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# Effects of conservation soil water management practices on soil moisture dynamics across growth stages and soil depths in rainfed maize

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ABSTRACT

Drought stress driven by intra-seasonal rainfall variability and rising evaporative demand constrains maize productivity in rainfed sub-humid systems of sub-Saharan Africa. This study evaluated the effects of Conservation Soil Water Management Practices (CSWMPs), including straw mulch, half-moon pits, and permanent planting basins, on seasonal, phenological, and depth-wise soil moisture dynamics and their implications for crop water use and productivity across three maize growing seasons. Volumetric soil moisture was monitored at 0-40 cm depth using FDR probes and linked to soil water storage, deficit to field capacity, available water, and soil physical properties. CSWMPs consistently maintained significantly higher soil moisture than the control ($p \leq 0.05$) including during the critical reproductive stage of tasseling and silking, with half-moon pits showing the greatest retention. Grain yield increased from 2.7-4.9 t ha$^{-1}$ in the control to 7.0-8.2 t ha$^{-1}$ under straw mulch and permanent planting basins, while water use efficiency increased from 6-11 to 14-17.6 kg ha$^{-1}$ mm$^{-1}$ ($p \leq 0.05$). Evapotranspiration remained statistically similar across treatments ($p > 0.05$), indicating that yield gains resulted from improved partitioning of water into productive transpiration rather than increased water consumption. Mixed-effects modeling identified crop growth stage and soil water storage as dominant controls of soil moisture, with significant phenological interactions. Overall, SWMPs enhanced soil moisture retention, improved soil structural functioning, and strengthened maize resilience by improving apparent water productivity and crop yield under variable climatic conditions.

## 1. Introduction

Rainfed maize production in sub-Saharan Africa is increasingly constrained by intra-seasonal rainfall variability and rising evaporative demand associated with climate change (Cairns et al., 2021; Parihar & Nayak, 2019; Waha et al., 2013; Zhang et al., 2022). In smallholder farming systems, yield instability is often driven not by total seasonal rainfall alone, but by the timing of soil moisture availability relative to crop growth stages, particularly during water-sensitive periods such as tasseling and silking in maize (Mo et al., 2017; Sa et al., 2022). Therefore, enhancing in-situ soil water retention and buffering crops against prolonged dry spells is central to climate-resilient maize production under rainfed conditions.

Conservation Soil Water Management Practices (CSWMPs) including straw mulching, permanent planting basins, tied ridges, and half-moon pits have been promoted as low-cost adaptation strategies to enhance rainfall capture, reduce soil evaporation, improve soil hydraulic functioning and Crop productivity in rainfed systems of Sub-Sahara Africa (El-Beltagi et al., 2022; Zizinga et al., 2026). These practices improve infiltration, reduce evaporative losses, and modify soil structure, thereby influencing how water is stored and redistributed within the soil profile (Wang et al., 2025; Zizinga et al., 2026). Accordingly, CSWMPs are increasingly recognized as key interventions for improving soil moisture availability under variable climatic conditions (Das et al.,

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2025; Madembo & Nyagumbo, 2026; Rizzo et al., 2025; Tarolli et al., 2025), particularly for high water use crops like maize.

The CSWMPs reduce runoff and extend infiltration opportunity time, increasing water storage within the root-active zone; for example, straw mulch limits soil evaporation by moderating temperature fluctuations and reducing capillary water loss (Hou & Li, 2019; Keesstra et al., 2019; Li et al., 2018; Zizinga et al., 2026; Wang et al 2026). Over time, these practices increase soil organic matter, reduce bulk density, and improve aggregate stability, enhancing porosity and saturated hydraulic conductivity (Su et al., 2026; Yaseen et al., 2025). These improvements promote deeper water percolation and help sustain moisture availability during critical growth stages. Importantly, they influence both the amount and timing of soil water availability, and buffering crops against intra-seasonal dry spells. Thus, CSWMPs provide a mechanistic pathway for strengthening climate resilience in smallholder rainfed systems across sub-Sahara Africa.

