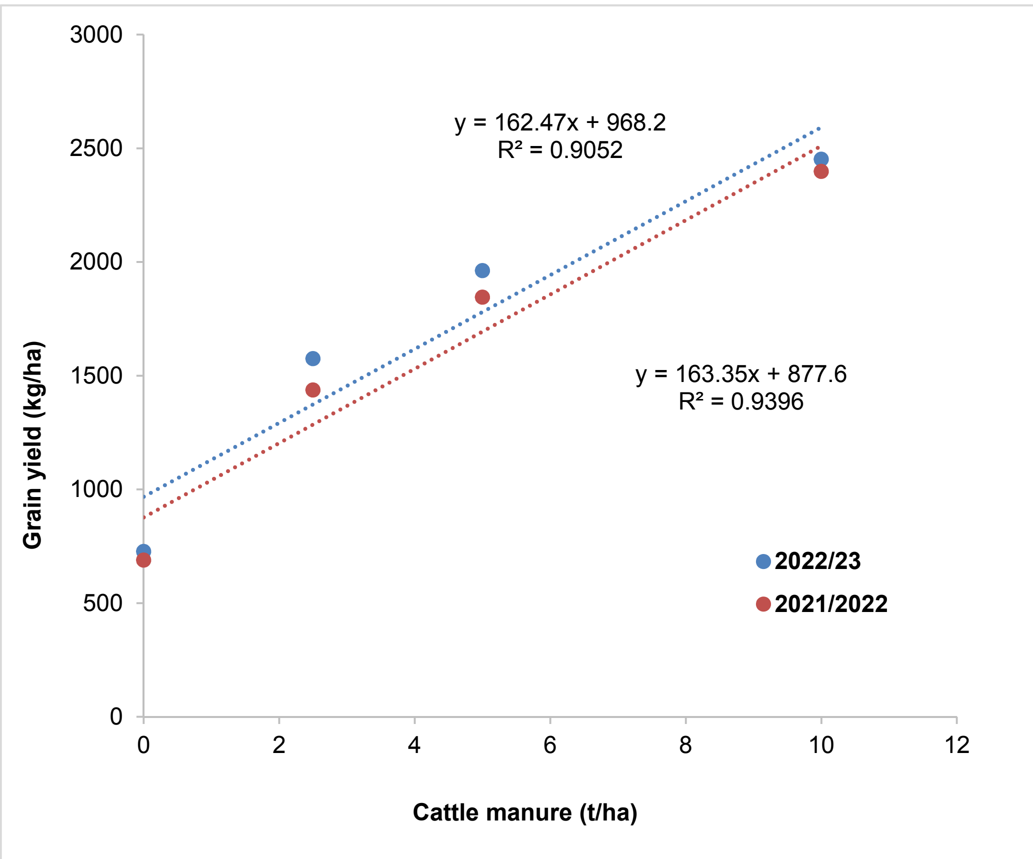

Figure 2 – Relationship between cattle manure and maize grain yield

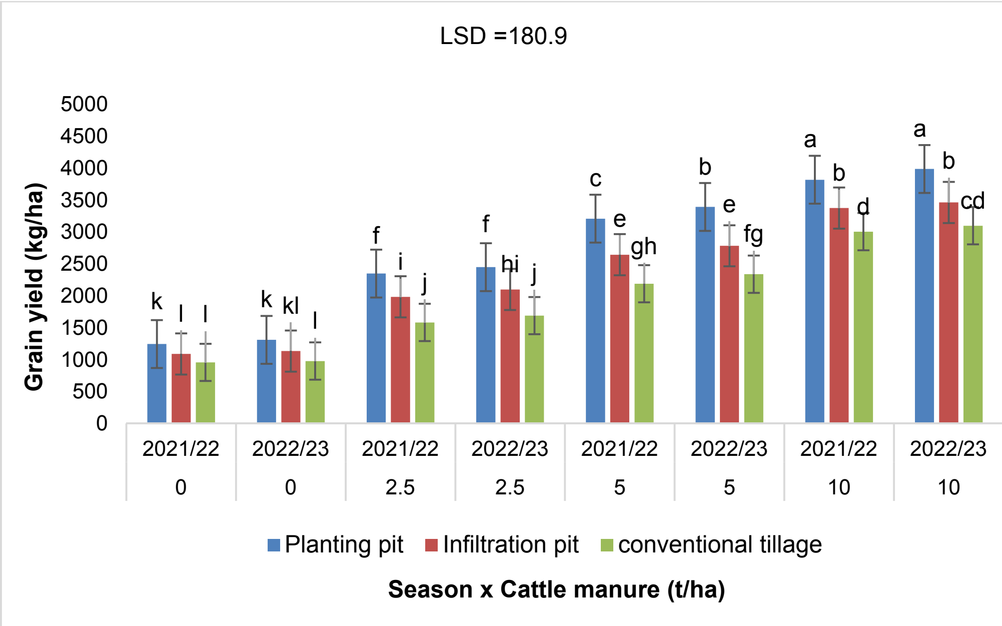

Figure 3 – Interactive effects of IRWH and cattle manure on maize grain yields.
Vertical bars represent the standard error (SE).
