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# *Zai* pit combined with integrated nutrient management for improving soil aggregate stability, moisture content and microbial biomass in drylands of Eastern Kenya

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**This study sought to assess the impact of selected soil conservation and water harvesting technologies as promising options for alleviating soil moisture crisis, enhancing soil fertility and reducing soil erosion in the drylands of Eastern Kenya. An experiment was set up to investigate the responses of soil aggregate stability, moisture contents and soil microbial biomass carbon and nitrogen (SMBC and SMBN) to *Zai* technology combined with selected integrated nutrient amendment. *Zai* pit technology involves the use of holes or basins with varying diameters for farming activities in drylands. The experiment was done in a completely randomized block design. Soils (0 to 15cm) from eight treatments (replicated thrice): *Zai* with no input (ZNO), *Zai* with sole manure (ZM60), *Zai* with full rate chemical fertilizer (ZF60), *Zai* with manure and mineral fertilizer (ZM30F30), conventional with sole manure (CM60), conventional with full rate mineral fertilizer (CF60), conventional with manure and mineral fertilizer (CM30F30) and control (CNO), were subjected to laboratory analyses using various methods as suggested by previous studies. ZM60 recorded 25% significantly high ($p<0.05$) stable aggregation compared to CM60. 32 days after sowing in the LR2019 season, ZM30F30 recorded 34% significantly high soil moisture content than CM30F30. ZM60 recorded the highest values for SMBC and SMBN which were 17.1% and 36.5% significantly higher that value recorded CM60. The results of this study demonstrate the importance of using *Zai* technology combined with organic and inorganic amendments as an agricultural intervention that can improve soil aggregate stability, soil moisture content and soil microbial biomass, thus contributing in the overall improvement of soil health and fertility.**

**Key words:** Aggregate stability, Mean weight diameter, Soil moisture content, Volumetric water content, *Zai* pit technology.

## INTRODUCTION

As a result of the insufficient utilization of nutrient amendments and water management strategies, reduced agricultural productivity has become a serious worry for most rain-fed reliant small-holder agricultural systems in

Sub-Saharan Africa (SSA) (de Graaff et al., 2011). High population increase in this region has led in the development and expansion of agricultural practices, which has resulted to soil degradation Tully et al., 2015). In sub-Saharan Africa, most subsistence farmers practice conventional agriculture, where the land is physically ploughed, and hills and furrows made for sowing using a hand-hoe (NDMA, 2017). The benefits of this system are clearly evident; efficient sowing operations and effective weed control (Ngetich et al., 2014b; Jin et al., 2007). Contrastingly, this agricultural management practice causes a lot of physical disturbance to the soil particles such as breaking down of macroaggregates (Barto, 2010; Lal, 2008). This results to nutrient loss through erosion since the loose soil particles are extremely vulnerable to erosion (Nyamangara et al., 2014). Conventional agricultural practice causes redistribution of organic matter during tillage, thus resulting to reduced stability of soil aggregates therefore increasing their susceptibility to erosion (Ngetich et al., 2014b; Nyamangara et al., 2014; Nyamadzawo et al., 2013; Verhulst et al., 2010). The conventional practice is also characterized by low soil moisture retention due to high soil water evaporation resulting from the high temperatures ((Zelelew et al., 2018; Nyamadzawo et al., 2013). Therefore, the low unreliable rainfall and high temperatures in the area, coupled with the common conventional agricultural practice has led to decreased crop production and even crop failures in some instances (Kebenei et al., 2021; Ngetich et al., 2014b). Enhanced soil moisture infiltration and the replenishment of nutrient are critical to enhancing soil productiveness and improving livelihoods in dryland areas prone to drought (Baptista et al., 2015). Researchers have looked into a number of options for addressing the problem of soil moisture scarcity and increasing agricultural output in semiarid environments. In dryland settings, a blend of water harvesting innovations and soil fertility modifications has been found to potentially impact on soil quality restoration and increase dryland crop output (Mekuriaw et al., 2018). Integrated soil fertility management (ISFM) techniques employ careful amendment of soil with organic and inorganic inputs to improve the fertility of soils and boost or maintain crop yield (Ndung'u et al., 2021). This technique advocates for the use of locally available organic manures to enhance soil fertility (Kiboi et al., 2018; Kiboi et al., 2019). Benefits have been realized when soil moisture management technologies are used in combination with soil fertility enhancement measures, resulting in increased water utilization efficiency and yields (Jägermeyr et al., 2016). Soil moisture conservation technologies like the *Zai* pit (Partey et al., 2018), which integrate soil and water management and conservation operations, promote rainfall efficiency and help overcome episodes of intra-seasonal dry spells, resulting in higher agricultural output (Wildemeersch et al., 2015; Dile et al., 2013). *Zai* pit is an old dryland agricultural practice that involves the use of troughs or basins with diameters ranging from 20 to 60cm and depths of 10 to 60 cm for farming activities (Danjuma and Mohammed, 2015; Sawadogo, 2011). Since they provide control to soil erosion and promote soil and water conservation, their use has been proven to lower the impacts of droughts. By capturing and storing rainwater, *Zai* pits enhance the volume of moisture contained in the soil layers (Mutunga, 2001). Water held in *Zai* pits delays the occurrence and commencement of extreme moisture stress; consequently, protecting crops from destruction resulting from water shortages in instances of dry spells (Nyamadzawo et al., 2013). *Zai* pits boost water infiltration, improve soil moisture storage, and minimize runoff, resulting in increased amounts of soil moisture available for uptake by plants. By collecting run-off and rainwater, *Zai* mitigates the negative effects of unpredictable precipitation and dry spells, thus boosting soil moisture availability to crops (Reij et al., 2009). Previous studies indicate that *Zai* pits allow crops to succeed under conventional planting systems in areas where crop failure is a high risk such as arid and semi-arid areas (Critchley and Gowing, 2012; Kimaru-Muchai et al., 2021). *Zai* pit technology have been found to be one of the most effective techniques aimed towards addressing water scarcity issues, enhancing efficient nutrient utilization and increasing crop output in semi-arid area (Kebenei et al., 2021; Kimaru-Muchai et al., 2021). *Zai* pit technology is designed to boost crop output by replenishing soil water and restoring soil fertility (Danjuma and Mohammed, 2015). While advocating for the *Zai* pit system as a potential option for increasing yield output in semi-arid areas, it's important to understand its influence on soil aggregate stability, moisture content and soil microbial biomass, when combined with various soil nutrient amendment options.

One of the most fundamental soil physical qualities that impact on soil organic matter variability is soil aggregate stability, which is the ability to withstand breakdown by external pressures (Six et al., 2000). It is a factor of great significance not only for enhancing soil sustainability and productivity but also for reducing soil erosion (Six et al., 2000), improving nutrient availability and storage and enhancing physical properties such as water infiltration, aeration, water retention and water utilization efficiency (Yuan et al., 2012; Hyun et al., 2007), crop growth and soil biological activity (Amezketa et al., 2003; Barthès and Roose, 2002). Binding agents, such as organic materials, have been found to significantly enhance the stability of

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soil aggregates (Villasica et al., 2018; Garland-Agroscope et al., 2017). Su et al. (2006) and Six et al. (2004) reported that soil organic matter promotes the formation of stable soil aggregates, and as a result, these organic compounds play a vital role in promoting the resistance of soil to erosion (Zeng et al., 2018). Aggregate stability is essential to maintaining a porous soil structure and the related water movement (Bronick and Lal, 2005). Stable aggregates provide physical protection to soil organic materials from rapid decomposition by microorganisms. Previous research work indicates that the stability of soil aggregates is greatly affected by tillage intensity (Al-Kaisi et al*.,* 2014). Conventional farming system affects soil aggregation directly through physical disruption of the macroaggregates (Barto et al*.,* 2010). Greater aggregate stability has been reported in no and low-tillage agricultural systems compared to traditional tillage-intensified system (Caesar-TonThat et al*.,* 2011; Gathala et al*.,* 2011) and have been associated to the high carbon levels in these systems (Al-Kaisi et al*.,* 2014). Even though *Zai* pit technology is majorly designed for soil moisture retention, it is regarded as a low tillage technology due to the fact that there is minimal soil disturbance in this system (Twomlow et al*.,* 2008), and thus its utilization has been linked to improved stability of soil aggregates. Aggregations of soil particles and soil moisture retention have been found to be affected by nutrient inputs. In comparison to other treatments, Ayuke et al. (2011) found that applying combined organic manure combined and chemical fertilizer brought about more stable aggregation at 0 to 15 cm soil depth. Previous studies have found aggregate stability to be higher in organic than chemical fertilization (Tejada et al*.,* 2008; Blair et al*.,* 2006) and systems characterized by minimal cultivation practice compared to conventional systems (Bottinelli et al*.,* 2010; Daraghmeh et al*.,* 2009). In general, *Zai* pit system enables farmers to concentrate both moisture and fertility close to plant root zone, thereby, addressing some of Sub-Saharan Africa's greatest agricultural production concerns (Tejada et al., 2008). The majority of Kenya's dryland areas are characterized by inconsistent rainfall distribution patterns and deteriorating soil productiveness, making rain-fed farming in such areas unsustainable (Ngetich et al., 2014a; Miriti, 2011). ASALs account for around 83% of Kenya's land surface. This means they receive low unpredictable rainfall (100 to 900 mm per year), which makes agricultural production unsustainable (Liwenga et al*.,* 2016). The significant variability of precipitation onset, rain fall quantities and distribution, and frequent and severe droughts, which typically occur throughout the planting season, all have an impact on agricultural production, commonly resulting in low harvests and crop failures (Ngetich et al., 2014a; Miriti et al*.,* 2012). There is need for sustainable practices aimed at boosting soil quality and fertility and as a result enhance crop production so as to guarantee food security among subsistence farmers in dry regions. Despite the abundance of research on the effects of *Zai* pit technology on crop yield gains, its impact on soil moisture content and aggregate stability in the study area remains comparatively sparse