Despite their widespread promotion and implementation, there remains limited quantitative evidence on how CSWMPs regulate soil moisture dynamics across growth stages, soil depths, and which underlying soil biophysical mechanisms drive these responses under variable climatic conditions. Soil moisture dynamics are inherently dependent on crop development, reflecting interactions between rainfall inputs, root development, canopy expansion, and evapotranspiration demand (Mulebeke et al., 2013; Zhang et al., 2025). Evidence increasingly suggests that soil moisture dynamics result from the interaction between rainfall distribution, crop development, root water uptake, and evapotranspiration demand. Rainfall provides the primary water input, whereas crop development stage influences the temporal depletion and availability of soil water through changes in water uptake and transpiration (Magaia, 2017; Novick et al., 2024; Sa et al., 2022; Mei, et al., 2025). Consequently, crop growth stage gives a basis for interpreting in-season soil moisture dynamics than static indicators such as seasonal water deficit or fixed soil water thresholds which affect crop productivity. Yet, few studies explicitly integrate phenological stages, depth-resolved soil moisture measurements, water use, crop yield and soil physical indicators to disentangle the relative roles of soil water storage, deficit to field capacity, crop productivity, and management-induced changes in soil structure.

This study addresses this knowledge gap by examining seasonal, stage-specific, and depth-wise soil moisture dynamics under contrasting CSWMPs (control, straw mulch, permanent planting basins, and half-moon pits) in a rainfed maize production system. It evaluates: (i) variation in soil moisture across maize growth stages and crop water use, (ii) the extent to which selected CSWMPs buffer soil moisture against seasonal variability, and (iii) the relative influence of soil water storage, water deficit, and soil physical properties on soil moisture dynamics. By integrating depth-resolved soil moisture measurements with crop productivity, water use efficiency, and soil physical indicators, this study provides a mechanistic assessment of how CSWMPs influence soil water availability and apparent water productivity across critical growth stages. Unlike studies based primarily on seasonal averages, this approach explicitly quantifies stage-specific soil water responses and their implications for maize productivity under variable climatic conditions.

## 2. Materials and methods

### 2.1. Experimental layout

The study evaluated soil moisture dynamics under selected CSWMPs in a rainfed maize system which was established using a Randomized Complete Block Design (RCBD) with three treatments and a control on acric ferralsols environment (USDA, 2014 and Zizinga et al., 2022). The soil texture for the topsoil (0-10 cm) and the subsoil (10-40 cm) were sand clay and clay; respectively. The control (C) was conventional tillage without any CSWMP. The three CSWMPs included straw mulch of 2 cm thick covered on soil surface (M), half-moon pits (HM), and permanent planting basins (PPB). The control and the three treatments were replicated five times each. The straw mulch treatment consisted of locally sourced dry grass straw applied uniformly at 2 cm as surface thickness (equivalent to about 4-5 t $ha^{-1}$) applied immediately after planting at the start of each season across the three growing seasons. Half-moon pits were established once at the beginning of the experiment and consisted of six semi-circular pits per plot, each 30 cm deep, 50 cm wide, and approximately 100 cm in circumference, spaced 30 cm apart to enhance rainfall capture and infiltration. Permanent planting basins were also established at the start of the experiment and comprised circular basins of 15 cm in diameter and 30 cm deep. Both HM and PPB treatments were maintained through periodic removal of weeds and accumulated sediment to preserve their original dimensions, without re-excavation during the three seasons of experiment. Treatments were randomly assigned within each block to account for spatial variability across the field. The plots used in this experiment measured 5 × 5 m, with 1 m buffer zones between plots and 2 m between blocks.

### 2.2. Crop management and yield determination

Maize (Longe 9H variety) seeds were planted at a depth of 5 cm with spacing of 75 cm × 30 cm, and thinned after two weeks of planting to one plant per hill, resulting in a density of 44,444 plants per hectare across all treatments (C, M, HM, PPB). All plots received a blanket basal application of di-ammonium phosphate (DAP) at 60 kg P $ha^{-1}$ and muriate of potash (MOP) at 60 kg K $ha^{-1}$ at planting. Urea was applied as top dressing at a rate of 90 kg N $ha^{-1}$ eight weeks after planting.

