

**EFFECTS OF INTEGRATED SOIL AND WATER CONSERVATION
TECHNOLOGIES ON MAIZE GROWTH AND GRAIN YIELD IN SEMI-ARID
MAKUENI COUNTY, KENYA**

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ABSTRACT

In the semi-arid areas, maize production is limited by low soil moisture availability, unreliable rains and deteriorating soil fertility. Potential solutions involve the use of technologies that can enhance the ability to capture water, hold moisture and provide nutrients in what are known as an integrated soil and water conservation technology. The study assessed the impact of the Soil and Water Conservation (SWC) technologies implemented in combination on soil moisture, maize growth and yield in the OND 2025 and MAM 2026 seasons in Mbooni Sub-County of Makueni County, Kenya. A total of 18 treatment combinations of Zai pits, Jembe holes; mulch; farmyard manure (FYM); and diammonium phosphate (DAP) were tested. Analysis of variance was used to analyze soil moisture content; growth parameters of maize and yield and treatment means were separated at 5% significance level. The integrated treatments affected soil water availability and maize growth, with different effects on different growth parameters and seasons. Overall, the most complete treatment (Zai + mulch + hydrogel + FYM + DAP, T09) consistently recorded the highest yield of 6.03 t ha⁻¹ in OND 2025 and 6.13 t ha⁻¹ in MAM 2026 seasons. Overall, treatment performance was highly related between both seasons ($r = 0.826$, $P < 0.001$), suggesting consistency in the relative effectiveness of the integrated technologies for the different seasons. Results show that the integration of water-harvesting structures, moisture-retention practices and fertility inputs are more beneficial for maize production than less integrated approaches. The study identifies the potential of integrated Zai pit-based technologies to enhance maize productivity and the resilience of rain-fed farming systems in semi-arid

Keywords: Integrated Soil and Water Conservation; Zai Pits; Soil Moisture; Maize Productivity; Semi-arid Agriculture; Climate Resilience; Kenya.

1. INTRODUCTION

Maize (*Zea mays* L.) is one of the most significant cereal crops in the world and is used for food, animal feed and raw material for industry. In sub-Saharan Africa, the crop is a key contributor to food security and rural livelihoods, and a big source of calories and income for millions of smallholder farming households (FAO, 2022). Maize is the largest share of cultivated land in Kenya and the leading staple food crop in the country. Despite ongoing investments in improved seed varieties, fertilizers and agronomic management, national production of maize continues to fall short of local demand, due to reduced soil fertility, climate uncertainty, frequent periods of

drought and land degradation, including in the dry and semi-arid lands (ASALs) of the country (FAO, 2022).

Climate change is becoming a serious threat in the ASALs of Kenya due to the increased variability in rainfall, longer droughts and higher evapotranspiration. The conditions significantly decrease soil moisture availability during a critical period for crop growth, which adversely affects the productivity of maize. Makueni County in the ASAL region of Kenya is typical of the above production constraints. Maize production in the county is highly vulnerable to moisture stress, with highly erratic rainfall and frequent droughts, and soil fertility is decreasing (Bowers et al. 2024; Kebenei et al., 2023). As a result, maize yields are still low and unreliable, especially when farmers follow the recommended conventional fertilizer application rates and use better varieties. The shortfall in production persists as a food security and income concern for the households, and a challenge to the resilience of smallholder farming systems in the region.

In the context of low water availability, soil and water conservation (SWC) technologies have proven to be efficient and promising tools for enhancing agricultural productivity and output while protecting the environment. Zai pits, mulching, hydrogel application, farmyard manure (FYM) and suitable inorganic fertilizer management promote infiltration capacity of rainfall, decreases runoff and evaporative water losses, increases water storage capacity, and improves the physical and chemical properties of soil (Kiboi et al., 2023). Additionally, soil moisture conservation practices provide the proper environment for continued crop growth during the growing season, and organic amendments will enhance soil structure, microbial activity, and nutrient availability. Thus, the combined use of these technologies has been increasingly suggested as a sustainable approach to enhance crop performance and resilience in semi-arid conditions (FAO, 2022).

Earlier research has shown that adoption of single soil and water conservation technologies has been beneficial in crop production under semi-arid conditions. For instance, zai pits have been shown to increase the infiltration and retention of water in the soil, which can help crops establish and produce good yields (Bowers et al., 2024). Likewise, Makumi et al. (2025) found that moisture conservation technologies applied in eastern Kenya led to substantial increases in productivity for pearl millet. While these promising results are available, most of the current research has focused on the assessment of single technologies and has paid less attention to the integrated conservation systems, where soil moisture conservation and nutrient management are combined. Furthermore, the performance of integrated SWC technologies is dependent on the agroecological zones due to variations in rainfall and soil properties and management practices and therefore field evaluation of the technologies is recommended prior to widespread recommendations.

While combined use of soil and water conservation technologies is gaining momentum in Kenya as part of climate-smart agriculture implementation, empirical evidence on combined impact of these technologies on maize growth and yield in the semi-arid climate of Makueni County is still limited. In particular, the locally generated evidence on combinations of zai pits, mulching, hydrogel and farmyard manure and inorganic fertilizer under field conditions is insufficient. The lack of this knowledge restricts extension recommendations and farmers' capacity to implement optimal and profitable conservation strategies for enhancing maize productivity under moisture limited conditions (Getare & Mucheru-Mucheru-Muna, 2024). The need to generate location-specific evidence to inform sustainable agricultural intensification, build climate resilience and enhance food security in dryland farming systems in Kenya is therefore paramount.

The current study aimed to assess the effect of the combined use of soil and water conservation technologies on maize growth and yield under semi-arid condition in Makueni County, Kenya. It was specifically aimed at determining the performance of different treatments (zai pits, jembe holes, mulching, using farmyard manure and diammonium phosphate (DAP) fertilizers) on plant height, stem diameter, number of leaves per plant, number of cobs per plant and yield during the 2025 short rains (OND) and 2026 long rains (MAM) season. The outcomes provide scientific basis for adopting integrated soil and water conservation technologies as climate smart management practices that will enhance maize production and enhance the livelihoods of smallholder farmers in semi-arid regions of Kenya.

2. MATERIALS AND METHODS

Study Area

The field experiment was carried out in Waia/Kako Ward, Mbooni Sub-county, Makueni County, Kenya in October-December (OND) 2025 short rain season and March-May (MAM) 2026 long rain season. Makueni County is in the arid and semi-arid lands (ASALs) of Kenya which rely mostly on rain-fed farming and are very sensitive to rainfall fluctuations. The climate is bimodal with annual rainfall from around 500-900 mm and mean annual temperatures ranging from 20-30°C. Soils are mainly sandy clay loam to sandy loam and low in organic matter, moisture holding capacity, and fertility as a result of the prolonged cultivation, and the lack of soil fertility enriching practices. Maize is the major staple food crop grown by smallholder farmers and it is the major source of food security for households in the study area (FAO, 2022).

Experimental Design and Treatment Structure

The experiment was a split-plot design in a randomized complete block design (RCBD) with three blocks. A total of 18 treatment combinations, including various soil and water conservation (SWC) technologies were tested in fifty-four experimental plots. The treatments consisted of various combinations of zai pits, jembe holes, mulching, hydrogel, farmyard manure (FYM) and diammonium phosphate (DAP) fertilizer to enhance soil water holding capacity and nutrient availability in water deficient conditions.