In light of this, the current study aimed at investigating the effect of *Zai* pit technology combined with selected integrated soil fertility amendment options on soil aggregate stability, soil moisture content and soil microbial biomass

## MATERIAL AND METHODS

### Site description

The experiment was conducted in Kabati area of Kenya's Kitui County (1° 14’13.0" S 37° 54’52.2"E) (Figure 1). The County rises between 400 to 1,830 m above sea level (KCIDP, 2018). The climate is hot and dry with unreliable rainfall. The climate falls under two climatic zones that is, arid and semi-arid with most of the County being classified as arid with a mean annual temperature of 24°C (Jaetzold et al*.,* 2007). The County experiences high temperatures throughout the year, ranging from 14 to 34°C. The maximum mean annual temperature ranges from 26 to 34°C, while the minimum mean annual temperature ranges from 14 to 22°C (KCIDP, 2018). The high temperatures experienced in the county often results to high evaporation rates with mean annual potential evaporation in the county's central and northwest regions ranging between 1800 and 2000 mm, while in the eastern and north-eastern regions ranging between 2200 and 2400 mm (Jaetzold et al., 2007). The area’s annual precipitation is bimodal, with long rains occurring between March and May (MAM); while the short rains occur between October and December (OND). The long rains are usually very erratic and unreliable while the short rains are reliable. Annually, rainfall ranges between 250 to 1050 mm with 40% reliability for the long rains and 66% reliability for the short rains (KCIDP, 2018). Rainfall is highly unpredictable from year to year. There is approximately 180.81 rainy days (49.54%) with rainfall that is greater than 1 ml. The wettest month is November, with an average of 209 mm of rain (Jaetzold et al*.,* 2007). Agricultural activities, including livestock rearing and crop production, forms the cornerstone of the local economy and is primarily the major income source for most families (KCIDP, 2018). Maize (*Zea mays),* beans (*Phaseolus vulgaris*), sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*) and pigeon peas (*Cajanus cajan)*, are grown primarily for subsistence, whereas green grams *(Vigna radiata)*, horticultural crops including mangoes *(Mangifera indica)*, tomatoes *(Solanum lycopersicum)*, pawpaw *(Carica papaya)*, bananas (*Musa acuminata*), onions *(Allium cepa)* and watermelons *(Citrullus lanatus)* and vegetables like spinach *(Spinacia oleracea)* and kales *(Brassica oleracea)* are grown primarily for cash generation and home use. The soil types are majorly sandy red and black clay cotton soils (Jaetzold et al*.,* 2007, Republic of Kenya, 2005) which are predominantly vulnerable to erosion, poorly drained and are restricted in their ability to reserve moisture and nutrients. Table 1 shows the chemical attributes of the soil in the experimental site.

### Experimental design and treatment

The field tests were designed in a randomized complete block design (RCBD), with experimental plots having a dimension of 600 by 450 cm. The field experiment lasted four cropping seasons:

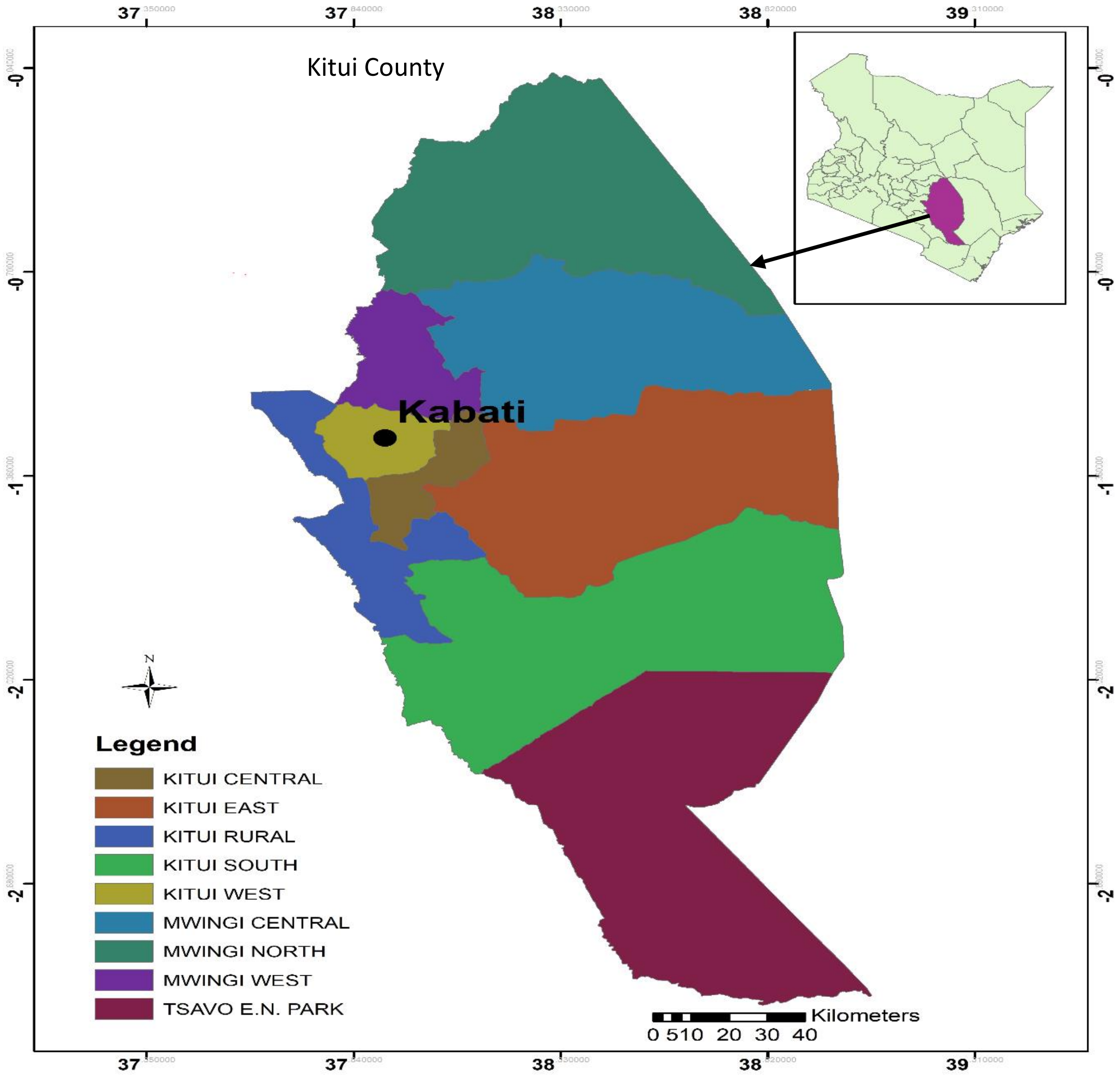

**Figure 1**. Location map, showing Kabati area, the study site in Kenya's Kitui County.
Source: author.

**Table 1.** Soil chemical characteristics (0–15 cm) at Kabati, Kitui County, Kenya.

| Soil parameters | Mean values |
|---|---|
| Soil pH ($H_2O$) (1:5) | 5.5 |
| Sand % | 61 |
| Silt % | 8 |
| Clay % | 30 |
| Bulk density (q/cm$^3$) | 1.22 |
| Total Nitrogen (%) | 0.37 |
| Total Organic Carbon (%) | 1.29 |
| Phosphorous (ppm) | 10.04 |
| Electrical conductivity (mS/m) | 208.97 |

**Table 2.** Experimental treatments during SR2018, LR2019, SR2019 and LR2020 and sources of Nitrogen (N) and Phosphorous (P) (kg ha$^{-1}$) in Kabati, Kitui County, Kenya.