During the first season, land preparation was performed across all the treatment plots. In Seasons 2 and 3, plots under CSWMPs (M, HM, PPB) were maintained without tillage, and land preparation consisted only of slashing to preserve the established conservation structures. In contrast, control plots were prepared using conventional hand hoe tillage before planting each season. Weed control was conducted manually through periodic hand weeding throughout the growing season. No major pest or disease outbreaks occurred during the study period that required chemical control.

At maturity stage (140 days after planting), grain yield was measured from a net harvested area of 2 m × 2 m located at the center of each plot to minimize border effects. Grain samples were weighed in the field to determine fresh weight, transported to the laboratory, and oven dried at 60°C for 48 h to constant weight. Grain yield was adjusted to 12% moisture content and expressed as t $ha^{-1}$.

### 2.3. Calibration of the access tube and moisture measurements

The access tubes were installed permanently in plots at 10, 20, 30 and 40 cm depths prior to the experimental measurements. Each access tube was vertically installed into representative soil profiles following manufacturer guidelines (Delta-T Devices Ltd, 2013), to ensure good contact between the tube and surrounding soil, no air gaps around the tube. Soil moisture calibration was performed after three months once the soil had settled after installation of the access tubes. During calibration soil moisture reading from the access tubes were compared with those obtained using gravimetric methods from the surrounding soils at the different soil depths. A strong correlation was observed between the two ($R^2$= 0.82) and the Root Mean Square Error was 0.025 $m^3$ $m^{-3}$; confirming that the site soil dielectric properties matches the default manufacturer values.

#### 2.3.1. Rainfall of the study area

The study was conducted at Bulindi mid-western Uganda (sub-humid climate with ~1200 mm annual rainfall) (Fig. 1). Daily rainfall data indicated marked intra and inter-seasonal variability across the three cropping seasons. Season 1 (April-August 2019) was characterized by episodic rainfall with high intensity storm events (> 30-40 mm $day^{-1}$)