The integrated treatment allowed for the evaluation of the individual and combined contribution of water harvesting, moisture conservation and soil fertility management practices on maize growth and grain yield. Experimental bias was minimized and comparisons between treatments were made more precise by randomly assigning all treatment combinations within each replication.

The experiment was laid out as eighteen treatment combinations to assess the effect of in situ soil and water conservation practices and soil fertility management practices on maize growth, soil moisture conservation and grain yield. The various treatments involved mulching, hydrogel, farmyard manure (FYM), and diammonium phosphate (DAP) in combination with each other in different combinations with Zai pits or Jembe holes. The treatment combinations used are described in detail in Table 1.

Table 1: Treatment combinations evaluated during the study

Treatment Code	Treatment Combination
T01	Zai pits + Mulch + FYM
T02	Zai pits + Mulch + DAP
T03	Zai pits + Mulch + FYM + DAP
T04	Zai pits + Hydrogel + FYM
T05	Zai pits + Hydrogel + DAP
T06	Zai pits + Hydrogel + FYM + DAP
T07	Zai pits + Mulch + Hydrogel + FYM
T08	Zai pits + Mulch + Hydrogel + DAP
T09	Zai pits + Mulch + Hydrogel + FYM + DAP
T10	Jembe hole + Mulch + FYM
T11	Jembe hole + Mulch + DAP
T12	Jembe hole + Mulch + FYM + DAP
T13	Jembe hole + Hydrogel + FYM
T14	Jembe hole + Hydrogel + DAP
T15	Jembe hole + Hydrogel + FYM + DAP
T16	Jembe hole + Mulch + Hydrogel + FYM
T17	Jembe hole + Mulch + Hydrogel + DAP
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP

Crop Establishment and Field Management

Experimental plots were planted prior to rains according to recommendations given for maize production in semi-arid areas. The planting holes were made in a similar manner as the Zai pits and jembe holes with minimum of 24 hours before planting in the designated treatments, and a land preparation involved incorporation of farmyard manure for nutrient mineralization before the establishment of the crop. The planting was done with Diammonium phosphate (DAP) fertilizer as per the treatments and for better water holding capacity, hydrogel was added to the planting holes in the respective treatments. Immediately after crop establishment, the mulching material was applied to minimize the evaporative water loss and improve the conservation of soil water.

The recommended planting spacing for the study area was followed in the planting of maize under rain-fed conditions. All plots were uniformly treated as regards agronomic practices and other crop husbandry operations to ensure that differences in treatment were due to the soil and water conservation technology and not differences in agronomic practices.

Data Collection

The effects of the integrated soil and water conservation technologies on soil moisture, maize growth and grain yield were evaluated in both the OND 2025 and MAM 2026 cropping seasons. During the growing seasons soil moisture conditions were periodically measured to assess the differences in soil moisture holding capacity between the treatment combinations.

Plant height, stem diameter, number of leaves per plant and number of cobs per plant were used to assess the growth of maize. The height of the plants was measured from the soil surface to the top of the plants with the help of a measuring tape. The diameter of the stem was measured at the

base of representative plants with a vernier caliper. Fully expanded number of leaves and number of cobs/plant were counted on representative plants at each assessment period in each experimental plot.

Maize was harvested from the net plot area at physiological maturity (PY) for grain yield. Harvested cobs were then dried and shelled, and grain weight was measured on a plot basis, then converted to tonnes per hectare. Grain yield was evaluated separately for the OND 2025 and MAM 2026 cropping seasons to account for the possible seasonal differences in the performance of the treatments.

Statistical Analysis

GenStat software was used for data analysis. Analysis of variance (ANOVA) was employed to evaluate the effects of the treatments combinations of soil and water conservation on soil moisture content, maize growth parameters and grain yield. The means of treatment were separated from each other where significant treatment effects were found at 5% level of significance with Fisher's Least Significant Difference (LSD) test. The analyses were done independently for both OND 2025 and MAM 2026 cropping seasons. A p value of < .05 was considered to be statistically significant.

3. RESULTS

Effects of Integrated Soil and Water Conservation Technologies on Soil Moisture Content

The integrated soil and water conservation technologies had an impact on soil moisture availability during both the OND 2025 and MAM 2026 cropping seasons. The moisture content of the soil differed between the treatment combinations and in time, reflecting variations in the ability of the technologies to capture, retain and conserve soil moisture in the maize root zone.

Soil Moisture Content during the OND 2025 Cropping Season

Soil moisture status varied throughout the maize growing season for the various combinations of the integrated soil and water conservation practices during the OND 2025 cropping season (Table 2). The multiple moisture conservation treatments in general had higher soil moisture compared to the less integrated treatments. Specifically, the Zai pit-based treatments that included mulch, hydrogels and fertility inputs had higher soil water content at all sampling intervals.

The application of Zai pits, mulch, hydrogel, farmyard manure (FYM) and diammonium phosphate (DAP) (Treatment T09) had the highest value of soil moisture among the treatments during the growing season. On the other hand, the comparatively low soil moisture content was recorded for several Jembe hole-based treatments with less integrated components. The findings showed that synergistic use of complementary water harvesting and moisture-retention practices increased the soil moisture available in relatively moisture constrained OND season.

Table 2: Mean soil moisture content (%) at 0–30 cm soil depth under different integrated soil and water conservation technologies during the OND 2025 cropping season.

Treatment	Treatment combination	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T01	Zai pits + Mulch +	23.30cd	25.12cde	26.48def	27.73cd	25.83cde	24.13de

	FYM						
T02	Zai pits + Mulch + DAP	23.20c d	25.13cd e	27.10def	27.43c	25.23cd	23.45cde
T03	Zai pits + Mulch + FYM + DAP	23.30c d	25.43cd e	26.68def	27.77cd	25.27cd	23.48cde
T04	Zai pits + Hydrogel + FYM	23.30c d	25.78de	27.72efg h	28.58cd e	27.42efg	23.92de
T05	Zai pits + Hydrogel + DAP	23.80d	25.38cd e	27.35def g	29.32def	26.97def	24.78ef
T06	Zai pits + Hydrogel + FYM + DAP	23.50d	26.05ef	28.10fgh	28.38cd e	26.40cde f	24.28e
T07	Zai pits + Mulch + Hydrogel + FYM	25.60e	27.78fg	29.22ghi	31.52g	28.38fg	26.63g
T08	Zai pits + Mulch + Hydrogel + DAP	25.50e	27.82fg	30.18i	30.27efg	29.08g	26.35fg
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	25.70e	28.42g	29.58hi	30.65fg	28.17fg	26.82g
T10	Jembe hole + Mulch + FYM	18.60a	20.77a	22.97a	23.57a	21.73a	20.13a
T11	Jembe hole + Mulch + DAP	19.30a	21.37a	23.18a	23.52a	21.35a	19.85a
T12	Jembe hole + Mulch + FYM + DAP	18.80a	20.75a	22.47a	24.00a	21.85a	20.08a
T13	Jembe hole + Hydrogel + FYM	19.80a	21.18a	23.32a	24.92a	22.78ab	21.17ab
T14	Jembe hole + Hydrogel + DAP	19.70a	21.48a	23.90ab	24.65a	23.13ab	20.32a
T15	Jembe hole	20.20a	21.82ab	24.13abc	25.13ab	23.08ab	20.43a

	+ Hydrogel + FYM + DAP	b					
T16	Jembe hole + Mulch + Hydrogel + FYM	21.70b c	23.60bc	25.65bcd	26.88bc	24.77bc	22.22bc
T17	Jembe hole + Mulch + Hydrogel + DAP	21.60b c	24.00cd	25.97cde	26.87bc	24.60bc	23.47cde
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	22.30b c	23.92cd	26.15de	27.30c	24.45bc	22.57bc d

Note: Values are treatment means. Means followed by the same letter(s) within a column are not significantly different according to Fisher's Least Significant Difference (LSD) test at $P \leq 0.05$.