Bars with different letters (a–l) are significantly different at p≤0.05

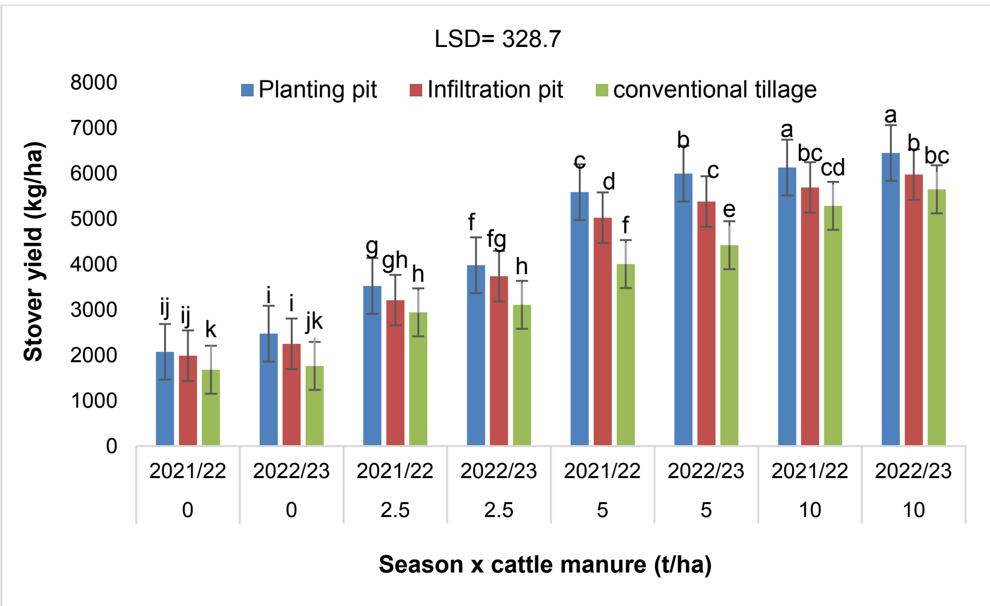

Figure 4 – Interactive effects of IRWH and cattle manure on maize stover yields.
Vertical bars represent the standard error (SE).
Bars with different letters (a–k) are significantly different at p≤0.05