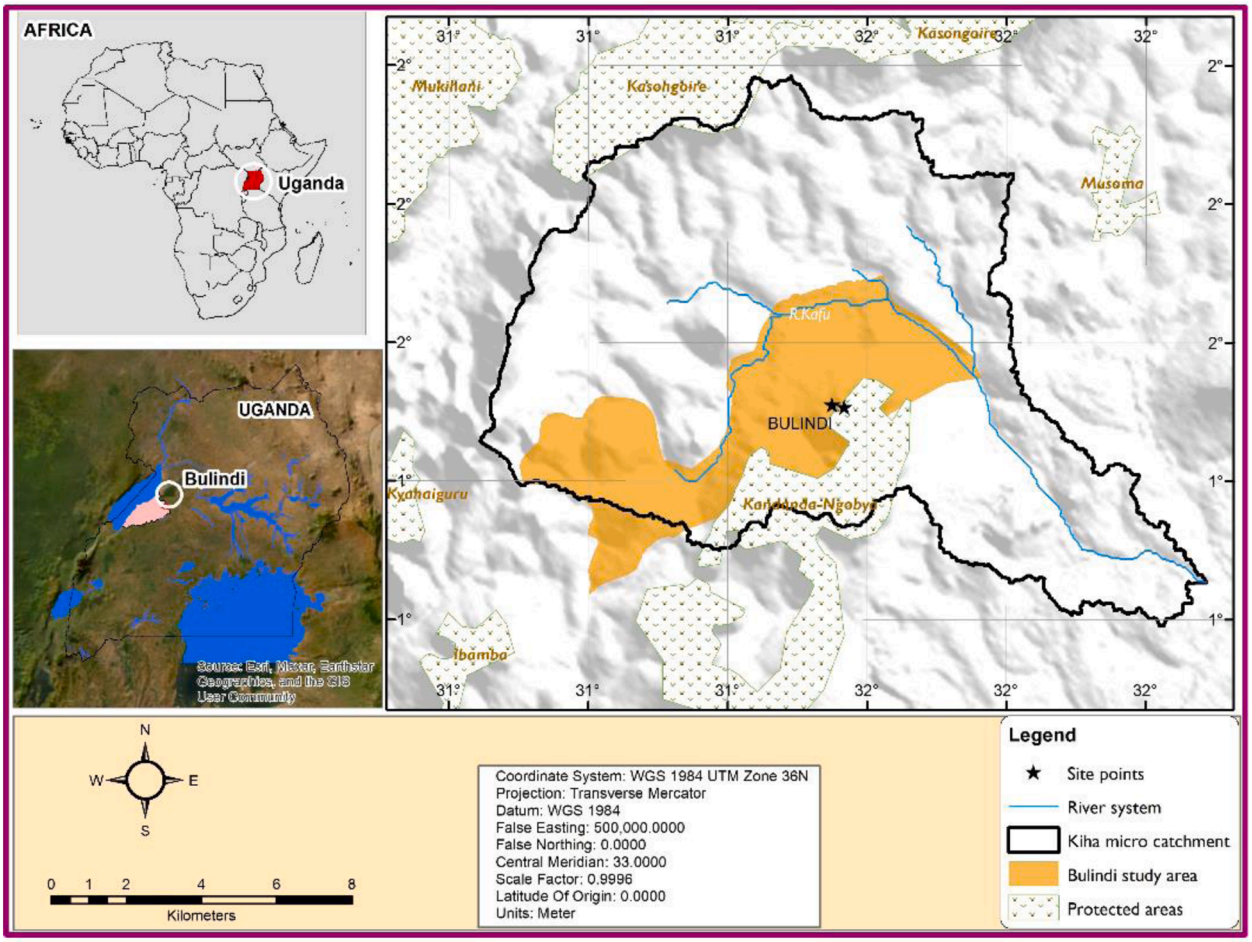



**Fig. 1.** Map of the study area at Bulindi zonal agriculture research and development institute, mid-western Uganda.

interspersed with short dry spells, indicating event-driven recharge and potential runoff losses (Fig. 2 season1). Season 2 (October 2019-February 2020) exhibited a shorter, more concentrated rainy period, with peaks in mid-November and early December (>30 mm day$^{-1}$), followed by an extended dry phase during January, mid-to-late season moisture limitation (Fig. 2 season 2). In contrast, Season 3 (March-August 2020) showed intense early-season rainfall (>30 mm day$^{-1}$), followed by intermittent events, providing substantial early recharge with increasing variability later in the season (Fig. 2 season 3). Overall, Season 1 and Season 3 showed greater rainfall intensity and distribution than Season 2, which was more temporally restricted, reflecting bimodal tropical rainfall patterns with implications for soil moisture availability, and crop water uptake stability (Fig. 2).

#### 2.3.2. Soils of the study site

Soils were characterized based on selected physical and hydraulic properties, including saturated hydraulic conductivity, bulk density, and soil water retention parameters (field capacity and permanent wilting point), which describe the soil's capacity to store and transmit water (Table 1).

### 2.4. Soil physical properties

Soil physical properties were characterized across treatments using field and laboratory measurements at depths of 0-10, 10-20, 20-30, and 30-40 cm. Composite soil samples were collected using a soil auger, while undisturbed core samples were used to determine bulk density (BD). Saturated hydraulic conductivity (Ksat) was measured using the constant-head permeameter method (Eijkelkamp Soil & Water, 2017) and soil texture was determined using the Bouyoucos hydrometer method (Okalebo, 2002).

Key soil hydraulic parameters, including field capacity (θFC), permanent wilting point (θPWP), and soil water content at saturation (θsat) were derived using the Rosetta pedotransfer functions (Schaap et al., 2001). All soil physical measurements were conducted at the onset of the experiment for each treatment to provide baseline conditions and all parameters were constant across replicates within the same soil unit and depth, allowing consistent comparison across all treatments.