Soil Moisture Content During the MAM 2026 Cropping Season

The situation was found to be similar during the MAM 2026 cropping season, with the soil moisture levels depending on the seasonality of rainfall and the stage of crop development (Table 3). Generally, the more integrated treatment combinations maintained the highest soil moisture whereas the treatments with fewer conservation components lost moisture. Mulch and hydrogel treatments were shown to be more effective than a number of treatments in Jembe holes, and treatments with Zai consistently showed greater moisture retention than several Jembe hole-based treatments.

Generally, the highly integrated treatment combinations maintained favourable soil moisture conditions throughout the growing season (T09). However, treatments with less moisture retention tended to have more soil moisture reductions during the growing season. The results show the potential of combining complementary technologies in an effort to enhance soil water availability in semi-arid rain-fed conditions.

Table 3: Mean soil moisture content (%) at 0–30 cm soil depth under different integrated soil and water conservation technologies during the MAM 2026 cropping season.

Treatment	Treatment combination	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T01	Zai pits + Mulch + FYM	25.57cd	31.83bcd	29.12cd	28.10b	26.83c	25.37b
T02	Zai pits + Mulch + DAP	25.95cdef	31.90bcd	29.65cde	28.68b	26.47c	24.67b
T03	Zai pits + Mulch + FYM + DAP	26.32cdef	32.08bcde	29.70cde	28.72b	26.82c	25.43b

T04	Zai pits + Hydrogel + FYM	26.08cdef	31.77bcd	29.82def	29.43b	27.97cdef	25.65bc
T05	Zai pits + Hydrogel + DAP	24.58bc	30.38b	28.17cd	28.02b	25.92c	23.90b
T06	Zai pits + Hydrogel + FYM + DAP	25.43cd	31.70bc	29.03cd	29.12b	27.20cd	25.18b
T07	Zai pits + Mulch + Hydrogel + FYM	28.32f	33.82de	31.77ef	32.07c	29.60ef	28.58d
T08	Zai pits + Mulch + Hydrogel + DAP	27.70def	33.45cde	31.43ef	31.78c	29.32def	27.78cd
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	28.03ef	34.03e	31.90f	31.87c	29.97f	28.17d
T10	Jembe hole + Mulch + FYM	22.23ab	28.00a	25.45a	25.12a	23.33a	21.45a
T11	Jembe hole + Mulch + DAP	21.82a	27.00a	25.17a	24.38a	22.27a	20.70a
T12	Jembe hole + Mulch + FYM + DAP	22.10a	27.78a	25.95ab	24.85a	22.98a	20.55a
T13	Jembe hole + Hydrogel + FYM	21.35a	26.92a	25.03a	24.75a	23.35ab	20.88a
T14	Jembe hole + Hydrogel + DAP	20.78a	26.65a	24.62a	23.70a	22.32a	20.32a
T15	Jembe hole + Hydrogel + FYM + DAP	21.55a	27.55a	24.92a	24.87a	22.98a	21.30a
T16	Jembe hole + Mulch + Hydrogel + FYM	24.92c	30.55b	27.62bc	28.32b	26.30c	24.97b
T17	Jembe hole +	24.70c	30.23b	27.77bcd	27.83b	25.73bc	23.97b

	Mulch + Hydrogel + DAP						
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	25.70cde	30.88b	29.18cd	29.00b	27.30cde	25.60bc

Note: Fisher's LSD test was used to determine that means followed by the same letter in the same column are not significantly different at the 5% level.

Effects of Integrated Soil and Water Conservation Technologies on Maize Growth

The impact of soil and water conservation technologies on maize growth was found to be different for different growth parameters and seasons. Four parameters of maize growth namely the number of leaves per plant, the number of cobs per plant, plant height and stem diameter were used to evaluate the growth of maize. Progressive growth was associated with all the treatments, but the intensity of the treatment effects varied with crop growth parameters and in different seasons.

Effects on Plant Height

Under all the treatment combinations in both the cropping seasons, the plant height increased progressively during the course of maize crop. In the OND 2025 season, the difference in plant height was seen as numerical differences between the treatments during the assessment periods. The treatment resulted in less responses however, compared with the following season of MAM 2026.

Table 4 shows the mean plant height values under various treatment combinations during the OND 2025 season. The more integrated treatments performed as well as or numerically higher in plant height as compared to the less integrated treatment combinations, but magnitude of the differences varied by growth stage.

Table 4: OND 2025 Mean plant height (cm) of maize under different integrated soil and water conservation technologies.

Treatment Code	Treatment	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T01	Zai pits + Mulch + FYM	19.13a	48.80a	91.90a	141.30a	188.50a	219.00a
T02	Zai pits + Mulch + DAP	17.23a	52.60a	92.33a	139.60a	191.00a	222.10a
T03	Zai pits + Mulch + FYM + DAP	18.27a	47.63a	89.23a	137.50a	190.30a	221.70a
T04	Zai pits + Hydrogel + FYM	18.70a	52.07a	92.80a	143.20a	189.10a	219.70a
T05	Zai pits + Hydrogel + DAP	18.80a	49.10a	90.27a	139.40a	191.30a	220.30a
T06	Zai pits + Hydrogel + FYM + DAP	20.60a	50.60a	88.03a	138.40a	190.10a	223.20a

T07	Zai pits + Mulch + Hydrogel + FYM	19.60a	49.33a	89.40a	140.60a	188.30a	220.60a
T08	Zai pits + Mulch + Hydrogel + DAP	20.03a	49.37a	90.90a	141.90a	189.30a	219.60a
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	20.73a	49.80a	91.63a	137.70a	188.00a	220.20a
T10	Jembe hole + Mulch + FYM	20.60a	50.47a	90.53a	137.60a	191.60a	220.60a
T11	Jembe hole + Mulch + DAP	21.37a	52.03a	88.20a	141.00a	190.80a	219.20a
T12	Jembe hole + Mulch + FYM + DAP	19.97a	52.20a	92.47a	138.80a	190.20a	221.60a
T13	Jembe hole + Hydrogel + FYM	16.37a	50.40a	91.27a	136.10a	191.00a	223.70a
T14	Jembe hole + Hydrogel + DAP	19.87a	47.43a	90.03a	138.80a	191.50a	221.20a
T15	Jembe hole + Hydrogel + FYM + DAP	18.93a	50.13a	88.17a	137.50a	190.40a	223.20a
T16	Jembe hole + Mulch + Hydrogel + FYM	20.80a	51.00a	89.50a	141.80a	187.80a	220.10a
T17	Jembe hole + Mulch + Hydrogel + DAP	19.87a	48.57a	92.87a	140.20a	190.70a	218.80a
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	17.27a	49.57a	92.13a	140.30a	192.30a	223.40a

Figure 1 illustrates changes in maize plant height across the growing period. Plant height increased steadily under all treatments, reflecting normal crop development, although differences in growth trajectories were observed among the treatment combinations.

