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ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

Research Paper

Interactive Effects of Zai Pits and Convectional Practices with Soil Amendments on Soil Physico-chemical Properties

Serah, W.K. Muchai[1*], Monica W. Mucheru- Muna[2], Felix K. Ngetich[3], Harun I. Gitari[4], Emmanuely Z. Nungula[5] and Mary Baaru[5]

[1]Department of Social and Development Studies, Mt. Kenya University, Thika, Kenya
[2]Department of Environmental Science, School of Agriculture and Environmental Sciences, Kenyatta University, Nairobi, Kenya
[3]School of Agricultural and Food Sciences, Jaramogi Oginga Odinga University of Science and Technology, Bondo, Kenya
[4]Department of Agricultural Science and Technology, School of Agriculture and Environmental Sciences, Kenyatta University, Nairobi, Kenya
[5]Department of Environment and Sustainable Development, Mzumbe University, Morogoro, Tanzania
[6]Department of Environmental Studies and Community Development, Kenyatta University, Nairobi, Kenya

*Corresponding author: swkimaru@mku.ac.ke (**ORCID ID:** 0000-0002-5134-7894)

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ABSTRACT

Soil fertility decline and moisture deficits are major challenges facing crop production in semi-arid areas. Soil water conservation, in combination with nutrient management, might be useful in agricultural land restoration in tropical developing countries. This study aimed to examine the interactive effect of Zai pits and conventional planting with soil amendment on restoring soil physico-chemical properties in semi-arid areas. The selected physico-chemical properties were soil pH, soil organic carbon, nitrogen content, available phosphorus, aggregate stability, and soil moisture. A field experiment was carried out for three consecutive cropping seasons SR20, SR21, and LR21. Two planting techniques (conventional and Zai pit) and five soil amendment options (control, cattle manure, *Tithonia diversifolia*, 60 kg N ha^{-1}, cattle manure + 30 kg N ha^{-1}, Tithonia + 30 kg N ha^{-1}) were tested. Randomized Complete Block Design (RCBD) with twelve treatments and three replications was used. Results revealed a significant increase in soil fertility parameter pH (p<.001), TN (p=0.003), OC (p=0.014), and Av. P (p=0.004). A significant increase in aggregate stability in Zai pits than in conventional planting was equally observed. Additionally, a significant increase in volumetric water content was observed in Zai treatments as compared with conventional treatments at a depth of 35 cm. The combination of soil amendments with Zai pits and conventional planting enhanced soil nutrient availability meanwhile improving water retention. Application of soil amendment with Zai pits and conventional planting is therefore recommended in semi-arid areas. Particularly, Zai pits would be essential for moisture retention and infiltration of water in arid and semi-arid areas.

HIGHLIGHTS

- Declines in soil fertility and moisture deficits are major challenges to crop production in semi-arid areas.
- Soil water conservation, in combination with nutrient management, might be useful in agricultural land restoration in tropical developing countries.
- The study aimed to examine the interactive effect of Zai pit and conventional planting with soil amendment on restoring soil physico-chemical properties in semi-arid areas.
- The study revealed a significant increase in soil fertility parameters, aggregate stability, and volumetric water content at a depth of 35 cm in Zai pits than under conventional treatments.
- Zai pits and conventional planting enhanced soil nutrient availability while improving water retention.

Keywords: Nutrients, Soil moisture, Aggregate stability, Organic inputs, *Tithonia diversifolia*, Manure

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More than 46% of the global land area is occupied by dryland and habitat of more than 2.4 billion people in the world. Arid and semi-arid lands, constitute about 55% of land in Africa and 80% of land in Kenya and are characterized by limited soil moisture causing low crop yields (Alhammad *et al*. 2023; Gitari *et al*. 2019). Droughtisa very common incidence in semi-arid areas which in turn increases water losses through the evaporation process, interferes with plant root water uptake capacity, and consequently leads to low yields (Wildemeersch *et al*. 2015). Strategies to increase agriculture production relying on rainfall in arid and semi-arid areas will be crucial as it impacts the majority of the population (Maitra *et al*. 2023; Sahoo *et al*., 2023). Reducing the risk associated with rainfall variability is a promising option for increasing yields (Gitari *et al*. 2018). Alongside seizing viable irrigation opportunities in semi-arid areas, there is a need to integrate rainwater management with other agronomic practices to supplement soil moisture deficit. As a result, there is a need to invest in more techniques that will improve soil fertility as well as water retention to make crop production worthwhile in arid and semi-arid areas (Seleiman*et al*. 2018; Gitari *et al*. 2019).

Soil water-related constraints have been attributed to low crop production in the arid and semiarid zones (Vanlauwe *et al*. 2015). Among other environmental factors, soil physico-chemical properties determine the accessibility of both water and plant nutrients by plant and therefore, the specific crops to be grown in certain areas (Baveye *et al.* 2016; Nungula *et al*. 2023).Arid and semi-arid regions are usually characterized by unfavorable soil physical and chemical properties resulting in poor water-holding capacity and inherently low fertility (Alkharabsheh *et al*. 2023). According to Shah and Wu (2019), soil water and soil fertility can be significantly modified to increase the productivity of agricultural lands (Otieno *et al*. 2023; Nungula, 2024). Adoption of soil fertility management practices that would enhance the availability of soil nutrients and increase water-holding capacity are vital in achieving an increase in soil productivity meanwhile enhancing rural livelihoods in dryland farming systems in semi-arid environments.