| Soil and water conservation strategies | N and P from inorganic fertilizer | N and P from cattle manure |
|---|---|---|
| *Zai* pit + Sole Cattle Manure | 0 | 60 N and 60 P |
| *Zai* pit + Sole Mineral fertilizer | 60 N and 60 P | 0 |
| *Zai* pit + Cattle Manure + Mineral Fertilizer | 30 N and 30 P | 30 N and 30 P |
| *Zai* pit + No inputs | 0 | 0 |
| Conventional + Sole Cattle Manure | 0 | 60 N and 60 P |
| Conventional + Sole Mineral fertilizer | 60 N and 60 P | 0 |
| Conventional +Cattle Manure + Mineral Fertilizer | 30 N and 30 P | 30 N and 30 P |
| Conventional + No inputs (Control) | 0 | 0 |

**Figure 2.** A photo demonstrating the *Zai* pit farming technique in the study's experimental site.

two short rains seasons of 2018 (SR2018) and 2019 (SR2019), and two long rains seasons of 2019 (LR2019) and 2020 (LR2020). The experiment had eight treatments (Table 2) established as: *Zai* without input (ZNO), *Zai* with sole cattle manure (ZM60), *Zai* with sole full rate chemical fertilizer (ZF60), *Zai* with combined cattle manure and half rate chemical fertilizer (ZM30F30), conventional with exclusive cattle manure (CM60), conventional with exclusive full rate mineral fertilizer (CF60), conventional with combined manure and half rate chemical fertilizer (CM30F30) and the control (CNO). Each treatment was replicated thrice (to make 24 experimental units). The *Zai* pits were spaced at 0.7 and 0.75 m between and within-row respectively and measured 0.6 m (length) by 0.6m (width) by 0.3 m (depth). The experimental test crop was Sorghum Gadam (Figure 2). Nutrient additions were done at the start of the experiment (Table 2), to give an equivalent of 60 kg N ha$^{-1}$and 60 kg P ha$^{-1}$, the optimum recommended nitrogen and phosphorous rates in the study area. The cattle manure used contained organic matter 40.61%, total nitrogen (N) 2.13%, total phosphorus (P) 0.56%, total potassium (K) 1.78% and had moisture content of 58.6%, as established through a laboratory analysis. Before ploughing, manure was scattered over the conventional plots, while for *Zai* plots, it was combined with soil in the pits. Chemical fertilizer was pre-weighed for each plot and administered with dollop cups so as to maintain homogenous distribution within each plot.

### Soil sampling

Soil sampling for organic carbon and aggregate stability analyses was done at the completion of the fourth season (LR2020). Using an alderman auger, soil samples for organic carbon analysis were obtained at a soil depth of 0-15 cm. Across all the experimental plots, samples were collected from five spots following a W-shape. For the plots with *Zai* pits, sampling was done in five randomly selected *Zai* pits. The samples were then bulked into a composite sample, from which a sub-sample was taken for laboratory analyses. For aggregate stability, three undisturbed soil samples were obtained at a depth of 0 to 15cm using a soil auger from randomly selected spots across each plot. Samples for soil moisture content analysis were collected fortnightly at a soil depth of 0 to15 cm from the sowing date in each season. All the collected samples were sealed in plastic bags, marked for easy identification and transferred to the laboratory for analysis of the different parameters using the

**Table 3.** Percentage soil particles of different aggregate size classes retained at sieve openings after the dry sieving method.

| Treatments | % Soil particles retained at sieve opening size (mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **3.35** | **2.00** | **1.00** | **0.50** | **0.25** | **0.18** | **0.063** |
| ZNO | 34.68 | 19.51 | 13.85 | 10.57 | 9.03 | 4.27 | 5.50 |
| ZM60 | 43.03 | 18.46 | 12.18 | 9.47 | 7.85 | 3.19 | 3.71 |
| CM60 | 29.52 | 18.32 | 15.94 | 12.43 | 10.13 | 4.52 | 5.58 |
| CNO | 21.90 | 20.43 | 17.96 | 15.18 | 12.26 | 5.01 | 5.81 |
| ZF60 | 28.65 | 22.55 | 16.01 | 11.55 | 9.60 | 4.21 | 4.89 |
| CF60 | 20.29 | 19.19 | 17.54 | 15.25 | 12.88 | 5.34 | 6.16 |
| ZM30F30 | 46.62 | 15.99 | 11.29 | 8.42 | 7.08 | 3.30 | 4.80 |
| CM30F30 | 20.64 | 23.15 | 17.82 | 14.18 | 11.31 | 4.54 | 5.42 |

ZNO=Zai without inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha$^{-1}$), CF60=Conventional + full rate chemical fertilizer (60 kg N ha$^{-1}$), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha$^{-1}$), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha$^{-1}$).

methods described in this study.

## Laboratory analyses

### *Soil organic carbon*

The determination of organic carbon employed the Walkley and Black wet oxidation method as described by Ryan et al. (2001). Organic carbon was then calculated using equation 1:

$$\%\ Organic\ carbon = \frac{V_{Blank}\ - V_{Sample}\ \times\ M \times 3 \times 10^{-3} \times 100}{W_t} \quad (1)$$

Where: $V_{Blank}$=Volume (ml) of ferrous ammonium sulphate solution required to titrate the blank
$V_{Sample}$=Volume (ml) of ferrous ammonium sulphate solution required to titrate the sample
$W_t$=Weight (g) of air-dry soil
3 x $10^{-3}$=Equivalent weight of carbon
100=percentage
M=Molarity of ferrous ammonium sulphate solution (approximately 0.5M that is, 10/$V_{blank}$).

### *Aggregate stability*

In the laboratory, samples for analysis of stability of aggregates were air-dried at room temperature for 24 hours before sieving for stability tests. Dry-sieving method described by Gartzia-Bengoetxea et al. (2009) was employed in the determination of aggregate stability (Table 3).

Equation 2 below was used to calculate the mean weight diameter:

$$\mathrm{MWD} = \sum_{i=1}^{7} XW_i\ \# \quad (2)$$

Where *X* signifies the mean diameter of aggregates remaining on the different sieves, $W_i$ denotes the ratio of aggregate weight remaining on the sieve to total sample weight, and 7 refers the number of sieves employed for aggregate separation.

### *Soil moisture content*

Gravimetric method described by Ryan et al. (2001) was used to establish soil moisture content. The percentage moisture content was then calculated using equation 3:

$$\%\text{Moisture content} = \frac{(\text{Sample fresh weight} - \text{Sample dry weight})}{\text{Sample dry weight}} \times 100\% \quad (3)$$

### *Soil microbial biomass (C and N)*

SMBC and SMBN were measured using the chloroform fumigation-extraction method (Brookes et al., 1985; Vance et al., 1987) as shown in equation 4 and 5.

$$\text{Microbial Biomass C} = \left(\text{C}_{\text{fumigated}}\ - \text{C}_{\text{control}}\ \right) \quad (4)$$

$$\text{Microbial Biomass N} = \left(\text{N}_{\text{fumigated}}\ - \text{N}_{\text{control}}\ \right) \quad (5)$$

## Statistical analyses

Data was subjected to a two-way analysis of variance (ANOVA) in the R-studio program and means separated using the least significance difference (LSD) at p = 0.05. Pair-wise comparison of soil organic carbon in treatments between the commencement and completion of experiment was analyzed using t-test

# RESULTS

## Rainfall characteristics and distribution

Precipitation quantities varied across the four growing

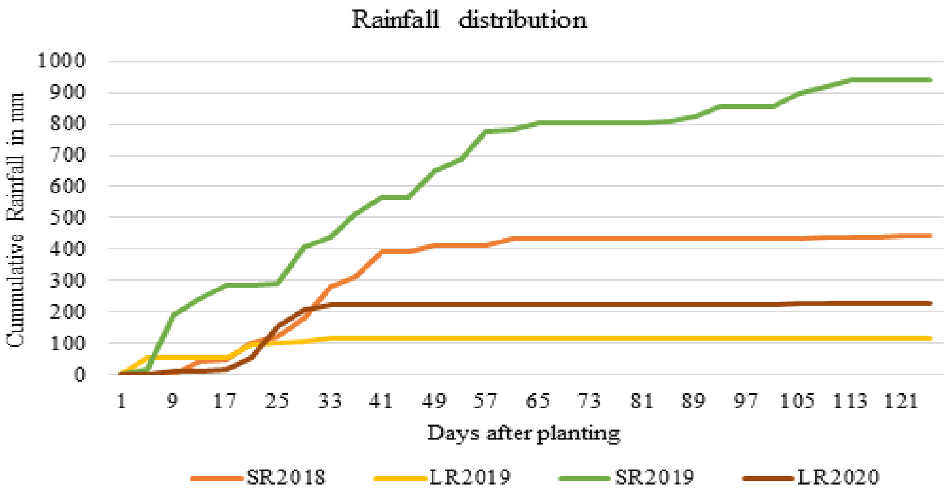

**Figure 3.** Rainfall distribution at different days after planting during the SR2018, LR2019, SR2019 and LR2020 seasons in Kabati, Kitui county.
(SR2018= Short rains season in the year 2018, LR2019= Long rains season of the year 2019, SR2019= Short rains season in the year 2019, LR2020= Long rains season in the year 2020).

seasons (Figure 3). Experimental seasons (SR2018, LR2019, SR2019, and LR2020) were distinguished by distinct rainfall patterns, with higher rainfall amounts being recorded in the SR seasons (SR2018-938 and SR2019-442 mm) as compared to the LR seasons (LR2019-116 and LR2020-228 mm).