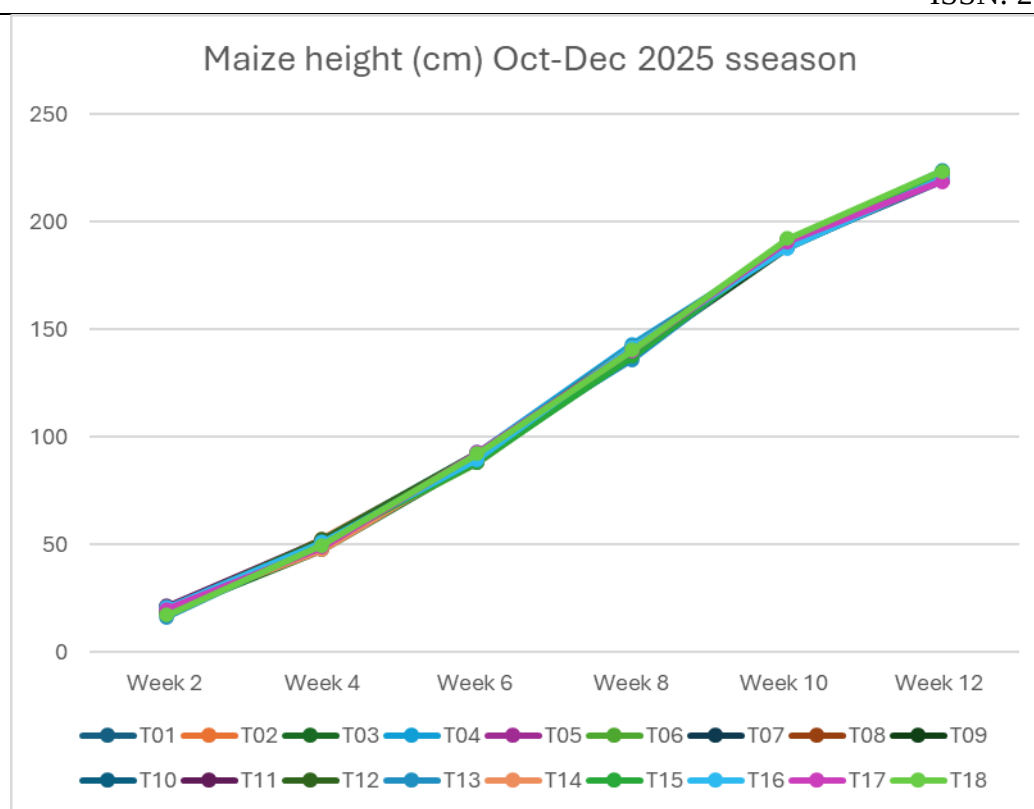


Figure 1: Changes in maize plant height under different integrated soil and water conservation technologies during the OND 2025 cropping season.

In the MAM 2026 season, the differences in treatment in height of the plant were more noticeable. The integrated treatments tended to yield taller plants than the less integrated treatments, often with the tallest mean plant heights during the assessments for the T09 treatments. The observed differences suggested that the impacts of the combination of the soil and water conservation technologies on vegetative growth were different under the different seasons.

Table 5: Mean plant height (cm) of maize under different integrated soil and water conservation technologies during the MAM 2026 cropping season.

Treatment	Treatment	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T01	Zai pits + Mulch + FYM	27.7abc	74abcd	129.5abc	182.0bcd	204.5abcdefg	209.1abc
T02	Zai pits + Mulch + DAP	28.4abc	76abcd	132.3abcd	175.3abcd	204.5abcdef	203.9abc
T03	Zai pits + Mulch + FYM +	29.67abc	76abcd	133.1abcd	189.0de	218.0fg	216.7bc

	DAP						
T04	Zai pits + Hydrogel + FYM	27.37ab	73abcd	130.0abcd	178.8abcd	196.5abcd	198.1abc
T05	Zai pits + Hydrogel + DAP	27.17ab	77abcd	129.0abc	174.6abcd	203.9abcdef	200.1abc
T06	Zai pits + Hydrogel + FYM + DAP	30.10abc	78bcd	141.4cd	186.1cde	217.5efg	218.3bc
T07	Zai pits + Mulch + Hydrogel + FYM	29.20abc	83cd	133.7abcd	185.0bcde	214.6cdefg	215.2abc
T08	Zai pits + Mulch + Hydrogel + DAP	29.47abc	76abcd	139.9bcd	190.5de	216.0defg	217.6bc
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	32.17c	86d	148.3d	201.1e	224.3g	221.1c
T10	Jembe hole + Mulch + FYM	29.27abc	65a	125.3abc	167.9abc	188.6a	190.2a
T11	Jembe hole + Mulch + DAP	25.80a	68ab	124.5ab	167.4ab	195.7abc	193.8ab
T12	Jembe hole + Mulch + FYM + DAP	27.47abc	77abcd	132.5abc	178.2abcd	212.4bcdefg	210.6abc
T13	Jembe hole + Hydrogel + FYM	27.77abc	70ab	121.2a	162.8a	193.7ab	193.9ab
T14	Jembe hole + Hydrogel + DAP	26.43ab	69ab	122.0a	169.7abc	192.5a	192.5ab
T15	Jembe hole +	27.57abc	76abcd	130.9abc	180.7abcd	203.5abcdef	208.1abc

	Hydrogel + FYM + DAP						
T16	Jembe hole + Mulch + Hydrogel + FYM	28.40abc	72abc	126.4abc	174.3abcd	204.2abcdef	205.0abc
T17	Jembe hole + Mulch + Hydrogel + DAP	26.47ab	71abc	124.0ab	162.8a	197.8abcde	198.6abc
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	30.70bc	76abcd	137.6abcd	191.1de	214.6cdefg	215.8abc

Figure 2 illustrates the plant height growth stage development during MAM 2026 cropping season. In the more integrated treatments overall growth tended to be favourable throughout the assessment.

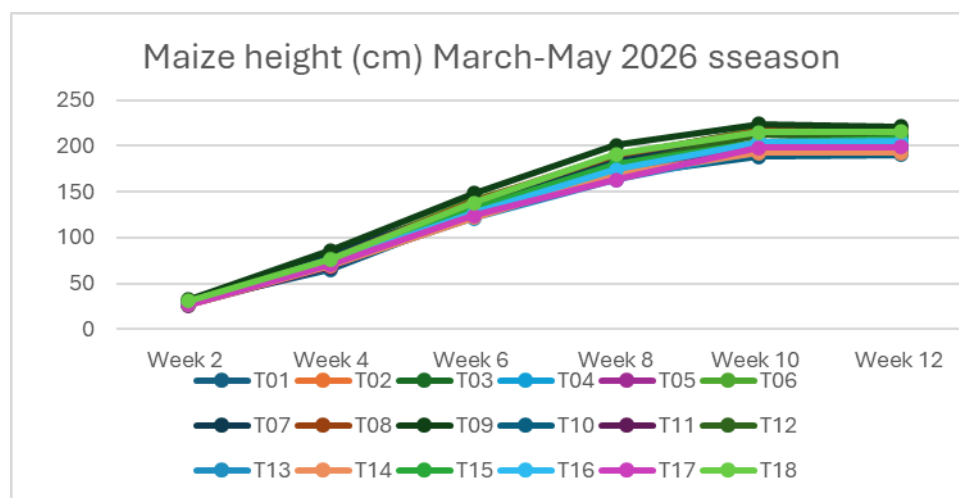


Figure 2: Changes in maize plant height under different integrated soil and water conservation technologies during the MAM 2026 cropping season.