To restore soils to a sufficient level of crop production, improved soil water conservation (SWC) measures have been widely promoted by research systems among smallholder farmers (Zougmoré *et al*. 2014). Among the recommended techniques to address the constraints of soil infertility and improve agricultural productivity potential in semi-arid areas are soil fertility amendments and water harvesting techniques such, as negarims, Zai pits, half moons, and semi-circular bunds (Nyamadzawo *et al*. 2013; Kimaru-Muchai *et al*. 2020, 2021). This study embarks on the Zai pit as a soil water conservation technique in combination with soil amendments. The soil fertility interventions entail the use of organic fertilizers like animal manure green manure and synthetic fertilizer (Vanlauwe *et al*. 2015). These practices enable farmers to maximize their production by improving land productivity and thereby increase economic return by increasing yields (Shao *et al*. 2023).

The combination of Zai pits with soil fertility amendments has been known to enhance soil productivity (Douxchamps *et al*. 2012; Fatondji *et al*. 2006). Fatondji *et al*. (2009), reported significant improvement inorganic matter and nitrogen content from 1 to 1.4% and from 0.05 to 0.8% respectively under Zai pits treatment. Considerably improvement in soil texture with an increase in clay content and a decrease in the sand fraction in Burkina Faso was reported by Mando *et al*. (2004). Applying the Zai technology enhances soil fertility due to applied amendments, and debris collected in the pits, and also improves soil moisture due to the surface crust breakage and consequently increased water infiltration (Fatondji *et al*. 2009). Organic manure accompaniment with mineral nutrients in the pits enhances biomass production and re-vegetation of different plant species, which breaks crusted soils for along time (Sawadogo, 2011; Roose *et al*. 1999; Kisaka *et al*. 2023). Despite the mentioned advantages, there is insufficient knowledge of Zai technology hence the need to explore it further. Many studies have been conducted on the effect of cattle manure and *T. diversifolia* under conventional planting but little is known about its effect on soil fertility when incorporated in zai pits. The main objective of the study was to evaluate the effects of Zai pits and organic/inorganic amendments on soil pH, soil organic carbon, nitrogen content, aggregate stability, and soil moisture.

MATERIALS AND METHODS

Study area

The study was carried out in Ciakariga, Tharaka-Nithi County, Kenya (Fig. 1). The study area featured with bimodal rainfall pattern; short rains season (SR) (October to December) and long rains season (LR) (March to May) with an average annual rainfall between 500–750 mm and the mean annual temperatures of 24°C. The area has two cropping seasons per year: the first uncertain cropping season, and the second short cropping season. The area is predominated by highly weathered and leached ferrasols, characterized by soil erosion during the rainy seasons due to inadequate soil organic matter associated with poor water retention and poor infiltration rate.

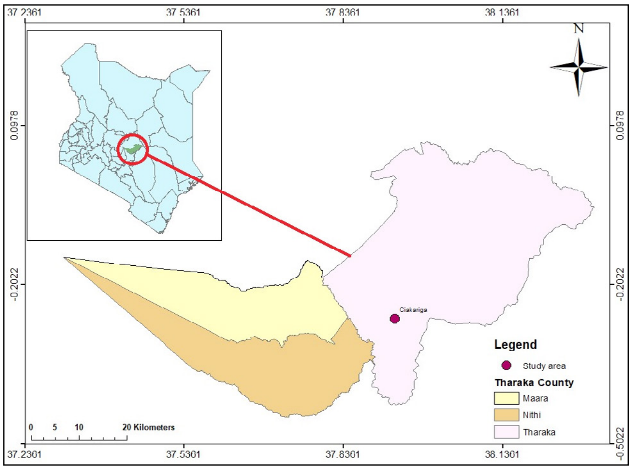

Fig. 1: Study area map

Treatment and experimental design

Field experiment was carried out in the three consecutive cropping seasons; Short rain 2020 (SR20), Long rain 2021 (LR21), and Short rain 2021 (SR21). The study adopted a randomized complete block design (RCBD) with 36plots with 4.5 m × 6 msized plots. There were twelve treatments (Table 1) with three replications.