The number of rainy days differed between the four seasons with SR2019 and SR2018 recording higher number of days 47 and 31, respectively). With 10 and 11 wet days, respectively, LR2019 and LR2020 recorded the least rainy days. Majority of the rainfall fell during the first two months of the SR2018 and SR2019 seasons, with an extended dry spell commencing from the 64th day after sowing and lasting till end of the growing seasons. In contrast, during the first month of the long rains' seasons (LR2019 and LR2020), there were alternating periods of wet and dry days. The LR seasons, LR2019 and LR2020, had 73 and 69 days intra-seasonal dry spells, respectively, whilst SR seasons, SR2018 and SR2019, recorded drought episodes of 43 and 14 days, respectively. Every year, precipitation in Eastern Kenya is separated into two contrasting seasons: LR which occurs from March to May and SR which prevail between October to December. Since short rains season receives the majority of the total annual rainfall, it is regarded as more reliable. In comparison to the LR season, crop yields are higher during this season. In this study, the short rains had the highest total season rainfall amounts, which positively influenced soil moisture in comparison to the LR seasons.

## Soil organic carbon

In general, when compared to the values obtained at the commencement of experimental activities, higher soil organic carbon contents were recorded at the end of the experiment for all the treatments (Table 4). This indicates that all treatments had a positive influence on soil organic carbon. However, the treatment effect on organic carbon between the start and finish of the experiment was only significant ($p<0.05$) in the control treatment, *Zai* with manure and conventional with exclusive cattle manure which, at the completion of the experiment, recorded values that were 54,71 and 25% higher than values recorded at the onset of the experiment. At the completion of the experiment, higher soil organic carbon amounts were recorded in treatments amended with organic inputs either exclusively or combined with chemical fertilizer (Table 4). The treatment effect on soil organic carbon was highest (2.22) in conventional with manure combined with chemical fertilizer and this was 38% higher than *Zai* with combined cattle manure and chemical fertilizer. *Zai* with sole manure application recorded the highest organic carbon content among the *Zai* treatments and this was 13% significantly higher ($p<0.05$) as opposed to equivalent treatment in the conventional practice. Among the *Zai* treatments, *Zai* with cattle manure application recorded 19, 21 and 26% higher organic carbon content than *Zai* with combined manure and mineral fertilizer, *Zai* without input and *Zai* with exclusive mineral fertilizer, respectively (Table 4). Conventional with manure and mineral fertilizer recorded 43, 34 and 31% higher soil organic carbon content than conventional with sole fertilizer, the control and conventional with manure, respectively. Generally, under both *Zai* and conventional systems, the treatment influence on soil organic carbon was highest in treatments with absolute cattle manure and those with manure combined with inorganic fertilizer, although the effect

**Table 4.** Combined effects of *Zai* pit technique with selected soil nutrient input amendments on total organic carbon (start and end of experiment) and soil aggregate stability (end of experiment) under *Zai* and conventional systems (0–15 cm) at Kabati, Kitui County, Kenya.

| **Treatments** | **Soil Organic Carbon (% SOC)** | | | **Aggregate Stability (mm)** |
|---|---|---|---|---|
| | **2018** | **2020** | **t-test** | **2020** |
| *Zai* with no input | $1.33^{a}$ | $1.57^{ab}$ | -1.03 | $1.78^{abc}$ |
| Conventional with no input (Control) | $1.07^{a}$ | $1.65^{ab}$ | -3.07* | $1.44^{cd}$ |
| *Zai* pit with sole manure (60 kg N $ha^{-1}$) | $1.12^{a}$ | $1.91^{ab}$ | -4.49* | $2.01^{ab}$ |
| Conventional with sole manure (60 kg N $ha^{-1}$) | $1.35^{a}$ | $1.69^{ab}$ | -3.16* | $1.61^{cd}$ |
| *Zai* pit with sole mineral fertilizer (60 kg N $ha^{-1}$) | $1.37^{a}$ | $1.51^{ab}$ | -0.56 | $1.66^{bcd}$ |
| Conventional with sole mineral fertilizer (60 kg N $ha^{-1}$) | $1.28^{a}$ | $1.55^{b}$ | -1.06 | $1.36^{d}$ |
| *Zai* pit with manure (30 kg N $ha^{-1}$) and half rate mineral fertilizer (30 kg N $ha^{-1}$) | $1.36^{a}$ | $1.6^{b}$ | -1.32 | $2.06^{a}$ |
| Conventional with manure (30 kg N $ha^{-1}$) and half rate mineral fertilizer (30 kg N $ha^{-1}$) | $1.44^{a}$ | $2.22^{a}$ | -1.52 | $1.44^{cd}$ |
| LSD | 0.4815 | 0.6578 | | 0.387 |
| *P*-value | 0.5889 | 0.2481 | | 0.0038 ** |

LSD=Least significant differences between mean. Means followed by different letters denote significant differences between treatments at p=0.05.

was not significant (Table 4).

## Aggregate stability

Generally, aggregate stability of soil particles was significantly higher ($p<0.05$) in *Zai* treatments as opposed to alike treatments in the conventional system. The aggregate stability for the soils from *Zai* pit with manure combined with inorganic fertilizer recorded the highest significant ($p<0.05$) mean weight diameter of 2.06 mm followed by *Zai* with sole manure (2.01 mm). The mean weight diameter recorded in *Zai* with manure combined with chemical fertilizer was significantly high ($p<0.05$) by 35.43% than conventional approach with manure combined with mineral fertilizer which recorded a mean weight diameter of 1.44 mm (Table 4). *Zai* with sole manure recorded a mean weight diameter of 2.01 mm and this value was significantly higher by 25% than conventional with sole manure which recorded a mean weight diameter of 1.61 mm (Table 4). *Zai* pit with no input (1.78 mm) and *Zai* with full rate mineral fertilizer (1.66 mm) recorded mean weights diameters of 1.78 and 1.66 mm which were significantly high ($p<0.05$) by 24 and 22% than the control and conventional with mineral fertilizer (Table 4). Under *Zai* pit system, *Zai* with combined manure and half rate inorganic fertilizer had the highest mean weight diameter which was 2.5, 15.7 and 24.1% higher than *Zai* with sole manure, *Zai* without input and *Zai* pit with exclusive inorganic fertilizer, respectively. In the conventional system, conventional with sole mineral fertilizer had the highest mean weight diameter of 1.61 mm which was 6.41, 11.15 and 11.06% higher than conventional approach with sole organic manure (1.51 mm), conventional with combined manure and inorganic fertilizer (1.44 mm) and conventional with no input (1.44 mm), respectively (Table 4). Generally, all the treatments, except conventional with sole mineral fertilizer, recorded a significantly higher mean weight diameter than the control (Table 4). Mean weight diameter was significantly impacted on by the planting system and input amendment at 0 to 15 cm (Table 4).