### 2.5. Soil water measurements

Volumetric soil moisture measurements were conducted at each crop growth stage (planting, vegetative, silking, tasseling and maturity) using calibrated Frequency Domain Reflectometry (FDR) moisture probe-type PR2/4 (Delta-T Devices Ltd., 2005) across the three consecutive growing seasons to capture temporal variation in soil water availability. Measured volumetric soil moisture ($\theta$) was converted to soil water depth (mm) to enable comparison of water storage and deficit across treatments (CSWMPs). It was calculated as follows;

$$W = \theta \times Z$$

where:

$W$ is soil water storage (mm),

$\theta$ is volumetric soil water content (m$^3$ m$^{-3}$), and

$Z$ is soil layer thickness or soil depths (mm).

The upper limit (field capacity FC) and lower limit (permanent wilting point PWP) of plant-available water were defined as:

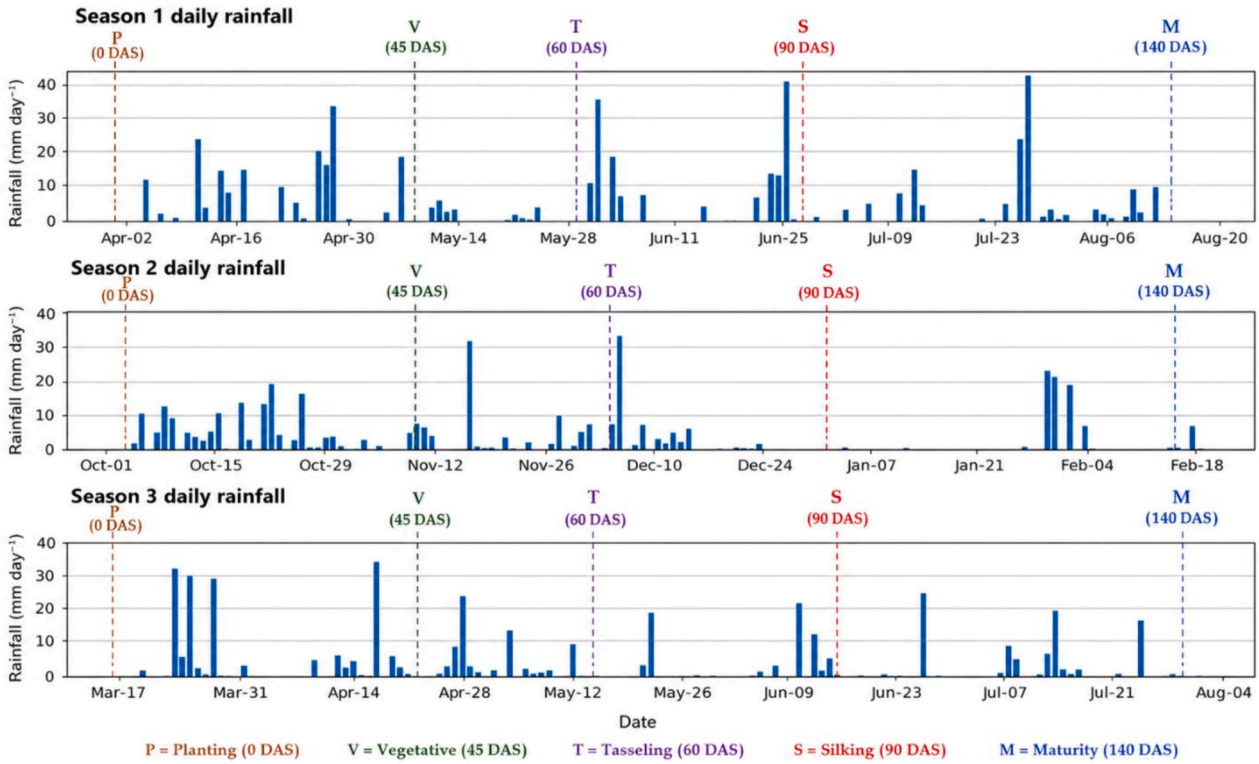



**Fig. 2.** Daily rainfall distribution during the three maize growing seasons (Season 1, Season 2, and Season 3). Vertical dashed lines indicate the timing of soil moisture measurements corresponding to key maize phenological stages: Planting (P, 0 DAS), Vegetative growth (V, 45 DAS), Tasseling (T, 60 DAS), Silking (S, 90 DAS), and Physiological Maturity (M, 140 DAS).