Table 1: Experimental treatments

Treatment code	Treatment description
ZNO	Zai pits
ZC	Zai pits + Cattle manure
ZT	Zai pits + *Tithonia diversifolia*
ZF60	Zai pits + Mineral fertilizer (60 kg N ha^{-1})
ZC30	Zai pits + Fertilizer (30 kg N ha^{-1}) + Cattle manure
ZT30	Zai pits + Fertilizer (30 kg N ha^{-1}) + *Tithonia diversifolia*
CCM	Conventional planting + Cattle manure
CT	Conventional planting + *Tithonia diversifolia*
CF60	Conventional planting + Mineral fertilizer (60 kg N ha^{-1})
CC30	Conventional planting + Fertilizer (30 kg N ha^{-1}) + Cattle manure
CT30	Conventional planting + Fertilizer (30 kg N ha^{-1}) + *Tithonia diversifolia*
CN0	Conventional planting

Crop establishment and field management

Before the onset of the rain, the land was cleared and well-prepared. A0.6 m deep 0.6 m wide, and 0.1 m deep holes were dug. During the experiment sorghum Gadam variety was planted at a spacing of 0.75 m 0.6 m and 0.75 m by 0.2 m as inter- and intra-row were used for zai pits and conventional planting respectively. Cattle manure and *Tithonia diversifolia* (Table 2) were incorporated into the holes during land preparation. An inorganic fertilizer (NPK 23:23:0) was spot applied and thoroughly mixed with soil during planting at a rate of 60 kg N ha^{-1} for the sole and 30 kg N ha^{-1} for the integrated as per treatment. Standard agronomic management practices for sorghum production were observed and followed during the experiment.

Soil sampling and analysis

Soil sampling was done twice during the Short Rain

Table 2: Nutrient composition (%) of organic amendments used

Organic amendment	Nutrients					
	Nitrogen (N)	Potassium (K)	Magnesium (Mg)	Phosphorus (P)	Calcium (Ca)	Ash
Cattle manure	1.5	1.9	0.4	0.2	1.0	46.3
Tithonia diversifolia	3	2.9	0.7	0.3	2.1	13.2

2020 (SR20) and Short Rain 2021 (SR21) seasons to the depth of 30 cm using an auger and followed a W-shaped sampling technique. Laboratory analysis of the soil properties was done based on the method described by Ryan *et al.* (2001). Soil moisture content was determined by fortnightly capacitance probes (PR-2 probes) at a depth of 5 and 35 cm during the cropping season. Soil pH was determined using a pH meter. Soil organic carbon (OC) and TN analyses wereperformed using Walkley-Black and Kjeldahl methods, respectively. Extractable phosphorus was determined using the Olsen method. Aggregate stability was determined by the Dry-sieving method using the formula (Eq. 1) (Gartzia-Bengoetxea *et al.* 2009; Kemper and Rosenau 1986).

$$MWD = \sum_{i=1}^{n} \bar{y}_i z_i \qquad \text{...Eq.1}$$

Where; *MWD* is a mean weight diameter (mm), $\bar{y}_i$ is a mean diameter of each size fraction size *i* (mm), z_i is a total sample weight (g) size fraction *i* and *n* is the number of size fractions.

Data analysis

Data from the field were entered in Excel and subjected to analysis of variance using SAS 9.2 software. The significant means were examined using the least significant difference (LSD) at 95% confidence.

RESULTS

Rainfall distribution

The total rainfall recorded during the SR20, LR21, and SR21 cropping seasons were 342 mm, 250 mm, and 461 mm, respectively (Fig. 2). SR20 experienced 25 rain days, followed by SR21 and LR21 with 16 and 12 rain days, respectively. The highest total daily rainfall was observed during the SR21 (between 2.8 mm and 123 mm) followed by LR21 (ranging between 2 mm and 120 mm) while that of SR20 had ranges of 2.6-60 mm. The SR21 recorded the highest daily rainfall event on the17th (110 mm) and 24th (123 mm) day after planting and for LR20 the highest daily rainfall was on the 24th and 33rd after planting. SR20, LR21, and SR21 experienced a dry spell on the 57th, 28th, and 46th day after planting, respectively.

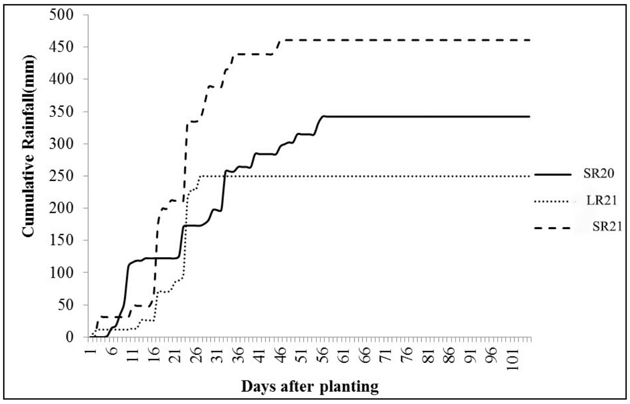

Fig. 2: Rainfall distribution during the SR20, LR21 and SR21

Soil chemical properties

There was a significant increase in pH when the treatment with cattle manure and fertilizer (30 kg Nha^{-1}) changed to neutral from slightly acidic. Similarly, there was a significant difference in pH value to Zai pit plus cattle manure and Zai pits with cattle manure and fertilizer (30 kg Nha^{-1}) at (p=0.05) from slightly acidic to neutral (Table 3). However, the study revealed that pH decreased under conventional planting and Zai pits with no amendment (Table 3) this is due to the increase in hydrogen levels in the soil due to rainfall (Chappa *et al.* 2023). There was no significant difference in pH value in the Zai pit and conventional planting with single soil amendments during the experiment. Results imply that the Zai technique applied as sole had no significant effect on the pH but Zai pits combination with soil amendment had a significant effect.