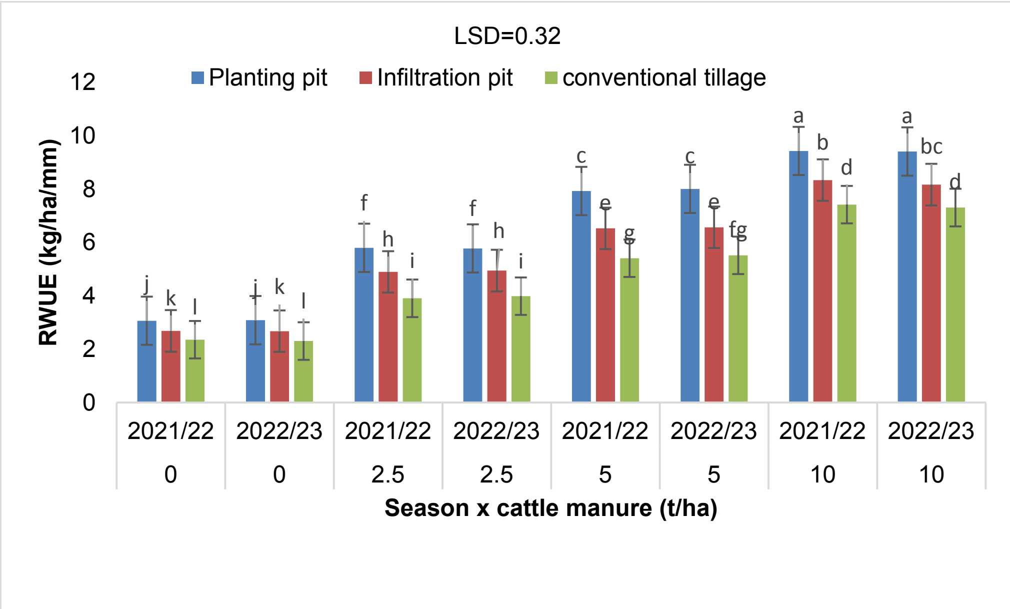

Figure 5 – Interactive effects of infield RWH and cattle manure on RWUE. Vertical bars represent the standard error (SE). Bars with different letters (a–l) are significantly different at p≤0.05. RWH means rainwater harvesting and RWUE means rainwater use efficiency

Effects of infield RWH and cattle manure on agronomic use efficiency (AE)

Infield RWH, cattle manure, and cropping season had significant effects on AE. Agronomic efficiency was the highest in PP, which showed significant differences among the other RWH techniques ($p<0.05$). The application rate of 2.5 t ha^{-1} showed significant effects ($p<0.05$) on AE compared with the other rates. The integration of infield RWH, cattle manure, and season showed significant differences ($p<0.05$) in AE (*Figure 6*). An increase in the cattle manure application rate decreased AE regardless of the infield RWH technique and cropping season. Agronomic efficiency was highest with PP and 2.5 t ha^{-1} cattle manure in the 2022/23 cropping season, with an average of 0.46 kg kg^{-1}. In addition, AE decreased by an average of 16% with an increase in the cattle manure application rate.

Effects of infield RWH and cattle manure on the value–cost ratio (VCR)

Infield RWH, cattle manure, and season had significant effects on the value cost ratio (VCR) ($P<0.05$). The application rate of 2.5 t ha^{-1} had the highest VCR, which was significant among all application rates ($p<0.05$). The interactive effects of infield RWH and cattle manure, RWH and season, and cattle manure and season were also significant ($p<0.05$). Interactive effects of RWH, cattle manure, and season were significant ($p<0.05$). *Figure 7* shows that the VCR decreased with an increase in the cattle manure application rate, regardless of the RWH technique and season. The VCR decreased by an average of 145.8% from the application rate of 2.5 to 10 t ha^{-1}. Furthermore, VCR was better in the 2022/23 cropping season than in the 2021/22 season. Although VCR decreased with the application rate, VCR was always above 2, indicating that profits were incurred.

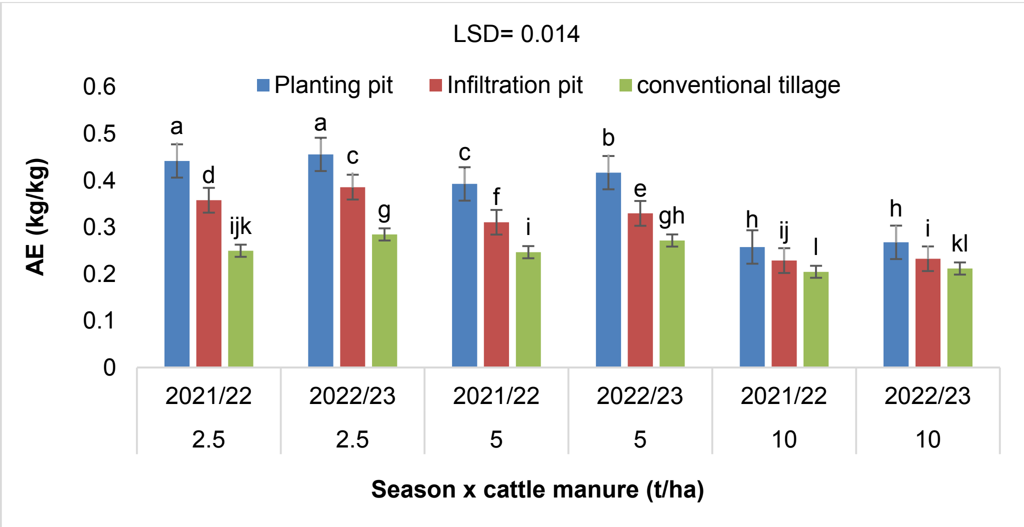

Figure 6 – Interactive effects of infield RWH and cattle manure on AE

Vertical bars represent the standard error (SE). Bars with different letters (a–l) are significantly different at p≤0.05. RWH means rainwater harvesting and AE means agronomic efficiency