## Soil moisture content

The determination of Soil moisture content was done at different days (18, 32, 46, 60, 74, 88, 102 and 116) after sowing during the four study seasons. Generally, soil moisture content, which was expressed as volumetric water content ($g/cm^3$), recorded higher values during the SR seasons (SR2018 and SR2019) compared to the LR seasons (LR2019 and LR2020). There was variability in the volumetric water content across the different days within the four study seasons, with low values being recorded towards the end of seasons. There was a variation in average soil moisture content among different treatments (Figure 4a–d). A significant ($p<0.05$) treatment influence was observed across the four seasons. All treatments in the *Zai* pit technology significantly influenced soil moisture content as opposed to comparable treatments under the conventional approach system across the different days in all the four seasons. In the SR2018, cumulatively about 281.2 mm of rainfall was recorded in the first 32 days of the season (Figure 4a) and soil moisture content increased concurrently in all experimental treatments during this period. Thereafter, soil moisture content decreased for all the treatments (Figure 4a). During the whole season, the general trend was soil moisture content fluctuating in response to the rainfall patterns until the end season. Treatment under *Zai* technology recorded significantly high soil moisture

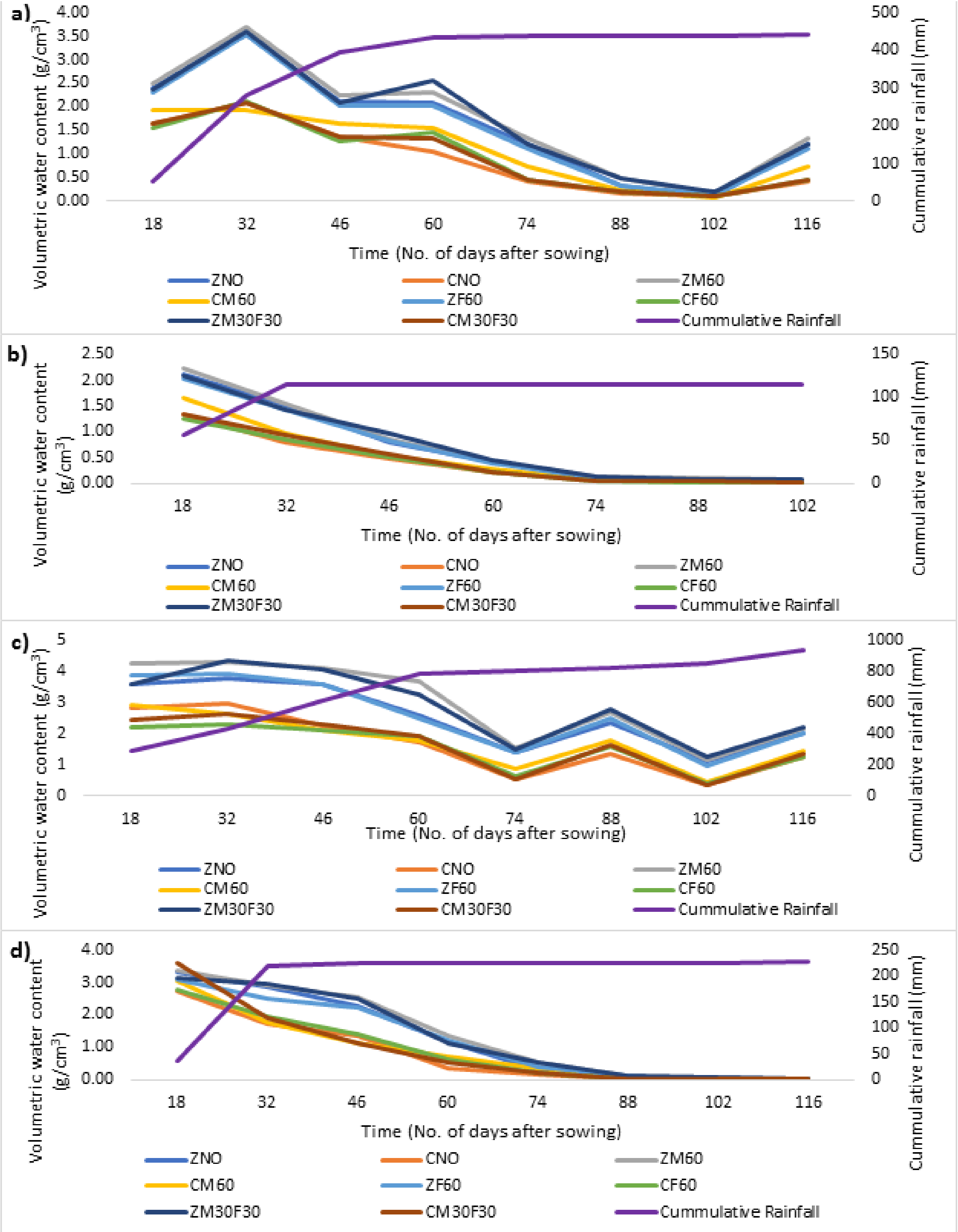

**Figure 4.** Soil moisture variations under different treatments at 0-15 cm soil profile during the four study seasons; a) SR2018, b) LR2019, c) SR2019 and d) LR2020 in Kabati.

*(ZNO=Zai with no inputs, ZM60=Zai + sole manure, CM60= Conventional + sole manure, CNO= control, ZF60=Zai+ full rate chemical fertilizer (60 kg N ha$^{-1}$), CF60=Conventional + full rate chemical fertilizer (60 kg N ha$^{-1}$), ZM30F30=Zai+ manure+ half rate chemical fertilizer (30 kg N ha$^{-1}$), CM30F30=Conventional + Manure + half rate chemical fertilizer (30 kg N ha$^{-1}$)).*

content values in contrast to similar treatments in the conventional approach. In the same season, eighteen days after sowing, with a cumulative rainfall of 53.9 mm and two previous non-rainy days, *Zai* pit with sole manure recorded the highest volumetric water content (2.51 g/cm$^3$), which was 23% significantly higher as opposed to conventional with sole manure treatment (Figure 4a). On the same day, among the treatments under conventional system, conventional with sole manure recorded a significantly ($p<0.05$) highest volumetric water content value (1.93 g/cm$^3$) which was 18, 25, and 18% higher than the control, conventional with inorganic fertilizer and conventional with combined manure and chemical fertilizer. Across the four study seasons, lowest volumetric water content values were recorded during the LR2019 season. In this season, about 115.8 mm of precipitation fell in the first 32 days just after sowing leading to the concurrent rise in soil moisture content in experimental treatments both *Zai* and conventional systems (Figure 4b). Eighteen days after sowing with cumulative rainfall of 57.2 mm and a 7-day dry-spell, all treatments, except conventional with sole mineral fertilizer recorded values higher than the control. On the same day, all the treatments under *Zai* pit farming approach recorded a significant ($p<0.001$) treatment influence on volumetric water content compared to their counterpart treatments in the conventional system. 32 days after sowing with a cumulative rainfall of 115.8mm, *Zai* with sole manure recorded the highest volumetric water content (1.55 g/cm$^3$) value which was significantly high ($p<0.05$) by 58% than the volumetric water content value (0.98 g/cm$^3$) recorded under conventional with exclusive cattle manure application treatment. Conventional with sole chemical fertilizer recorded the lowest soil moisture content. The longest dry period in this season occurred immediately after the 32nd day lasting up to the 100th day. Generally, treatments under *Zai* technology with cattle manure and those with combined manure and inorganic fertilizer had highest significant treatment effect on soil moisture contents (Figure 4b).

The trend in SR2019 was similar to that observed in SR2018. Compared to the LR seasons, high rainfall amount was experienced (Figure 4c) and soil moisture build up increased with increasing rainfall amounts during the initial days of the season. Soil moisture fluctuated concurrently in all treatments as influenced by rainfall. A significant ($p<0.05$) treatment effect was observed in this season, with treatments under *Zai* system recording significantly ($p<0.05$) higher treatment influence on volumetric water content as compared to their counterpart treatments under conventional system (Figure 4c). Eighteen days days after sowing, with a cumulative rainfall of 287.2 mm and two previous non-rainy days, *Zai* with sole manure recorded the highest (4.25 g/cm$^3$) soil moisture content value while the lowest value was recorded under conventional with sole mineral fertilizer (2.23 g/cm$^3$). *Zai* with sole manure, *Zai* pit with combined manure and chemical fertilizer, *Zai* with sole chemical fertilizer and *Zai* without input recorded 71, 75, 66 and 54% significantly higher ($p<0.05$) soil moisture content values than similar treatments under conventional system, respectively (Figure 4c). In this season, sixty days after sowing, with a cumulative rainfall of 783.6 mm and being after an 18-day dry-spell, *Zai* with sole manure recorded the highest volumetric water content value (4.25 g/cm$^3$) which was 44% (Figure 4c) significantly higher as opposed to conventional treatment with sole manure (2.95 g/cm$^3$). In the same season, 46 days after sowing, with accumulative rainfall of 610.6 mm and being after four non-rainy days, *Zai* pit with sole manure (4.12 g/cm$^3$), *Zai* pit with no input (3.60 g/cm$^3$), *Zai* pit with manure combined with mineral fertilizer (4.09 g/cm$^3$) and *Zai* pit with sole mineral fertilizer (3.62 g/cm$^3$) recorded significantly ($p<0.05$) high volumetric water content values that were 94, 58, 78 and 71% higher than comparable treatments under conventional approach, respectively (Figure 4c).