Nitrogen content increased significantly for all the conventional planting techniques except for the treatment without amendments. Nitrogen content increased significantly at p=0.05 for the Zai pit with full-rate cattle manure and conventional planting with cattle manure. There was a significant increase in carbon content in conventional planting with cattle manure treatment and conventional planting with *Tithonia diversifolia*. Zai pit soil water conservation technique combined with mineral fertilizer reduced more in carbon content as compared to conventional planting with mineral fertilizer, although the changes were not statistically different (Table 3).

Tithonia diversifolia increased phosphorus significantly in both the Zai pit and conventional

Table 3: Selected soil chemical properties (0–15 cm) at the beginning and end of the experiment

Soil parameter	pH (H_2O)		TN (%)		OC (%)		Av.P (ppm)	
Treatment	**Start**	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
CCM	6.14^{a}	7.43^{a}	0.17^{a}	0.26^{a}	1.53^{a}	2.5^{a}	22.32^{a}	42.36^{c}
CC30	6.21^{a}	6.95^{b}	0.14^{b}	0.16^{b}	1.49^{a}	1.87^{b}	22.84^{a}	52.78^{bc}
CF60	6.18^{a}	6.01^{d}	0.16^{ab}	0.13^{b}	1.48^{a}	1.52^{b}	23.16^{a}	60.89^{b}
CN0	6.08^{a}	5.96^{d}	0.18^{a}	0.14^{b}	1.52^{a}	1.41^{ab}	23.82^{a}	43.36^{c}
CT	6.20^{a}	6.58^{c}	0.15^{ab}	0.19^{b}	1.52^{a}	2.51^{a}	23.34^{a}	71.70^{a}
CT30	6.16^{a}	6.56^{c}	0.16^{ab}	0.15^{b}	1.54^{a}	1.96^{b}	21.92^{a}	71.67^{a}
ZC	6.10^{a}	7.23^{a}	0.18^{a}	0.25^{a}	1.51^{a}	1.82^{b}	23.66^{a}	61.36^{b}
ZC30	6.12^{a}	6.78b	0.14^{b}	0.15^{b}	1.46^{a}	1.51^{b}	22.75^{a}	61.71^{b}
ZF60	6.23^{a}	6.00^{d}	0.16^{ab}	0.15^{b}	1.56^{a}	1.46^{ab}	23.18^{a}	58.36^{ab}
ZN0	6.16^{a}	6.05^{d}	0.17^{a}	0.14^{b}	1.54^{a}	1.42^{ab}	23.32^{a}	48.34^{abc}
ZT	6.21^{a}	6.29^{d}	0.18^{a}	0.16b	1.45^{a}	1.56^{b}	23.36^{a}	62.32^{b}
ZT30	6.15^{a}	6.43^{c}	0.16^{ab}	0.15^{b}	1.52^{a}	1.63^{b}	23.28^{a}	50.56
P value	0.124	<.001	0.073	0.003	0.48	0.014	0.594	0.004

Means with the same letter in each column are not statistically different at p < 0.05. Start; SR20, End; SR21. The treatment description is given in Table 1.

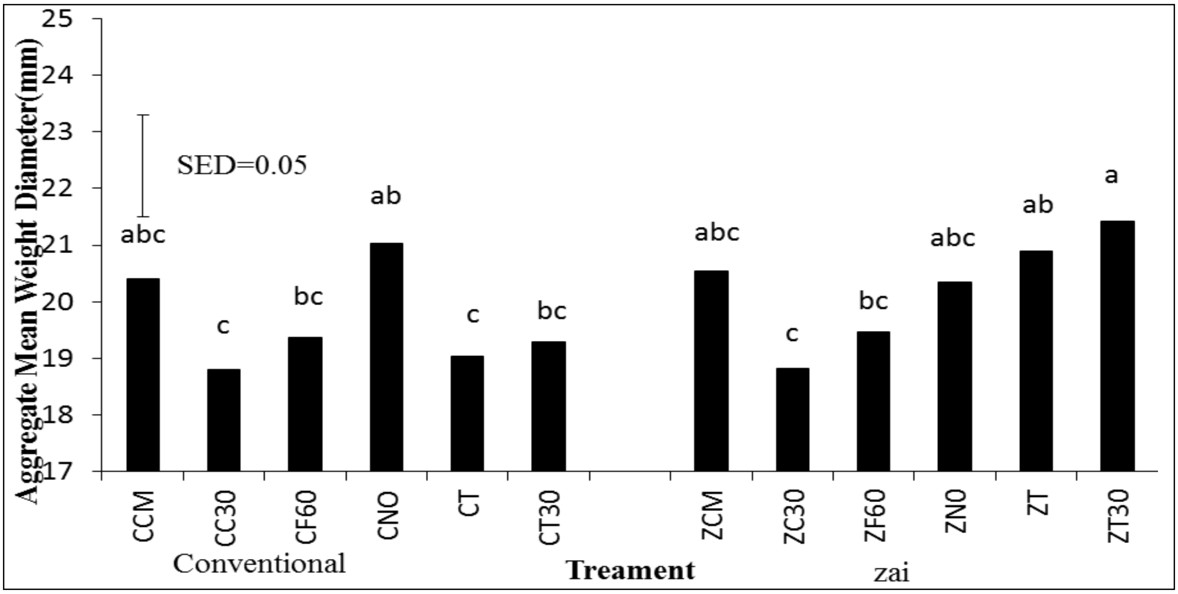

Fig. 3: Soil aggregate stability (0–15 cm). Means with the same letter in each column are not statistically different at $p < 0.05$. The treatment description is given in Table 1