Effects on Stem Diameter

Maize stem diameter increased with the growth of maize plants under all treatment combinations in both cropping seasons. But for some of the other growth parameters, treatment effects were generally more pronounced than stem diameter.

In OND 2025, differences in stem diameter were noted between treatments, but the treatment effects were not consistently statistically significant. Likewise, in the MAM 2026 season, great

differences were noticed at some stages of crop development, but in general, the differences were not very large at the later stages of the crop.

Effects on Number of Leaves per Plant

The number of leaves per plant increased progressively during the vegetative growth stages in both cropping seasons. Treatment effects were more noticeable at the early and intermediate growth stages of the crop, especially when the differences among the treatments as soil moisture availability was greatest.

In the OND 2025 season, considerable differences were seen in the growth stages at selected stages between the different treatments. This is because more integrated treatment combinations often resulted in more leaves than the less integrated treatments, especially in the early stages of crop development. However, these differences became less pronounced as the crop progressed toward maturity.

Table 6: Mean number of leaves per maize plant under different integrated soil and water conservation technologies during selected growth stages of the OND 2025 cropping season.

Treatment Code	Treatment	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T01	Zai pits + Mulch + FYM	5.00abc	10.00cd	14.00def	16.00efgh	17.00def	16.00a
T02	Zai pits + Mulch + DAP	5.00abc	9.00abcd	14.00def	14.00cdef	17.00def	16.00a
T03	Zai pits + Mulch + FYM + DAP	7.00c	10.00cd	15.00f	17.00gh	18.00ef	17.00a
T04	Zai pits + Hydrogel + FYM	4.00ab	9.00abcd	13.00cde	16.00efgh	16.00cdef	16.00a
T05	Zai pits + Hydrogel + DAP	6.00bc	8.00abcd	13.00def	14.00cdef	15.00cd	14.00a
T06	Zai pits + Hydrogel + FYM + DAP	6.00bc	11.00d	15.00ef	18.00h	18.00f	17.00a
T07	Zai pits + Mulch + Hydrogel + FYM	4.00ab	9.00bcd	13.00def	15.00defg	16.00cdef	16.00a
T08	Zai pits + Mulch + Hydrogel + DAP	4.00ab	8.00abc	12.00cd	14.00cde	15.00cde	15.00a
T09	Zai pits + Mulch +	5.00abc	9.00bcd	14.00def	16.00fgh	17.00def	17.00a

	Hydrogel + FYM + DAP						
T10	Jembe hole + Mulch + FYM	4.00ab	8.00abcd	12.00cd	14.00cdef	14.00bc	14.00a
T11	Jembe hole l + Mulch + DAP	4.00ab	8.00abc	11.00bcd	13.00bcd	14.00abc	14.00a
T12	Jembe hole + Mulch + FYM + DAP	6.00bc	8.00abcd	12.00cd	14.00cdef	15.00cde	15.00a
T13	Jembe hole + Hydrogel + FYM	4.00a	7.00ab	10.00abc	12.00abc	14.00abc	13.00a
T14	Jembe hole + Hydrogel + DAP	4.00a	7.00ab	9.00ab	12.00abc	12.00ab	11.00a
T15	Jembe hole + Hydrogel + FYM + DAP	5.00abc	8.00abc	12.00cd	13.00bcd	14.00abc	14.00a
T16	Jembe hole + Mulch + Hydrogel + FYM	4.00ab	7.00ab	9.00ab	11.00ab	12.00ab	12.00a
T17	Jembe hole + Mulch + Hydrogel + DAP	3.00a	6.00a	9.00a	10.00a	11.00a	11.00a
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	4.00ab	7.00ab	10.00abc	12.00abc	12.00ab	12.00a

Figure 3 illustrates the temporal changes in leaf development during the OND 2025 cropping season.

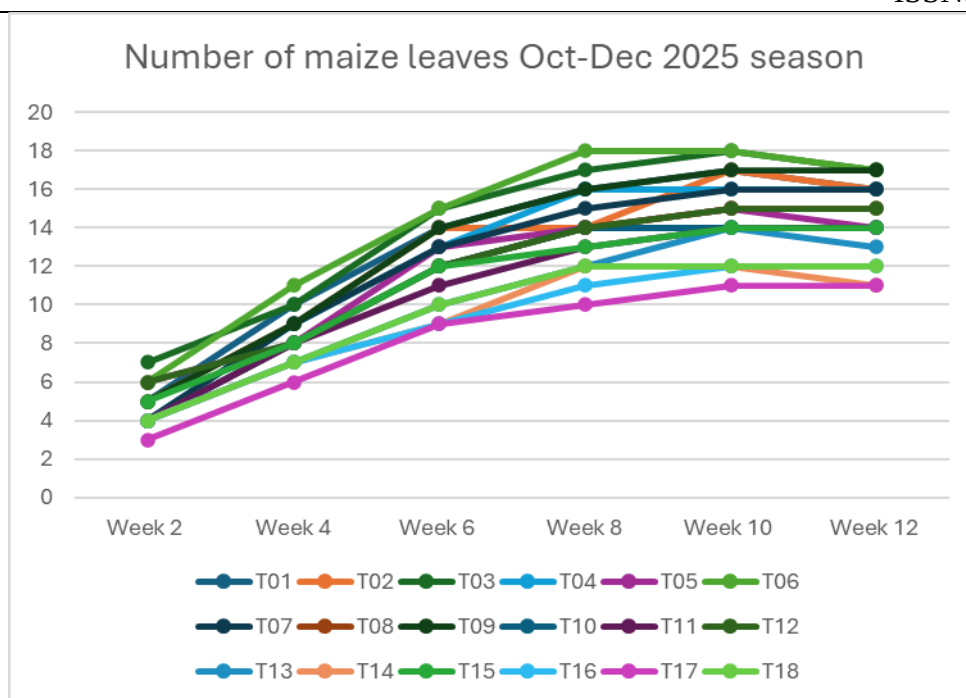


Figure 3: Changes in the number of maize leaves per plant under different integrated soil and water conservation technologies during the OND 2025 cropping season.

Progressive development of leaves was similar in the MAM 2026 cropping season. Generally, the more integrated treatments had more leaves at vegetative growth stages but the differences were not consistent across growth stages and years.

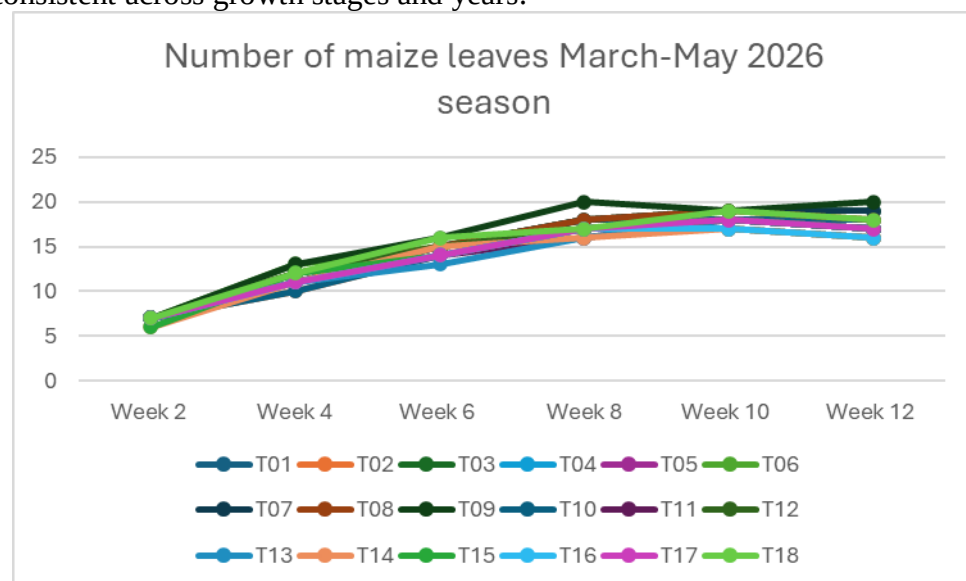


Figure 4: Changes in the number of maize leaves per plant under different integrated soil and water conservation technologies during the MAM 2026 cropping season.