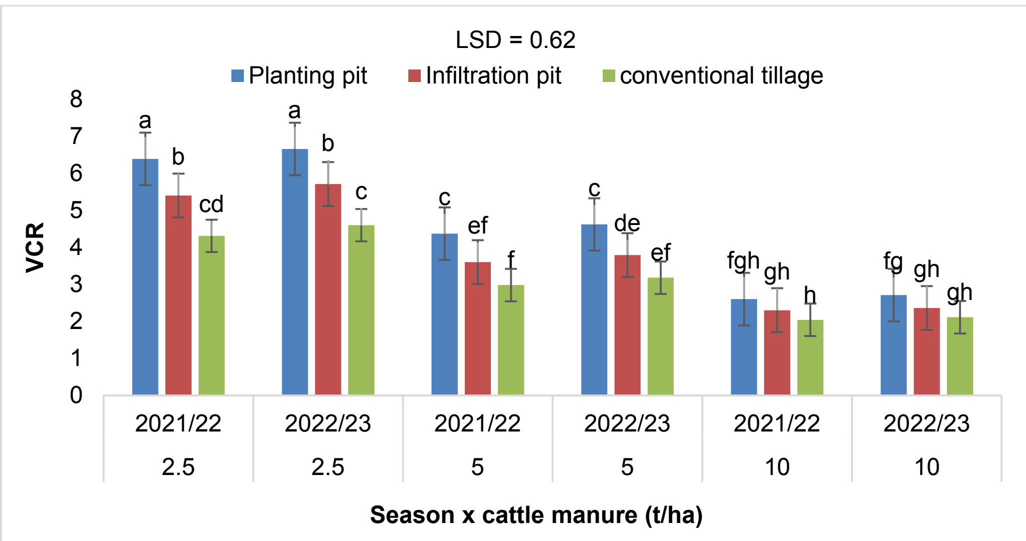

Figure 7 – Interactive effects of infield RWH and cattle manure on VCR

Vertical bars represent the standard error (SE).
Bars with different letters (a–h) are significantly different at p≤0.05

DISCUSSION

Maize grain yield

The maize grain yield obtained in this study was in the same range as the findings of Kiwia *et al.* (2022), with an average of 1700 kg ha^{-1} with fertiliser under Nitisols in East Africa. Maize grain yields have been constrained by nutrient and moisture stress in semi-arid areas. These areas receive low and erratic rainfall, which cannot sustain crop maturity. Infield rainwater harvesting techniques include PPs, harvesting rainwater, reducing surface runoff, and increasing the soil water content (Mudatenguha *et al.*, 2014; Swai *et al.*, 2023). Recharging the soil water content improves plant water availability in the root zone and increases crop growth. Increased crop growth is attributed to better yields, especially in areas with low rainfall.

Planting pits can hold water and reduce soil erosion in the field. This increases the infiltration of water into the root zone, reduces water stress, and increases nutrient absorption (Kimaru-Muchai *et al.*, 2021). This contributed to the higher grain yields realised in all treatments with IP.

Related studies by Chilagane *et al.* (2020) and Kugedera *et al.* (2023a) showed that the use of PPs is associated with good crop yields, especially in dry regions. Infiltration pits had low grain yields, which may be due to their positioning in the field, which affects the distribution of water in the root zone. The field slope also contributes to the uneven distribution of water, with the upper slope receiving more water than the lower and middle slopes, thereby affecting the soil water content. This agrees with the findings of Nyagumbo *et al.* (2019), who reported that the soil moisture content varies with the position of plots in the field, with those up slope receiving more water, which promotes higher yield upslope. The positioning of PPs in the field and their number increased the amount of water captured, thereby recharging more water in the plant root zone. Nyakudya *et al.* (2014) reported that PPs can capture more water, which is available to plants for more days during dry spells. This promotes growth and development, thereby preventing water stress during critical physiological stages, such as grain filling. High soil moisture retention in PPs is critical for growth and other processes that play an important role in protein synthesis and carbohydrate accumulation (Kebenei *et al.*, 2023). Planting pits, unlike CT, are reduced tillage systems that improve soil physical quality and aggregation, which are important for reducing leaching and retaining more water (Gotosa *et al.*, 2023).