planting at p=0.01(Table 3). Potassium content increased significantly in conventional planting plus cattle manure treatment as compared to Zai pit plus cattle manure treatment (Table 3). Zai pit combination with cattle manure and mineral fertilizer and cattle manure plus half rate of mineral fertilizer also had a significant increase in potassium content (Table 3). Cattle manure increased potassium content by 188% with conventional planting, but it increased by 49% with Zai pits (Table 3). There was a significant decline in potassium content in the Zai pit with no amendments at p=0.05.

Aggregate stability

The aggregate stability within the Zai pits combination with *Tithonia diversifolia* and half-rate of mineral fertilizer had the highest significance (p<0.05) with mean weight diameter of 21.43 mm compared to other treatments (Fig. 3), followed by conventional planting with no treatment and Zai pit with *Tithonia diversifolia* with mean weight diameter of 21.04 mm and 20.89 mm, respectively (Fig. 2). Also, there was a significant increase in mean weight diameter (p<0.05) between Zai treatment with *Tithonia diversifolia* and half-rate mineral fertilizer and conventional planting with *Tithonia diversifolia* and half-rate mineral fertilizer. Zai pits, in combination with cattle manure and half-rate mineral fertilizer, and conventional planting in combination with cattle manure and half-rate mineral fertilizer had the lowest mean weight diameter of aggregates (Fig. 3). However, the mean weight diameter of aggregates for Zai planting with no amendments was less than conventional planting with no amendments.

Soil mean weight diameter was statistically higher in the Zai pit treatment as compared with the conventional planting system. Among the Zai pit soil water conservation techniques, Zai pits in combination with *Tithonia diversifolia* and half-rate mineral fertilizer had the highest mean weight diameter followed by Zai pit with sole *Tithonia diversifolia*. In conventional planting, the mean weight diameter of aggregates was highest with no amendments followed by conventional planting with cattle manure. The lowest mean weight diameter of aggregates was recorded in conventional planting in combination with cattle manure and half-rate mineral fertilizer. The study revealed that Zai increased soil aggregation.

Soil moisture content

During the SR21 season, 10 days after sowing, with rainfall of 11.63 mm and 5 days of dry spell, conventional planting with *Tithonia diversifolia* combination at 5 cm depth shows the highest volumetric water content (0.23 $m^3m^{-3)}$ followed by conventional planting plus mineral fertilizer (0.22 m^3m^{-3}) (Table 4). Within Zai pits treatments, Zai pits combination with cattle manure (0.21 m^3m^{-3}) and Zai pits with no inputs (0.11 m^3m^{-3}) revealed the highest and lowest volumetric water content respectively. The volumetric water content for conventional planting plus cattle manure was 6.6% higher than Zai pits plus cattle manure while conventional planting with no inputs was 48% higher than Zai pits with no inputs at 5 cm depth (Table 4). At 35 cm depth, Zai pits plus *Tithonia diversifolia* had the highest volumetric water content (0.21 m^3m^{-3}) followed by Zai pits plus cattle manure (0.20 m^3m^{-3}) and Zai pits with cattle manure and mineral fertilizer (0.20 m^3m^{-3}), respectively and the one with no input had lowest volumetric water content (0.17 m^3m^{-3}). In conventional treatments, conventional planting with minerals had the highest volumetric water content (0.0.16 m^3m^{-3}) while conventional planting plus *Tithonia diversifolia* had the lowest moisture content (0.10 m^3m^{-3}) at 35 cm depth (Table 4). The volumetric water content for Zai pit plus *Tithonia diversifolia* was 110% higher than conventional planting plus *Tithonia diversifolia* at a depth of 35 cm, while volumetric water content for Zai pits plus cattle manure was 54.4% higher than conventional planting plus cattle manure (Table 4).

In the SR21 seasons, with accumulative rainfall of 249.7 mm and 20 days a dry period, 52 days after sowing at 5cm depth, conventional planting alone had the lowest volumetric water content (0.10 m^3m^{-3}) while conventional planting with *Tithonia diversifolia* had the highest volumetric water content (0.20 m^3m^{-3}). Contrary to Zai pits treatment at the same depth where Zai pits with no inputs had the highest volumetric water content (0.22 m^3m^{-3}) and Zai pits with *Tithonia diversifolia* and mineral fertilizer had the lowest (0.15 m^3m^{-3}). At 35 cm depth, Zai pits with cattle manure had the highest volumetric water content (0.24 m^3m^{-3}), and Zai pits with no inputs which had the lowest volumetric water content (0.17 m^3m^{-3}) (Table 4). On the other hand, conventional planting without input (0.17 m^3m^{-3}) and with *Tithonia diversifolia* and mineral fertilizer (0.18 m^3m^{-3}) was the highest among the conventional planting with *Tithonia diversifolia* (0.11 m^3m^{-3}) had the lowest.