The trend during the LR2020 season was similar to that observed in the LR2019 season. Both seasons had a distinct extremely prolonged within-season dry period. The LR2020 dry-spell commenced 33 days after sowing and continued to the 103rd day. Soil moisture decreased in all treatments progressively into the season, though in the conventional system treatments, the reduction happened much earlier and at a quicker rate than in the *Zai* pit system treatments (Figure 4d). Generally, in this season, treatments under *Zai* approach had significantly ($p<0.05$) higher treatment effects on soil moisture levels in comparison to similar treatments under conventional farming approach (Figure 4d). Eighteen days after sowing with a cumulative rainfall of 38 mm, *Zai* with sole manure recorded a 10% higher (3.38 g/cm$^3$) volumetric water content value than the value recorded in similar treatment under conventional system. On the same day, lowest (2.73 g/cm$^3$) volumetric water content value was recorded under conventional with no input. On the 46th day after sowing, with a cumulative rainfall of 225 mm and being after a 13-day dry-spell, *Zai* with manure combined with mineral fertilizer recorded the highest volumetric water content value (2.53 g/cm$^3$) which was 55% higher than the value recorded under conventional with manure combined with mineral fertilizer treatment ((Figure 4d). In the same season, under the conventional system, significantly ($p<0.05$) higher volumetric water content values were recorded under treatments with exclusive cattle manure or combined manure with chemical fertilizer across the different days (Figure 4d). In the 0-15cm soil depth, all the four study seasons were characterized by durations of wetness (water accumulation periods) and dry moments (water depletion periods). In terms of rainfall distribution during the four experimental season most of the rain fell in the first quarter of the seasons, with dry spells dominating the rest of the seasons (Figure 4a-d). The influence of

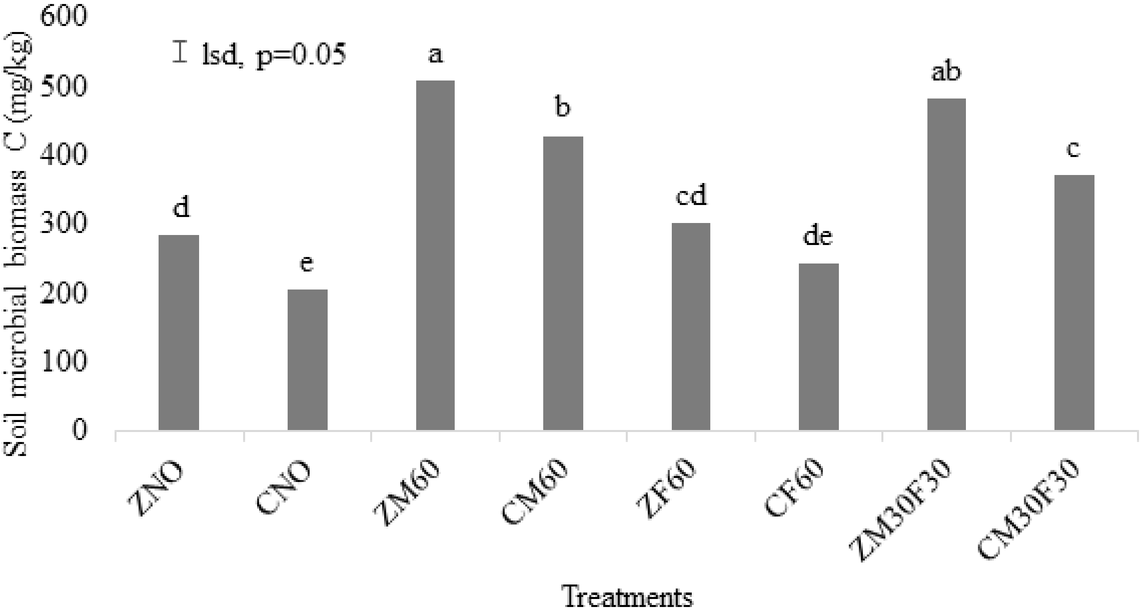

**Figure 5**. Soil microbial biomass carbon in different treatments at the end of the experiment.
ZNO, Zai with no inputs; CNO, Conventional with no inputs; ZM60, Zai + Manure; CM60, Conventional + Manure; ZF60, Zai + 60 kg N ha$^{-1}$; CF60, Conventional + 60 kg N ha$^{-1}$; ZM30F30, Zai + Cattle manure + 30 kg N ha$^{-1}$; CM30F30, Conventional + Cattle manure + 30 kg N ha$^{-1}$. The error bar denotes the least significant difference (lsd) at p = 0.05. Different small letters indicate significant differences at p<0.05.

rainfall increased soil moisture content during the wet period early in the seasons. Treatments under Zai pit system recorded significantly (p<0.05) higher volumetric water content values as opposed to values recorded in alike treatments under conventional system across different days in all the four seasons (Figure 4a-d). Higher values were recorded in treatments with absolute manure and those with organic manure combined with chemical fertilizer under both systems. These results clearly indicate that the interaction between Zai pit system and the selected input amendments had significant treatment effect on soil moisture content compared to conventional planting system.

## Responses of soil microbial biomass (carbon and nitrogen)

### *Soil microbial biomass carbon (SMBC)*

Generally, Microbial biomass Carbon was significantly higher (p<0.05) in treatments under *Zai* technology as compared to similar treatments under conventional system. Microbial biomass carbon for the soils from *Zai* pit with sole manure recorded the highest significant (p<0.05) Microbial biomass carbon value (508 mg/kg) followed by *Zai* with manure and mineral fertilizer (481 mg/kg). Microbial biomass carbon value obtained in *Zai* with sole manure was significantly (p<0.05) higher by 17% than conventional with sole manure which recorded a microbial biomass carbon value of 428 mg/kg. *Zai* with manure and mineral fertilizer recorded a microbial biomass carbon that was 26% significantly (p<0.05) higher than conventional with manure and mineral fertilizer which recorded a microbial biomass carbon value of 372 mg/kg. *Zai* pit with no input and *Zai* with sole mineral fertilizer recorded microbial biomass carbon values of 283 mg/kg and 301 mg/kg which were significantly (p<0.05) higher by 32% and 21% than conventional with no input (205 mg/kg) and conventional with sole mineral fertilizer (243 mg/kg), respectively (Figure 5). Under *Zai* pit system, *Zai* pit with sole manure had the highest significant (p<0,05) microbial biomass carbon value which was 57, 51 and 6% higher than *Zai* with no input, *Zai* with sole mineral fertilizer and *Zai* pit with manure and mineral fertilizer, respectively. Under conventional system, conventional with sole manure had the greatest influence on microbial biomass carbon recording a significantly (p<0.05) high value which was 71, 55 and 14% higher than conventional with no input (205 mg/kg), conventional with sole mineral fertilizer (243 mg/kg) and conventional with manure and mineral fertilizer (372 mg/kg), respectively. Generally, all the treatments recorded a significantly (p<0.05) higher microbial biomass carbon values than the control. Soil microbial biomass carbon was significantly affected by the planting system and amendments application at 0-15 cm. The results indicate that *Zai* pit system significantly (p<0.05) increased microbial biomass carbon compared to the conventional system. It is also evident from the results that organic amendments had a significant influence on microbial biomass carbon whether applied solely or in combination with inorganics.

### *Soil microbial biomass nitrogen (SMBN)*

A significant (p<0.05) difference in treatment effect was observed among treatments under the two systems with regards to their effect on microbial biomass nitrogen, with treatments under *Zai* pit system recording significantly (p<0.05) higher microbial biomass nitrogen values as compared to their counterpart treatments under conventional system. *Zai* with sole manure recorded the highest (295 mg/kg) microbial biomass nitrogen value while the lowest value was recorded in the control (108 mg/kg). *Zai* with sole manure , *Zai* with manure and mineral fertilizer, *Zai* with sole mineral fertilizer and *Zai* with no input recorded 37, 13, 13 and 51% significantly (p<0.05) higher microbial biomass nitrogen values than similar treatments under conventional system, respectively. Among the treatments under *Zai* system, *Zai* with sole manure recorded the highest value of microbial biomass nitrogen which was significantly (p<0.05) higher than *Zai* with no input (181 mg/kg), *Zai* with sole mineral fertilizer (191mg/kg) and *Zai* with manure and mineral fertilizer (240 mg/kg) by 48, 43 and 21% respectively (Figure 5). Conventional with manure and mineral fertilizer recorded the highest microbial biomass nitrogen value (211 mg/kg) among the treatments under conventional system and this was 65, 3 and 23% significantly (p<0.05) higher than conventional with no input (108 mg/kg), conventional with sole manure (204 mg/kg) and conventional with sole mineral fertilizer (168 mg/kg). Generally, the trend among treatments under the two systems was similar to that observed under microbial biomass carbon, with high values being recorded in treatments under *Zai* systems compared to those under conventional system. Similarly, higher microbial biomass nitrogen values were recorded in treatments with organic amendments either solely or in combination with mineral fertilizer implying a positive effect of organic inputs on microbial biomass nitrogen.