Effects on Number of Cobs per Plant

Maize reproductive development was measured as number of cobs produced per plant to see the effect of the integrated soil and water conservation technologies. Significant differences were noted among the treatment combinations, with the more integrated treatments showing good reproductive performance results when compared with the less integrated.

The mean number of cobs per plant under the different treatments is presented in Table 7. The multiple treatments with more than one moisture conservation and fertility management component tended to have higher cob production, compared to the treatments with fewer complementary technologies.

Table 7: Mean number of cobs per maize plant under different integrated soil and water conservation technologies across the two cropping seasons.

Treatment Code	Treatment	Week 10	Week 12
T01	Zai pits + Mulch + FYM	2.00a	2.00a
T02	Zai pits + Mulch + DAP	2.00a	2.00a
T03	Zai pits + Mulch + FYM + DAP	2.00a	1.00a
T04	Zai pits + Hydrogel + FYM	1.00a	1.00a
T05	Zai pits + Hydrogel + DAP	2.00a	2.00a
T06	Zai pits + Hydrogel + FYM + DAP	2.00a	2.00a
T07	Zai pits + Mulch + Hydrogel + FYM	1.00a	1.00a
T08	Zai pits + Mulch + Hydrogel + DAP	2.00a	1.00a
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	2.00a	2.00a
T10	Jembe hole + Mulch + FYM	2.00a	2.00a
T11	Jembe hole + Mulch + DAP	1.00a	1.00a
T12	Jembe hole + Mulch + FYM + DAP	1.00a	1.00a
T13	Jembe hole + Hydrogel + FYM	1.00a	2.00a
T14	Jembe hole + Hydrogel + DAP	1.00a	1.00a
T15	Jembe hole + Hydrogel + FYM + DAP	1.00a	1.00a
T16	Jembe hole + Mulch + Hydrogel + FYM	1.00a	2.00a
T17	Jembe hole + Mulch + Hydrogel + DAP	2.00a	1.00a
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	1.00a	1.00a

Effects of Integrated Soil and Water Conservation Technologies on Maize Grain Yield

The combined soil and water conservation practices had significant effects on the maize grain production in both OND 2025 and MAM 2026 cropping seasons. There was significant difference in grain yields among the eighteen treatments, reflecting variance in the performance of the technologies in supporting maize productivity under the semi-arid rain-fed condition.

Maize Grain Yield OND 2025 Cropping Season

The main difference in maize grain yield between the treatments tested during OND 2025 cropping season was between the treatments of integrated soil and water conservation technology. Generally, the Zai treatments had higher grain yields than the Jembe treatments as a result of the pit-based treatments; especially when multiple complementary moisture conservation and fertility management strategies were implemented.

The highest grain yield was obtained in Treatment T09 (Zai pits, mulch, hydrogel, farmyard manure (FYM), and diammonium phosphate (DAP)) with a grain yield of 5.43 kg plot⁻¹ (which corresponds to 6.03 t ha⁻¹). Other highly integrated Zai pit treatments, which featured incorporation of both the fertility inputs and the hydrogel also had relatively high yields. However, the less productive treatments tended to be linked to the Jembe hole-based technology combinations.

Table 8: Mean maize grain yield under different integrated soil and water conservation technologies during the OND 2025 cropping season.

Treatment code	Treatment	Maize Yield (kg/plot)	Maize Yield (t/ha)
T01	Zai pits + Mulch + FYM	4.57cdef	5.08
T02	Zai pits + Mulch + DAP	4.72defg	5.24
T03	Zai pits + Mulch + FYM + DAP	4.963efgh	5.51
T04	Zai pits + Hydrogel + FYM	4.863efgh	5.40
T05	Zai pits + Hydrogel + DAP	4.92efgh	5.47
T06	Zai pits + Hydrogel + FYM + DAP	5.243gh	5.83
T07	Zai pits + Mulch + Hydrogel + FYM	4.797defg	5.33
T08	Zai pits + Mulch + Hydrogel + DAP	5.133fgh	5.70
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	5.43h	6.03
T10	Jembe hole + Mulch + FYM	3.483a	3.87
T11	Jembe hole + Mulch + DAP	3.75ab	4.17
T12	Jembe hole + Mulch + FYM + DAP	3.873ab	4.30
T13	Jembe hole + Hydrogel + FYM	3.80ab	4.22
T14	Jembe hole + Hydrogel + DAP	3.817ab	4.24
T15	Jembe hole + Hydrogel + FYM + DAP	4.08bc	4.53
T16	Jembe hole + Mulch + Hydrogel + FYM	3.807ab	4.23
T17	Jembe hole + Mulch + Hydrogel + DAP	4.243bcd	4.71
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	4.523cde	5.03

Maize Grain Yield During the MAM 2026 Cropping Season

The maize grain yield was also significantly different between the treatments during the MAM 2026 cropping season. The more integrated Zai pit-based treatments were mostly superior to the Jembe hole-based treatments, as in the OND 2025 season.

The grain yield of 5.52 kg plot⁻¹ (6.13 t ha⁻¹) was obtained from treatment T09 (Table 8). Other high-performing treatments included T03 (5.09 t ha⁻¹), T06 (5.07 t ha⁻¹), T18 (4.90 t ha⁻¹), T08 (4.86 t ha⁻¹), and T07 (4.84 t ha⁻¹). The lowest yields were recorded under T10 and T13, which produced approximately 3.33 t ha⁻¹.

Table 9: Average maize grain production from the various integrated soil and water conservation technologies under the MAM 2026 cropping season.

Treatment Code	Treatment Combination	Grain Yield (kg plot ⁻¹)	Grain Yield (t ha ⁻¹)
T01	Zai pits + Mulch + FYM	3.77c	4.19
T02	Zai pits + Mulch + DAP	3.727c	4.14
T03	Zai pits + Mulch + FYM + DAP	4.577f	5.09
T04	Zai pits + Hydrogel + FYM	3.717c	4.13
T05	Zai pits + Hydrogel + DAP	3.853cd	4.28
T06	Zai pits + Hydrogel + FYM + DAP	4.567f	5.07
T07	Zai pits + Mulch + Hydrogel + FYM	4.353def	4.84
T08	Zai pits + Mulch + Hydrogel + DAP	4.373def	4.86
T09	Zai pits + Mulch + Hydrogel + FYM + DAP	5.52g	6.13
T10	Jembe hole + Mulch + FYM	2.997a	3.33
T11	Jembe hole + Mulch + DAP	3.147ab	3.50
T12	Jembe hole + Mulch + FYM + DAP	3.937cde	4.37
T13	Jembe hole + Hydrogel + FYM	3.00a	3.33
T14	Jembe hole + Hydrogel + DAP	3.153ab	3.50
T15	Jembe hole + Hydrogel + FYM + DAP	3.943cde	4.38
T16	Jembe hole + Mulch + Hydrogel + FYM	3.613bc	4.01
T17	Jembe hole + Mulch + Hydrogel + DAP	3.52abc	3.91
T18	Jembe hole + Mulch + Hydrogel + FYM + DAP	4.41ef	4.90

Means followed by different superscript letters within the column are significantly different according to the applicable mean separation test at $P < 0.05$.