On the 49th day after sowing during the LR21, with 11 days of the dry spell and 14.9 mm of rainfall, at a depth of 5 cm, volumetric water content in the conventional planting alone and the conventional planting with mineral fertilizer (0.33 m^3m^{-3}) both had the highest volumetric water content, and conventional planting with *Tithonia diversifolia* and mineral fertilizer (0.28 m^3m^{-3}) had the lowest. Within Zai pit treatments, the Zai pit with no input had the highest volumetric water (0.08 m^3m^{-3}) compared with the Zai pit with cattle manure (0.04 m^3m^{-3}) which had the lowest moisture content (Table 4). Volumetric water content at a depth of 35 cm was higher in the Zai pit with mineral fertilizer (0.29 m^3m^{-3}) and lowest in Zai pit without input (0.23 m^3m^{-3}) (Table 4), implying that water infiltrated fast into the bottom of the profile with little rainfall after a dry period in Zai pits with no organic's

Table 4: Moisture content under conventional and Zai pit at 5 cm and 35 cm depth at Ciakariga, Tharaka Nithi County (m^3m^{-3})

Day	10 days after sowing SR21		52 days after sowing SR21		49 days after sowing LR21		119 days after sowing LR21	
Depth	5 cm	35 cm	5 cm	35 cm	5 cm	35 cm	5 cm	35 cm
CCM	0.19^{a}	0.13^{b}	0.17^{ab}	0.13^{cd}	0.32^{a}	0.20^{ab}	0.16^{a}	0.10^{cd}
CC30	0.21^{a}	0.15^{b}	0.13^{abc}	0.14^{cd}	0.28^{a}	0.12^{b}	0.14^{abc}	0.10^{cd}
CF60	0.22^{a}	0.16^{b}	0.19^{ab}	0.12^{cd}	0.33^{a}	0.08^{c}	0.14^{abc}	0.09^{cd}
CNO	0.21^{a}	0.15^{c}	0.10^{bc}	0.17^{c}	0.33^{a}	0.09^{c}	0.15^{ab}	0.05^{d}
CT	0.23^{a}	0.10^{b}	0.20^{a}	0.11^{d}	0.30^{a}	0.16^{b}	0.16^{a}	0.08^{cd}
CT30	0.19^{a}	0.16^{b}	0.17^{ab}	0.18^{c}	0.32^{a}	0.18^{b}	0.08^{bcd}	0.10^{cd}
ZCM	0.21^{a}	0.20^{a}	0.14^{abc}	0.24^{a}	0.04^{b}	0.25^{ab}	0.08^{bcd}	0.20^{a}
ZC30	0.17^{a}	0.20^{a}	0.07^{bc}	0.21^{ab}	0.07^{b}	0.23^{ab}	0.07^{bcd}	0.17^{ab}
ZF60	0.16^{a}	0.18^{a}	0.11^{abc}	0.20^{bc}	0.07^{b}	0.29^{a}	0.03^{d}	0.15^{ab}
ZNO	0.11^{b}	0.17^{a}	0.22^{a}	0.17^{c}	0.08^{b}	0.26^{ab}	0.02^{d}	0.17^{ab}
ZT	0.16^{a}	0.21^{a}	0.03^{c}	0.21^{ab}	0.06^{b}	0.23^{ab}	0.05^{d}	0.20^{a}
ZT30	0.12^{b}	0.19^{a}	0.15^{ab}	0.21^{ab}	0.09^{b}	0.27^{a}	0.07^{cd}	0.18^{ab}
P value	0.046	0.001	< .001	< .001	0.001	< .001	< .001	< .001

Means with the same letter in each column are not statistically different at p < 0.05. The treatment description is given in Table 1.

treatment. However, at the same depth of 35 cm. Also, in the same depth conventional planting with cattle manure had the highest volumetric water content (0.28 m^3m^{-3}) while conventional planting with mineral fertilizer (0.08 m^3m^{-3}) and without input (0.09 m^3m^{-3}) both had the lowest volumetric water content (Table 4). The implication of that is that the amount of rainfall that reaches the soil on conventional planting with mineral treatment and conventional planting without input evaporated before infiltrating to the lower levels while the organics in conventional planting may have contributed to the easy percolation of water.