## DISCUSSION

Soil aggregate stability, expressed as mean weight diameter (MWD), was significantly (p=0.0038) higher in all the *Zai* pit treatments in contrast to similar treatments in the conventional farming technique (Table 4). Soils from *Zai* with integrated manure and chemical fertilizer recorded the greatest significant (p=0.0038) mean weight diameter of 2.06 mm, followed by *Zai* with sole manure (2.01mm). In addition, under both systems, the treatments with organic amendments, whether solely or in combination with inorganic amendments, recorded higher mean weight diameter compared to those treatments without organic amendments (Table 4). A higher mean weight diameter in treatments under *Zai* pit system imply very stable soils as compared to the low mean weight diameter values under conventional system. High soil aggregation in *Zai* treatments is attributable to the minimal soil disruptions during the management and utilization of *Zai* pit system, thus macro-aggregates are not broken down as is the case in conventional system where macro-aggregates are broken down through ploughing (Ngetich et al., 2014b; Twomlow et al*.,* 2008). Previous research has found that the intensity of tillage activities has a significant impact on aggregate stability (Al-Kaisi et al*.,* 2014) The observed high aggregation in *Zai* treatments could also be as a result of the high organic carbon contents (Bolo et al., 2021; Ndungu et al., 2021; Al-Kaisi et al*.,* 2014). *Zai* pits have the potential to store nutrients in place thus minimizing losses through erosion and run-off, due to their design. Previous research has also reported higher aggregate stability under low or no tillage agricultural systems as compared to conventional systems characterized with high rate of soil disturbance through ploughing (Marumbi et al., 2020; Bottinelli et al., 2017; Khuzwayo, 2017; Caesar-TonThat et al., 2011; Gathala et al., 2011; Lal, 2008; Ngetich et al*.,* 2008). Conventional cultivation has been shown to affect soil aggregation both directly and indirectly by disrupting macro-aggregates and altering biological and chemical variables (Barto et al*.,* 2010). Lal (2008) has also documented a decrease in aggregate stability in relation to conventional cultivation. Ngetich et al. (2008) found out that the minimally tilled treatments recorded significantly high (p<0.05) mean weight diameter of soil aggregates than the conventionally tilled treatments. As a result, when compared to low-tillage systems, conventional tillage causes less aggregation (Yalcın and Cikar, 2006). The low values of aggregate stability observed in treatments under conventional system could be associated to loss of soil organic carbon during tillage (Nyamangara et al*.,* 2014). Since minute adjustments in soil organic carbon can affect aggregate stability, the loss of organic matter associated with conventional tillage increases the vulnerability of soil aggregates to disruption. (Nyamangara et al., 2014; Nyamadzawo et al., 2013; Verhulst et al., 2010; Six et al., 2000). Additionally, highest mean weight diameter values in treatments under *Zai* pit technology were recorded under those treatments with manure amended soils, either solely or combined manure with chemical fertilizer. Despite the low aggregation recorded in treatments under conventional system, treatments amended with organic inputs recorded higher mean weight diameters compared to the control and those treatments amended solely with inorganic inputs under this system. The results also indicate higher soil organic carbon (SOC) in treatments with organic amendments under both systems (Table 4) at the end of LR2020 season. These findings may as a result of the binding properties of humic compounds and other by-products of microorganisms resulting from the organic amendments (Bolo et al., 2021; Ndungu et al., 2021). Higher microbial biomass and, as a result, the generation of extracellular polysaccharides, which operate as a good binding agent of soil aggregates, could possibly have contributed to higher aggregate stability amongst organically amendment treatments. These findings corroborate with Huang et al. (2009), who observed increased aggregation under treatments amended with combined manure and mineral fertilizer. Organic matter has been found to be a major cementing agent for soil aggregation; hence the favorable impacts of organic input amendments on aggregation of soil particles in the current study can be attributed to increased aggregation linked with organic input (Yang et al., 2017). This study also observed that soil with inorganic amendment recorded lower aggregate stability values than the control treatments in both systems. This could be as a result of the acidic environment created by the chemical fertilizer thus creating a non-suitable environment for soil microorganisms to thrive thus resulting to the reduction in soil microbial biomass compared to the control. The higher aggregate stability values recorded in the controls could be as a result of slightly higher microbial biomass in the non-amended controls as compared to the chemically amended treatments. As a result, the generation of extracellular polysaccharides and other micro-organism by-products, which acted as a good binding agent of soil aggregates, could possibly have contributed to this observation.

A substantial positive association exists between organic carbon and aggregate stability (Kushwaha et al*.,* 2001). Soil organic carbon enhances soil aggregation, whereas aggregates in return store soil organic carbon, decreasing its decomposition rate (He et al*.,* 2018). Soil aggregates lower the rate of soil organic carbon turnover by establishing a physical barrier between microorganisms and enzymes. on the other hand, soil organic carbon performs a significant role in stabilizing soil aggregates through enhancing microbial proliferation, which promotes the binding together of soil micro-aggregates together (Six et al., 2000). According to Du et al. *(*2013), long-term fertilizers application, particularly organic fertilizers, increases aggregate stability on surface soil. A study by Du et al. *(*2013) attributed the enhanced aggregate stability in organically treated soils to higher microbial biomass, whose by-products are suitable binding agent for soil aggregates. The results of this study indicating higher mean weight diameter values recorded in treatments with organic inputs corroborate with the findings of previous studies where higher aggregate stability were reported in treatments with organic inputs (Bottinelli et al., 2017; Du et al., 2013; Ayuke et al., 2011; Kushwaha et al., 2001). A field experiment conducted by Wang et al. (2013) on China's Loess Plateau revealed improved aggregate stability in treatments treated with organic fertilizer while soils treated with no fertilizer exhibited reduced aggregation. The results of previous studies have also reported enhanced stability of soil aggregates in treatments with sustained incorporation of organic manures in various forms; composts, farmyard manure, crop residues, and straw returns, due to more accumulation of soil organic carbon and a constant supply of freshly broken-down carbon-containing materials (Ghosh et al., 2018; He et al., 2018; Benbi and Senapati, 2010; Chen et al., 2009; Sodhi et al., 2009; Singh et al., 2007). Thus, the findings of the present-day study indicate that the interaction between *Zai* pit system and organic soil amendments significantly promotes soil aggregation thus resulting to more stable soil aggregates and the associated increase in soil organic matter contents. In all the four study seasons, across different days within each season, higher soil moisture contents expressed as volumetric water content values were recorded in treatments under *Zai* pit system as compared to their conventional counterparts (Figure 4a-d). The observed higher volumetric water content values in treatments under *Zai* pit could be attributed to the water harvesting characteristic of *Zai* pit technology. The structure of the pits allows for more water to be captured in the pit thus enhancing the moisture content available for infiltration and uptake by plants (Kimaru-Muchai et al., 2021). The observed tendency can also be attributable to the function of *Zai* pits as basins, which trap infiltrating water, thus, limiting percolation and preserving water within the 0 to 30 cm soil depth. Moisture trapped in the *Zai* pits helps to delay the onset and incidence of moisture stress, thus protecting the crop from the effects of water shortages during periods of dry-spells (Nyamadzawo et al*.,* 2013). Other previous studies have reported higher soil moisture content in *Zai* pit treatments as compared to conventional systems (Zelelew et al., 2018; Nyamadzawo et al., 2013; Reij et al., 2009; Mutunga, 2001). *Zai* pits favors infiltration of moisture into the soil compared to conventional system. (Fatondji et al*.,* 2006). Findings of research by Vohland and Barry (2009) reported improved soil water storage in *Zai* treatments compared to conventional treatments. *Zai* pits have been proven to be capable of gathering up to 25% of run-off from 5 times their area (Malesu et al., 2006). By capturing or storing precipitation water, *Zai* pits enhance the quantity of water retained in the soil layers (Mutunga, 2001). In addition to enhancing the water levels retained in the soil profile, *Zai* pits promote water penetration and reduce run-off, thereby making soil moisture available for plant uptake in the occurrence of dry periods (Fatondji et al., 2006). The volumetric water content values were generally highest in treatments with absolute manure input and those with combinations of manure and mineral fertilizers under both *Zai* and conventional systems (Figure 4a-d). Higher volumetric water content in treatments amended with organic inputs could be linked to the improved soil particle aggregation in manure amended soils that might have improved water infiltration into the soil. Addition of manure into the soil also decreased evaporation rate of soil moisture from the soil by improving the soil's water retention capacity, thus the observed high volumetric water content values in manure-amended treatments. From the results of this study, organic amendments improved moisture infiltration to the lower layers in the soil profile. Manure application reduces compatibility and enhanced moisture retention in semi-arid soils (Blanco-Canqui et al., 2009). The findings of this study are in agreement with the observations of other previous studies where application of organic inputs led to enhanced soil moisture (Oduor et al., 2021; Kaluli et al., 2017; Shaheen et al., 2010; Blanco-Canqui et al., 2009; Overstreet and DeJong-Huges, 2009). The low volumetric water content values observed under convention treatments could be as a result of loss through surface run-off and evaporation, which may not encourage retention and infiltration into lower soil depths.