Comparison of Maize Grain Yield Across the Two Cropping Seasons

The pattern of the maize grain yield was fairly similar when comparing treatment performance between OND 2025 and MAM 2026 cropping seasons. The relatively high performing treatments tended to be high performing in both seasons, whereas the relatively low performing treatments tended to be low performing in both seasons.

In both seasons, the treatment T09 achieved the highest grain yield, from 5.43 kg plot⁻¹ (6.03 t ha⁻¹) in OND 2025 to 5.52 kg plot⁻¹ (6.13 t ha⁻¹) in MAM 2026. This treatment was consistently superior suggesting that Zai pit, mulch, hydrogel, FYM and DAP gave a sustainable production benefit under the varying seasonal conditions.

There was a strong positive correlation between treatment grain yields in the two seasons ($r = 0.826$, $P < 0.001$), which shows that there was a high consistency in the relative performance of the integrated soil and water conservation technologies. Overall, the integrated treatments based on the Zai pit system generally gave higher grain production compared to most of the Jembe hole-based treatments in both cropping seasons.

4. DISCUSSION

Integrated Technologies and Soil Moisture Availability under Semi-Arid Conditions

The results showed that the soil and water conservation structures, in combination with complementary moisture-retention and fertility management practices, increased soil moisture availability during both seasons of the crop. The combined technologies with complementary functions generally showed higher soil moisture levels under the more integrated treatments, especially those treatments involving the Zai pit-based combinations with mulch and hydrogel, demonstrating the importance of combining technologies with complementary functions. The combination of the different treatments encouraged rainwater harvesting and reduced water loss while enhancing soil water holding capacity in the root zone of the crop.

The relatively good performance of the Zai pit-based treatments is due to their ability to collect and concentrate the runoff in the planting area, thus enhancing the infiltration and minimizing the water loss due to surface runoff. This interpretation aligns with the results obtained in semi-arid Kenya where the in-situ water harvesting technologies (IWHTs) were shown to substantially enhance soil water content compared to conventional soil management systems (CSMSs) with Zai pits having higher soil water content (Chiturike et al., 2024). Likewise, research in Kenya has shown that Zai pits can be used to enhance the soil environment for maize crop production by creating a microenvironment within the planting basin, which promotes water and organic amendments to be concentrated in this area, thereby promoting improved crop establishment and development (Bowers et al., 2024).

The restoration of soil moisture found under the treatments containing organic mulch can be attributed to the contribution of soil cover in reducing direct evaporation and controlling soil surface conditions. Mulching reduces the amount of rainfall that falls on the soil surface and winds, and increases the amount of rainfall that penetrates the effective root zone. This mechanism has been proven in semi-arid Kenya where the use of residue mulch improved soil water availability and created a longer window of soil water availability above the maize water-stress threshold (Aluoch et al., 2022). In the present study, the contribution of mulch was thus likely especially significant during the periods between rainfalls when soil water conservation to maintain crop growth was particularly critical.

The complementary effects of hydrogel and organic amendments with highly integrated treatments may also be responsible for the superior moisture conditions. Hydrogels can absorb and temporarily hold the water that is then released to the plants when the surrounding soil becomes dry and FYM can increase the soil organic matter and physical properties related to water retention. These technologies can work in tandem with water-harvesting structures and surface mulch to provide more than one water-saving mechanism. This complementary effect can be a reason for the general improvement in soil moisture regime for treatments that included multiple moisture conservation components when compared to less integrated treatments.

This general pattern is consistent for the OND 2025 and MAM 2026 seasons, especially in relation to semi-arid rain fed agriculture. The more detailed analyses, while showing shifts in absolute soil moisture in response to the distribution of precipitation and crop water use, tended to show a general soil moisture surplus during the seasons. This indicates that combining the technologies of soil and water conservation together could be more resilient in dealing with the seasonal fluctuations in rainfall than single technologies alone. Previous studies in semi-arid Kenya also highlight that in-situ water harvesting along with proper soil fertility management

has the potential to enhance water availability for crop production and yield under water limiting conditions (Wafula et al., 2022).

In summary, the soil moisture results corroborate the concept of the value of complementary soil and water conservation technologies. The Zai-grated water capture and infiltration, the mulch help to minimize evaporative loss, and the hydrogel provide temporary water storage, while the organic amendments help to improve the physical conditions of the soil. This improvement in soil moisture availability helps to explain the differential responses subsequently seen in maize growth and grain yield, and offers an important biophysical basis for understanding this.

Differential Responses of Maize Growth Parameters to Integrated Technologies

Maize growth in response to the combinations of soil and water conservation technologies was not consistent among all the measured parameters. Responses to treatment and seasonality were more apparent for plant height and leaf development than they were for stem diameter. Such differences suggest that the growth responses of individual maize plants differ in terms of the moisture and nutrient availability. Therefore, changes in soil conditions may not lead to the same relative change in all vegetative properties.

The seasonality of the plant growth response to the integrated treatments is evident in the height response, particularly during MAM 2026, indicating that the integrated treatments enhanced water and nutrient availability, which facilitated vegetative growth during favorable seasons. Proper soil moisture is critical for cell expansion, nutrient availability, translocation and photosynthetic activity, and is important for plant growth (Bowers et al., 2024). This is consistent with the improved soil moisture conditions observed under the more integrated treatments and generally superior performance of the more integrated treatments. Maize growth has been observed to be better under Zai pits in semi-arid Kenya especially when implemented with organic or inorganic nutrient inputs (Arfania & Ghasemi, 2026).

The lack of consistent treatment differences in some growth parameters, however, such as stem diameter, indicates that some morphological characteristics might not be as responsive to short-term soil moisture and nutrient differences. Then, genotype, plant density, developmental stage, and how the assimilates are allocated within the plant all play a role in stem development, in addition to the amount of resources available. Therefore, treatment variation does not always equal to statistical variation in stem thickness. This finding shows the necessity to consider several measures of crop growth in assessing the effectiveness of a treatment, not just one vegetatively based measure.

The leaf development had a relatively strong response at certain growth stages of the crop, especially when growing under relatively dry OND 2025. Leaf production and maintenance is closely linked to the plant's ability to take up enough water and nutrients, and better soil moisture availability can decrease the limitations in leaf expansion and development caused by stress (Tuure et al., 2025). This is because the more integrated treatments had higher leaf numbers throughout the vegetative stage of the crop, supporting the idea that the combination of the technologies resulted in more favourable leaf development.

The differences in treatment response through the seasons also suggest that the performance of the integrated technologies is dependent on the climate. Differences in leaf development among treatments were more evident during the OND 2025 season when moisture limitations were relatively greater. However, other growth differences were more pronounced as regards plant height during the MAM 2026 season. This variability indicates that the advantages of integrated

technologies could be more pronounced when there is moisture stress on the crops, while relatively good rainfall conditions may minimize the differences among the treatments (Bowers et al., 2024). This interpretation aligns with previous studies that demonstrate positive impacts of soil and water management practices are highly dependent on seasonal rainfall and soil properties (Wafula et al., 2022).