For the 119th day after sowing during the LR21, after 69 days of a dry spell, at a depth of 5 cm Zai pit with cattle manure (0.08 m^3m^{-3}) had the highest volumetric while the Zai pit with no input had the lowest volumetric water content (0.02 m^3m^{-3}). At the same depth, conventional planting plus cattle manure and conventional planting with *Tithonia diversifolia* had the highest volumetric water content (0.16 m^3m^{-3}) and the lowest was on conventional planting with mineral fertilizer (0.14 m^3m^{-3}) (Table 4). At 35 cm depth, Zai treatments had more volumetric water content compared to conventional treatments. Zai pits without input had the lowest volumetric water content (0.17 m^3m^{-3}) while Zai pits with cattle manure had the highest volumetric water content (0.20 m^3m^{-3}). Conventional planting with cattle manure had the highest (0.10 m^3m^{-}3) while without input had the lowest volumetric water content (0.05 m^3m^{-3}).

Generally, the lowest volumetric water content within Zai pits was observed at the 5 cm depth contrary to conventional planting treatments with the highest volumetric water content at the same depth. But dissimilar trend was observed at 35 cm depth where high volumetric water content was observed for Zai treatments compared to conventional treatments (Table 4). During a drought of 20 days, the Zai pit with no amendments had more moisture at 5 cm depth than conventional treatments and other Zai treatments (Table 4). This could have been attributed to more storage of moisture at the higher levels as a result of the improved structure of soil hence more water being held by the soil molecules; thus, little water was lost through evaporation.

DISCUSSION

Generally, there was an increase in soil pH under Zai pits and conventional planting with manure treatment and with combination of manure and mineral fertilizer. Soil pH increase in the treatment with manure application contributed by the reduction of exchangeable aluminum which occurs through the precipitation process of aluminum on organic colloids (Mucheru-Muna *et al.* 2014); Cai *et al*. 2019). The alkalinity nature of organic materials neutralizes the soil acidity through decarboxylation and the ammonification of organic N (Rukshana *et al*. 2013; Gitari *et al*. 2015). Similar studies by Wildemeersch *et al*. (2015), record an increase in soil pH following the application of cattle manure from 4.2 to 5.0 g kg^{-1}. However, the decrease in pH trend following the application of mineral fertilizer could be due to the increase in H^+ ions, added to the exchange complex of soils from the synthetic fertilizer. The addition of nitrogen-containing fertilizer acidifies the soil through an oxidation process, through the production of H^+ in the exchange complex, and leads to the loss of basic cations, and nitrification (Mucheru-Muna *et al.* 2014). The application of inorganic nitrogen causes a decline in soil pH due to a significant reduction in exchangeable base cations in soils (Zhu *et al.* 2018). A decrease in soil pH triggers an increase in the availability of heavy metals that are toxic and contribute to the reduction of the microbial biomass in the soil (Zhu *et al*. 2018; Hassan *et al*. 2020; Cai *et al*. 2019). The observed results comply with studies by Cai *et al*. (2019), Parecido *et al.* (2021), and Mucheru-Muna *et al*. (2007).

Soil organic carbon rose significantly for the conventional planting with cattle manure, *Tithonia diversifolia,* and with combined organics and in organics amendment, from 0.33 to 1.0 g $kg^{-1}$of OC than in Zai pits (Table 3). Gong *et al.* (2009), indicated a more effective increase in SOC in zai pits and conventional planting with organics amendment or in combination with organic and inorganic amendment. The marked significant increases in SOC with an application of manure and with *Tithonia diversifolia* resulted in the addition of more carbon sources from animal and green manure (Hati *et al*. 2007; Bandyopadhyay *et al*. 2010). The application of manure increases carbon content in the soil and release nutrient. Similar findings were observed by Hati *et al*. (2007) and Dunjana *et al*. (2012) who revealed an increase in soil organic carbon followed addition of farmyard manure, crop residues, and root biomass as carbon sources. Bedada *et al*. (2014), Nyawade *et al*. (2019), Xin *et al*. (2016), and Kaur *et al*. (2007) reported an increase in soil organic carbon within a treatment with cattle manure and with a combination of manure and half rate of inorganic fertilizer.

There was a decrease in TN in treatments with mineral fertilizer application compared with the treatment with manure application. These results imply that the decrease in TN level could be due to the uptake by sorghum plants or soil erosion by runoff and nutrient leaching because experiments were carried out during rainy seasons due to the poor drainage of the soil. Furthermore, the decrease recorded in treatments with mineral fertilizer combination with cattle manure could be due to the increase in mineralization, leaching process, ammonia volatilization, and denitrification (Rahimi *et al*. 2022). These results comply with the studies by Van Diepeningen *et al*. (2006) and Nyawade *et al*. (2020) where reduction in total nitrogen due to losses by erosion, ammonia volatilization, and denitrification were recorded. However, a significant increase in TN to higher nitrogen content realized in treatments of conventional planting and Zai pits combined with cattle is also supported by Fatondji (2006).

Also, there was a significant increase in available phosphorus in both Zai pits and conventional. The increase in phosphorus level recorded in treatments with, cattle manure combined with mineral fertilizer and sole mineral fertilizer application was due to the mineral fertilizer used (NPK) which had a higher level of phosphorus. Cattle manure combined with mineral fertilizer within Zai treatments had a higher level of available phosphorus as compared to similar treatments under conventional planting. This is because cattle manure consists of all forms of organic and inorganic phosphorus. According to Van Diepeningen *et al.* (2006), Cattle manure is a vital source of phosphorus used by plants and its inorganic orthophosphates form constitutes more than 45% of the phosphorus in manure. Regarding the impact of soil amendment, treatments within Zai pits treatment show a higher level of available phosphorus than conventional planting treatments. This could be accompanied by the ability of the Zai pits technique to retain nutrients by preventing nutrient loss by erosion. These results are supposed by with the studies by Mwadalu *et al*. (2022) and

Alkharabsheh *et al*. (2023) revealed the benefit of cattle manure by supplying a higher level of available nutrients.