Soil nutrient stress can be reduced by the application of organic nutrient sources, such as cattle manure, which contains various nutrients. Cattle manure contains both macro and micro nutrients that can reduce nutrient deficiencies of nitrogen (N), phosphorous (P), and potassium (K), which mainly constrain maize in semi-arid areas (Kiwia *et al.*, 2019; Sileshi *et al.*, 2019). Owing to the low use of nutrient inputs and water conservation strategies in many smallholder farming systems under rainfed agriculture, maize production is declining. The use of cattle manure in this study showed a positive correlation with maize grain yield. Maize grain yield increased with increasing application rates, and 2.5 t ha^{-1} had the highest maize yield increment. This may have been attributed to the improved soil porosity and water and nutrient retention in sandy loam soils caused by the addition of cattle manure.

In a similar study in Eastern and Southern Africa, cattle manure application increased the water and nutrient use efficiency, thereby improving plant growth, ear development, and grain yield (Kiwia *et al.*, 2022). Cattle manure improves the soil structure, microbial population, and water retention capacity, which reduces nutrient leaching, increases crop growth, and promotes higher yields.

However, the separate use of infield RWH techniques and cattle manure cannot sustain crop productivity in semi-arid areas. There is a need to combine the two to improve soil fertility and water content, which may support plant maturity, even under low rainfall periods. Combining these two increases maize grain yield to above 1000 kg ha^{-1} and allows farmers to support households for more than two years. The increase in yield was due to the positive association between the water retention capacity by IRWH and nutrient availability caused by the application of cattle manure.

The integration of both techniques has soil conservation characteristics that promote nutrient and water availability to crops, reducing the chances of crop failure but increasing yield parameters (Kubiku *et al.*, 2022; Kugedera *et al.*, 2023a). Maize grain yield was low in plots where CT was integrated with cattle manure because more soil and nutrient losses were experienced, which reduced nutrient and water availability. Year-by-year ploughing loosens soil, making it prone to surface runoff, reducing nutrient and water retention capacity, and thus resulting in a low yield (Gotosa *et al.*, 2023).

Maize stover

The stover yield increased linearly with grain yield, which has been explained by several authors who reported that when maize has larger stocks, the grain yield is high (Chiturike *et al.*, 2023; Mutuku *et al.*, 2020; Nyakudya *et al.*, 2015). Stover with a high surface area increases the photosynthetic area due to a high leaf area index, which transforms more carbohydrates into grain yield (Sher *et al.*, 2022). The higher stover yield from PP was due to the high soil moisture content and nutrient availability compared to that under CT, where leaching was higher. PPs reduce surface runoff and soil erosion and increase water percolation.

Increasing application rates of cattle manure showed a high positive correlation, which was attributed to improved soil nutrient availability and a reduction in N, P, and K losses, both of which play key roles in maize growth (Kebenei *et al.*, 2023; Kiwia *et al.*, 2019). Combining IRWH and cattle manure can increase stover yield due to the additive effects on soil moisture content and nutrient availability. PP and cattle manure increased the soil moisture content and nutrient availability because nutrient sources are directly added to the pit and become available to plant roots immediately (Kimaru-Muchai *et al.*, 2021). This is why a higher yield was obtained in PP than in CT and IP.

Rainwater use efficiency

The use of infield RWH techniques increases RWUE compared with CT. Planting pits and IPs capture and store rainwater, allowing it to be used during dry spells.

Conventional tillage had the lowest RWUE because most of the rainwater was lost and storage was very low, reducing its use efficiency. This supports the results of Kubiku *et al.* (2023), who reported that the use of RWH techniques increased RWUE regardless of the amount of rainfall. The results from this study showed that the 2021/22 cropping season received lower rainfall than the 2022/23 cropping season but had a higher RWUE.

This corroborates the findings of Lian *et al.* (2016), Ajeigbe *et al.* (2018), and Swai *et al.* (2023), who reported that RWUE varied with the use of RWH techniques. Swai *et al.* (2023) reported that CT had a higher RWUE in seasons with low rainfall compared to seasons with high rainfall.

In addition, the integration of infield RWH and cattle manure increased RWUE regardless of treatment because cattle manure improved soil porosity and water retention. The location of the infield RWH techniques contributed well to RWUE because they harvest a large amount of water that can be accessed by plants without being significantly affected by slope and distance. This supports the findings of Kubiku *et al.* (2023), who reported a low RWUE from all plots, which were 10–15 m from RWH structures.