The results also show that the improvement of vegetative growth cannot be considered in isolation from the reproductive performance and grain production. A treatment may only have small differences in a specific vegetative trait but may be associated with large productivity gains due to small improvements in water availability, nutrient uptake, reproductive development and grain filling over time. Thus, the differential behavior of the growth parameters of maize in this study further confirms the need for evaluating integrated technologies with several parameters. The subsequent grain yield results give a more complete representation of the total agronomic gains that can be obtained through the simultaneous use of soil and water conservation structures, moisture conservation techniques, and fertilizer application.

Integrated Technologies and Maize Grain Yield

The grain yield results clearly showed the positive cumulative effects of combining soil and water conservation technologies and moisture-retention and fertility management practices. Treatment effects on individual vegetative growth parameters were inconsistent but grain yield differences were always apparent during both of the two cropping seasons. An increase in yield due to better soil moisture and nutrient status accumulated over the crop life appeared to be more pronounced during reproductive development and grain filling, as in the highly integrated treatments.

Treatment T09 (Zai pits + mulch + hydrogel + FYM + DAP) yielded the maximum grain in the both seasons of OND 2025 and MAM 2026. The result shows that a synergy between complementary technologies capable of tackling several production constraints at once can be a great benefit. Mulch reduces evaporative water losses, hydrogel helps in temporary storage and availability of water, FYM and DAP help in improving nutrient availability and Zai helps in rain water harvesting and infiltration. These functions are likely to have increased the moisture and nutrient availability in critical stages of maize growth, leading to better reproductive growth and grain filling.

The results are similar to those of Wafula et al. (2022) who found that the adoption of in-situ water harvesting technologies combined with fertilizer inputs had a significant effect on soil moisture and maize productivity in Kenya, a semi-arid country. They found that using water harvesting in combination with organic and inorganic nutrient sources is imperative to overcome the multiple stresses of water scarcity and soil fertility. In addition, Bowers et al. (2024) found that manure application was a key determinant of the productivity of Zai pits in semi-arid southern Kenya, indicating that the productivity of water-harvesting structures can be increased if they are accompanied by appropriate soil fertility management.

The technology advantage noted with T09 also reinforces technological compatibility. Single technologies can handle a particular constraint, but when used together, they can yield better agronomic results by offering several aspects of the crop production environment at the same time. In some cases, for instance, the greater availability of water may not translate to significant yield improvements if the nutrient availability is not adequate; or, under very strong moisture stress, fertilizers may produce low returns. It is possible to therefore increase the efficiency of

water use and nutrient use by the crops, by incorporating the water conservation in the fertility management. Dryland Kenya also provides evidence that Water Use Efficiency and crop productivity can be enhanced by the combination of various water management practices and nutrient inputs (moisture conservation and nutrient input) than by less water integrated practices (Kiboi et al., 2019).

The relatively poorer production results obtained under some Jembe hole based treatments further illustrate that the performance of an integrated package is not only dependent on the number of technologies comprising the package but also on the ability of the underlying conservation structure to capture and retain water. Zai pit treatments generally performed better and this may have been because the structure of the basin created a more favourable condition for accumulating runoff and keeping water in the root zone of the crop. The interpretation is in line with previous research that in-situ water harvesting technologies can positively impact soil moisture levels and yields in water-limited conditions (Wafula et al., 2022).

Importantly, the significant yield response seen with some differences in vegetative growth parameters suggests that grain yield is a more holistic indicator of treatment efficacy. Grain production reflects cumulative effects of resources over the crop cycle, ranging from water uptake and nutrient acquisition, photosynthetic activity, and reproductive development, to assimilate partitioning during grain filling. This means that treatments that yield only slight differences in height or stem diameter can still result in significant yield improvements when they reduce stresses during critical times of plant reproduction. Previous studies have also shown that keeping soil moisture levels and nutrient availability at an optimal level during critical periods of maize growth is especially crucial for high grain production in Kenya (Albalasmeh et al., 2022).

The overall grain yield results indicate that complementary technologies produced the highest productivity gains, rather than their individual application. In the light of the consistently better performance of T09, it is evident that the combination of Zai pits, mulch, hydrogel, FYM and DAP can create a more favourable soil-water-nutrient environment for maize production under the rain-fed conditions prevailing in the semi-arid tropics.

Seasonal Consistency and Implications for Climate-Resilient Maize Production

One of the key outcomes of this research was the uniformity of treatment effectiveness throughout the OND 2025 and MAM 2026 cropping seasons. Treatments which worked well in one season tended to work well in the other, despite the differences between seasons in the rainfall regime and soil moisture conditions. The high level of the positive correlation ($r = 0.826$, $P < 0.001$) between treatment grain yields across seasons suggests the relative performance of the integrated technologies was relatively constant, despite seasonal differences. This uniformity increases the confidence that the treatment effects seen were not the result of specific treatment conditions for one particular cropping season.

The consistent performance of T09 over both seasons is significant for rain-fed agriculture in semi-arid regions where rainfall uncertainty is a significant variable causing production uncertainty. A good performing technological package under favorable rainfall conditions may not be useful to the farmer who experiences frequent dry periods and unpredictable rains. The regular water harvesting and treatment performance in the fully integrated treatment, on the other hand, indicates that combining water harvesting, moisture retention and fertility management can help to reduce the impact of seasonal variability on maize production. This aligns with findings

in semi-arid Kenya where soil moisture conservation technologies can increase the soil water available in the maize root zone during droughts, and enhance crop resilience to irregularly occurring rainfall (Tuure et al., 2025).

The results also underscore the importance of integrated soil management as a climate-smart agriculture approach. Boosting maximum yield is not the only challenge for climate resilience in rain-fed agriculture, as it also requires stability of production under changing climate conditions. The addition of Zai pits and complementary soil amendments may help overcome this challenge by enhancing infiltration during rainfall, reducing moisture loss when dry conditions occur and promoting availability of nutrients during the growing season. In similar studies conducted in Southern Kenya, Zai pits were identified as having the potential to be a valuable climate-smart agricultural practice if linked with organic nutrient inputs (Bowers et al., 2024).

This seasonal consistency has also significance for the technology recommendations in the semi-arid farming system in this study. These findings indicate that the implementation of complementary technology packages by farmers could be more beneficial as opposed to implementing soil and water conservation practices alone. The fully integrated package, however, must also take into account practical issues such as labour needs, availability and cost of inputs, and farmers' ability to apply multiple interventions at once. While T09 produced the highest yields, its adoption may depend on whether the additional productivity benefits justify the resources required for its implementation.

Thus, future research should incorporate economic and adoption analysis to assess the viability of scaling up of integrated technology packages in smallholder farmers. These analyses might consider the costs and benefits of various treatment packages and suggest if less complicated packages would yield satisfactory productivity gains at lower implementation costs. This is especially crucial if technologies show good experimental performance but are constrained by the need for substantial labour inputs and/or high costs.

In general, the results suggest that the combined soil and water conservation technologies can play a role in enhancing resilience of maize production under semi-arid conditions. The uniform responses of the highly integrated Zai pit-based treatment over two cropping seasons highlights the importance of treating soil moisture and nutrient issues together. Integrated approaches, such as the use of rainwater, moisture retention, organic amendments and mineral fertilizers, instead of single interventions might offer more consistent means to enhance maize productivity in increasingly erratic rain-fed conditions.

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