Overall the results indicate that Zai pits have insignificant effects on soil chemical properties, unlike other studies that have reported higher impacts of Zai treatments on soil chemical properties in Burkina Faso (Zougmoré *et al.* 2004). The high nutrient content of minerals found in conventional planting plus cattle manure treatment could be attributed to the high nutrient level found in the cattle manure and low leaching of nutrients in the surface application as compared to Zai pit technology (Fatondji *et al.* 2009; Zougmoré *et al.* 2004). According to Mwadalu *et al*. (2022), the decomposition efficiency of cattle manure applied on the soil surface was more than 48% in the Zai pits. Whereas there could be some losses of nutrients due to runoff, water harvested in the pit may intensify the risk of nutrient leaching, and hence this may have contributed to the low nutrient found in Zai treatments. Fatondji *et al*. (2009) pointed out that Zai pits improve soil water, however, it can lead to loss of nutrients, particularly nitrogen. It is important to mention that Zai pit treatment had recorded higher stover and grain yields (data not presented here) which may be an indicator of high mineral uptake by the plants and thus low nutrients available in the soil as it had been reported by Fatondji (2006).

Soil aggregate stability is the most important soil physical property that influences infiltration and retention of water, soil aeration, and soil microorganism activity (Alkharabsheh *et al.* 2023). The findings show better stability in the Zai pit system compared to conventional planting. Previous studies indicate aggregate stability is much influenced by tillage intensity (Wacha *et al.* 2018). Better aggregate stability is reported in low-tillage systems compared with conventional tillage systems (Gathala *et al.* 2011). The reason for this could be related to high levels of carbon in the no and low tillage systems (Kisaka *et al.* 2023). In this study, the Zai pit system is considered a low tillage system since there is less disturbance of soil (Twomlow *et al.* 2008). Conventional tillage directly affects physical soil properties through disruption of the macro aggregates and indirectly through biological and chemical alteration of the soil properties (Alkharabsheh *et al.* 2023; Barto *et al.* 2010). Similar results were observed by Ngetich *et al.* (2008); and Yalcin and Cakir, (2006) that there is a significantly greater mean weight diameter of soil aggregates in minimal tilled land and reduced aggregation in conventional tillage.

A greater mean weight diameter was observed in conventional planting with no inputs was observed as compared to conventional planting with soil amendments. This is in contrast with Wang *et al.* (2013) findings that the combination of organic and mineral amendments improves aggregate stability while the application of inorganic fertilizers with no organic reduced aggregation due to the lack of soil aggregates disruption while applying the mineral fertilizers. Nyawade *et al.* (2019) observed that the long-term application of soil amendment, especially organic fertilizer makes a great impact in increasing aggregate stability of the soil. The increase in aggregate stability among organic treated soils may be attributed to increased microbial biomass and consequently the formation of extracellular polysaccharides which act as a good cementing agent of soil aggregates (Nyawade *et al.* 2019). However, according to Asgari (2014), the stability of soil aggregates is a result of the mixed effect of other factors, not just the effect of soil organic carbon.

The findings on soil moisture are with observations by Fatondji *et al*. (2006) that breaking the surface crust and digging pits was highly favorable for infiltration of water compared to the conventional treatments. Zai pits were observed to improve soil water storage (Vohland and Barry, 2009). Fatondji *et al.* (2006) also reported that the wetting front was shallower on non-Zai-treated plots compared to Zai treatments. Volumetric soil water content was higher at deeper layers in the Zai treatments than in conventional treatments even towards the end of the season. Observations made in the experiment also agree with the findings of other studies which report that increased organic matter content in the soil has a positive effect on increasing water infiltration (Minasny & McBratney, 2018). Shaheen *et al*. (2010), found that organic matter application had a significant beneficial impact on soil water and nutrient retention for crop production. Blanco-Canqui *et al*. (2015) observed that the application of manure reduced the soil compatibility and increased the water-holding capacity of the semiarid soils. The study revealed that the combination of organic amendments with Zai pits promotes moisture retention and increases water infiltration.

CONCLUSION

Cattle manure, *Tithonia diversifolia,* and inorganic fertilizers contribute to changes in soil nutrients, soil structure, and water infiltration. Zai pit as a water harvesting technique alone may not improve soil nutrients but has a significant contribution to soil aggregate stability and volumetric water content. In soils where the water harvesting function is not a priority compared to the soil enhancement function, the conventional application of organic and inorganic amendments may be more suited compared to the pit application of amendments. More novelties should be applied to the combinations of techniques to utilize on enhancing soil quality which will ultimately increase crop production in arid and semiarid areas.

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