Soil microbial biomass carbon (SMBC) was significantly affected by the planting system and amendments application at 0 to 15 cm. The results indicate that *Zai* pit system significantly ($p<0.05$) increased microbial biomass carbon compared to the conventional system. It is also evident from the results that organic amendments had a significant ($p<0.05$) influence on microbial biomass carbon whether applied solely or in combination with inorganics.

The high SMBC concentrations recorded in the treatments under *Zai* system than those under conventional system implies *Zai* technology had a significant positive impact on microbial activity. This could be attributed to the accumulation of organic carbon fractions in soil due to the low-tillage nature of the *Zai* technology. The accumulated labile carbon fractions offer sufficient food for micro-organisms and thus, maintain a higher SMBC concentration. In contrast to conventional system, where a sudden flush of microbial activity with tillage events results in considerable losses of carbon as carbon dioxide and also the associated losses through soil erosion, the lack of soil disturbance under *Zai* system offers a consistent source of organic carbon substrates for soil microorganisms, which boosts their activity and contributes for increased soil SMBC. Also, the minimum-tillage characteristic of *Zai* system guards the soil aggregates by holding fungal networks in place. Soil aggregates are an important habitat for the soil microbial biomass, hence high soil microbial populations resulting to high microbial activities, thus the observed significantly high SMBC in treatments under the *Zai* system. Another possible reason for the high SMBC concentrations recorded in treatments under *Zai* system could be due to availability of sufficient moisture for microbial activities in the soil. Unlike the conventional system, *Zai* pits are designed mainly for soil moisture retention. There are greater soil moisture losses through evaporation in the conventional system as a result of the frequent soil disturbance through tillage. The high SMBC accumulation in treatments amended with organic inputs in both systems could be as a result of the increased availability of organic carbon substrates for microbial activities through addition of manure. Manure application can directly contribute to the labile organic carbon pool and indirectly affect the conversion of plant residue-carbon into labile forms by enhancing microbial activity. Soil microbial biomass carbon (SMBC), which serves as a sink for labile nutrients or a source of nutrients for biota, has been extensively used to assess soil fertility under long-term fertilization regimes (Li et al., 2015). It is indicative of the size of the microbial biomass that does the decomposing (Powlson et al., 2012). The results of the current study are in tandem with the findings of Li et al. (2020) who reported increased SMBC in manure amended-treatments as compared to the treatments with chemical fertilizer amendments and the control. Li et al. (2018a) reported a significant increase in SMBC concentration with increasing rate of organic manure application in long-term fertilization experiment. Similar to the results of this study, significant increases in MBC with addition of manure have been reported by other previous studies, implying that organic manure, alone or in combination with mineral fertilizers, had favorable impacts on microbial activity, most likely by providing a readily accessible pool of carbon substrate (Kumar et al., 2018; Li et al., 2018b; Li et al., 2020; Lou et al., 2011; Naresh et al., 2017; Yang et al., 2012, 2018).

Mineral fertilizer effects on SMBC have been documented in a variety of ways, including positive, negative, and no effects (Gong et al., 2009; Lou et al., 2011; Xue et al., 2006). The significantly lower SMBC concentration in treatments with mineral fertilizer amendments has also been documented in previous similar studies (Gong et al., 2012; Kumar et al., 2018; Li et al., 2020). The significantly higher, compared to the control, SMBC concentrations recorded in treatments with mineral fertilizer amendments in this study are in line with the findings of Li et al. (2015) and Li et al. (2008), where the SMBC concentrations recorded in treatments with sole mineral fertilizer were 38% higher than the control. A significant ($p<0.05$) difference in treatment effect was observed among treatments under the two systems with regards to their effect on soil microbial biomass nitrogen (SMBN), with treatments under *Zai* pit system recording significantly ($p<0.05$) higher microbial biomass nitrogen values as compared to their counterpart treatments under conventional system. *Zai* with sole manure recorded the highest SMBN value while the lowest value was recorded under conventional with sole mineral fertilizer. Similarly, high values of SMBN were recorded in treatments with organic amendments either solely or in combination with mineral fertilizer implying a positive effect of organic inputs on microbial biomass nitrogen.

The observed significantly high SMBN concentrations in treatments under *Zai* system and those with organic amendments either solely or in combination with mineral fertilizer could be attributed to a number of factors. First, *Zai* is a minimum-tillage system and so losses through gaseous emissions are on the minimal, unlike in conventional system where the continuous soil disturbance through tillage activities enhances SMBN losses through gaseous emissions. The minimum-tillage characteristics of Zai system also protects soil aggregates and do not break fungal networks, which are an important habitat for the microbial biomass in soil, hence high soil microbe populations resulting to high microbial activities. Secondly, the high moisture retention associated with the *Zai* pit system enhances microbial activities, thus the observed significantly high SMBN concentrations in treatments under *Zai* system as compared to those under conventional systems. On the other hand, the significantly high SMBN values recorded in treatments with organic amendments either solely or in combination with inorganics, under both systems, could be as a result of the direct addition of organic carbon substrates that provides sufficient food for the soil microbes thus enhancing microbial activities. Also, organic inputs improve soil water retention which provides favorable conditions for increased microbial activities.

Similar observations were documented by Kumar et al. (2018) where significant increase in SMBN in surface soil (0 to 15 cm) was maintained in plots receiving fertilizer over unfertilized control plots. Similarly, findings of previous studies have documented significantly high ($p<0.05$) SMBN contents in treatments with combined organics and inorganics inputs which were higher than the values recorded under treatments with sole mineral fertilizers and the untreated controls (Xu et al., 2018; Liu et al., 2017; Li et al., 2016; Oladele et al. 2019; Ren et al., 2019; Neufeld et al., 2017). When comparing manure application to solitary mineral fertilizer application, Pan et al. (2009) found that manure application improved SMBN by 49%. As a result, manure amendment could be a viable alternative to the difficulties associated with excessive mineral fertilizer application while also boosting soil bio-fertility (Li et al., 2015; Pan et al., 2009). The findings of this study are consistent with previous research where significantly higher SMBN were recorded under systems characterized by reduced or zero tillage activities than the control (Carpenter-Boggs et al., 2003; Chen et al., 2009; Dou et al., 2016; Naresh et al., 2017; Wang et al., 2014; Wang et al., 2015). By enhancing soil aggregation and minimizing oxidation, zero/reduced tillage methods, such as *Zai* pits, allow carbon to build up in the plow layer, thus increased microbial activities (Carpenter-Boggs et al., 2003). Contradicting findings were documented by Kallenbach and Grandy (2011) who reported no effect on SMBN after application of organic amendment, suggesting that changes in microbial biomass (both carbon and nitrogen) cannot be attributed to amendment of soils with organic inputs only. In other similar studies, mineral fertilizer administration resulted in a 12 to 48% drop in SMBN when compared to no fertilizer or the initial values of the studies (Qiu et al., 2016). However, despite this, some researchers have suggested that the response of microbial biomass can be highly variable depending on soil types, management practices, and climate conditions (Esperschütz et al., 2007; Lentendu et al., 2014).

## CONCLUSION

Significant differences in soil aggregate stability, soil moisture content and soil microbial biomass were recorded among different nutrient amendment treatments under *Zai* and conventional systems. Across the four study seasons, soil aggregate stability (expressed as mean weight diameter), soil moisture content (expressed as volumetric water content) and soil microbial biomass (Carbon and Nitrogen) were significantly higher in treatments under *Zai* technology compared to similar treatments under conventional system. Additionally, significantly higher values of these three important soil parameters were recorded in treatments with exclusive manure applications and those with manure combined with chemical fertilizer under both systems. Similarly, all the three soil parameters were observed to be significantly high in treatments under *Zai* pit technique integrated with organic amendments as opposed to conventional approach with comparable nutrient input amendments. In conclusion, *Zai* pits, being a low-tillage system, is characterized by minimal soil disturbance and high levels of organic carbon that promotes the establishment of stable soil aggregates, which forms an important habitat for the microbial biomass in soil, resulting to high soil microbe populations, thus high microbial activities. The accumulation of labile carbon fractions in *Zai* treatments offers sufficient food for microorganisms. The design of the pits also promotes soil moisture retention within the root zone. On the other hand, organic amendments promote soil particles aggregation through the bonding influence of humic compounds and microorganisms' by-products while at the same time improving water infiltration and reducing loss of soil moisture through evaporation. Investing in better farming inputs and innovations is crucial to enhancing soil productivity on the currently low agriculturally productive lands, particularly in arid and semi-arid zones. When combined, *Zai* pit technology integrated with organic amendments is an agricultural intervention that has been demonstrated by this research to improve soil organic matter, stability of soil aggregates, soil moisture content and soil microbial biomass concentrations, thus contributing in the improvement of the overall health and fertility of soil for better productivity.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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