The use of manure has been reported to increase RWUE with a value above 4 kg ha^{-1} mm^{-1} (Sileshi *et al.*, 2019). This agrees with the findings from this study, which had a minimum of 4.6 kg ha^{-1} mm^{-1} with manure and RWH techniques.

Agronomic efficiency (AE)

Agronomic efficiency showed a decreasing trend with the application of cattle manure in all treatments. This may have been caused by low nutrient uptake because increasing the nutrient application rate without increasing the plant population reduces root biomass and allows more nutrients to be leached. The low application rate of cattle manure had the highest AE because most of the nutrients were absorbed and converted into yield.

This was similar to a related study by Desta *et al.* (2022) and Mwadalu *et al.* (2022), who reported that farmers must apply low quantities of organic manure to allow most of the nutrients to be absorbed and converted to yield. Salama *et al.* (2021) also indicated that nutrient efficiencies vary with the application rate, and increasing the application rates of farmyard manure decreases efficiency. Increasing the nutrient application rate regardless of the RWH technique decreased AE, which supports the results of Kubiku *et al.* (2023) and Mwadalu *et al.* (2022), who reported the same scenario in semi-arid areas of Zimbabwe and Kenya, respectively.

Value–cost ratio (VCR)

The VCR is a preferred measure of profitability, and a VCR of 2 represents a 100% return on the money invested in manure and warrants farmers' investment in manure (Kihara *et al.*, 2016; Kiwia *et al.*, 2022; Xu *et al.*, 2009). The VCR from this study had a low value of 2.04 and the highest value of 6.66. These results were in the same range as results by Kiwia *et al*. (2022) in East Africa, who reported a VCR of 0.8 to 4.5 under different soils and 2.5 from Nitisols. This was in the same range as the VCR obtained in this study for Nitisols. The values obtained from this study were appropriate for accommodating climate risks, even when using CT and 2.5 t ha^{-1} cattle manure. Jama *et al*. (2017) proposed that a VCR>3 is appropriate in high-risk production environments, whereas a VCR>4 was suggested to accommodate price and climate risks with good incentives to farmers (Kiwia *et al*., 2022).

This is highly supported by the results of this study, and farmers who adopt PP or IP and 2.5 t ha^{-1} are guaranteed more profit than those using 5 and 10 t ha^{-1} cattle manure under PP and IP. The use of PP and 2.5 t ha^{-1} highly guarantees that smallholder farmers in high-risk areas have adequate risk coverage against investment in cattle manure because the VCR ranges from 6.39 to 6.66.

Cost of production

Infiltration pits had the highest costs (US$320) incurred, followed by PP (US$295) and CT (US$250). However, PP resulted in higher yields, which have the highest chances of providing farmers with sustainable profits. This supports findings by Swai *et al*. (2023), who showed that CT had a low gross return and gross margin compared to other IRWH techniques.

Planting pits have better gross returns when compared with IPs (Chilagane *et al*., 2020). Chiturike *et al*. (2024) reported that RWH techniques using IPs had low return on investment, especially when low rainfall was received.

CONCLUSIONS

One of the key conclusions from this study is that there is a high probability of achieving grain yield greater than 2000 kg ha^{-1} in low rainfall areas with PPs and 2.5 t ha^{-1} cattle manure. This was because the combination of PP and 2.5 t ha^{-1} had the highest AE and VCR. The use of PP and an application rate of 2.5 t ha^{-1} resulted in greater assurance to smallholder farmers in high-risk climates due to a VCR>5, which means the technique is profitable. The second conclusion is that the use of 5–10 t ha^{-1} of cattle manure and PP increases RWUE and grain yield, but with less to little profitability due to low AE and VCR slightly above 2. This does not guarantee profit for smallholder farmers in high-risk climates. The total cost incurred for PPs differs with a cost of only US$40 from CT. However, this difference between gross income from PP and CT at 2.5 t ha^{-1} is US$261.8, which when subtract US$40 gives an estimated value of US$221.8, translating to 652.4 kg ha^{-1}. This yield difference allows farmers to survive during drought and/or obtain income for input procurement, which becomes an advantage. Therefore, we recommend the integration of PPs and 2.5 t ha^{-1} of cattle manure to increase grain yield above 1000 kg ha^{-1}, guaranteeing high profits from cattle manure investments by smallholder farmers in high-risk climates.

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