**Table 1**
Soil properties of the study site.

| Depth (cm) | Saturation ($cm^3\ cm^{-3}$) | Hydraulic conductivity ($cm\ d^{-1}$) | Field capacity ($cm^3\ cm^{-3}$) | Bulk density ($g\ cm^{-3}$) | Permanent Wilting Point ($cm^3\ cm^{-3}$) |
|---|---|---|---|---|---|
| 0-10 | 0.45 | 10.6 | 0.33 | 1.38 | 0.21 |
| 10-20 | 0.48 | 16.8 | 0.34 | 1.38 | 0.21 |
| 20-30 | 0.48 | 9.3 | 0.36 | 1.36 | 0.24 |
| 30-40 | 0.48 | 5.4 | 0.39 | 1.34 | 0.26 |

$W_{FC} = \theta_{FC} \times Z$

$W = \theta_{PWP} \times Z$

Total available water (TAW), i.e. the maximum volume of water that can be extracted by crops from the soil layer without inducing physiological stress was computed as:

$TAW = (\theta_{FC} - \theta_{PWP}) \times Z$

Plant available water (AW) at the time of measurement was calculated as:

$AW = \max [0, (\theta_{now} - \theta_{PWP}) \times Z]$

Soil moisture deficit (Dr), expressed as root-zone depletion relative to field capacity, was computed as:

$Dr = \max [0, (\theta_{Fc} - \theta now) \times Z]$

Higher Dr values indicate greater soil water stress.

Additional indices, including air-filled porosity (AFP) and relative saturation (RS) were calculated as:

$AFP = \theta_{sat} - \theta_{now}$, $RS = \frac{\theta now}{\theta sat}$, to characterize soil aeration and saturation status under different CSWMPs.

### 2.6. Determination of ET, WUE and soil water storage

Seasonal evapotranspiration (ET mm) for each conservation soil water management practice (CSWMP) was estimated using a simplified soil water balance approach following established methods (Bu et al., 2013; Lin et al., 2016). ET was calculated as:

$ET = P + \Delta SWS$

where P is total precipitation (mm) during the growing season and ΔSWS is the change in soil water storage (mm) between planting and harvesting. This approach assumes negligible runoff, deep percolation, and capillary rise, which is appropriate for well-managed rainfed experimental plots and besides it was established in a gently sloping area with a slope of <5%.

Soil water storage (SWS, mm) within the effective rooting zone was determined as:

$SWS = \overline{\theta} \times L$

where $\overline{\theta}$ is the mean volumetric soil water content across the measured soil profile and L is the effective rooting depth (cm). Soil moisture was measured at defined depths within the root zone, and depth-weighted averages were used to compute $\overline{\theta}$, allowing estimation of total water stored and available to the crop.

Water use efficiency (WUE) was calculated as:

$$WUE = \frac{Grain\ yield (kg\ ha^{-1} mm^{-1})}{ET}$$

This metric quantifies the efficiency with which crops convert water into economic yield, integrating both water availability and plant physio-

logical response.

### 2.7. Data aggregation and analysis

For each CSWMP and growth stage, mean values of volumetric soil moisture, plant available water, total available water, and deficit to field capacity were determined. Treatment effects were evaluated statistically using two-way ANOVA and linear mixed-effects model, in which CSWMPs and crop growth stage were specified as fixed effects and, replicate as random effect. All data analysis was conducted in R version 4.4.3 (R Core Team, 2020).

## 3. Results

### 3.1. Seasonal and phenological variation in soil moisture

Soil moisture differed significantly ($p \leq 0.05$) among conservation soil water management practices (CSWMPs), crop growth stages, and seasons (Table 2). Across all treatments, soil moisture generally increased from planting to the vegetative stage, reached maximum levels during tasseling and silking, and subsequently declined towards maturity. The highest soil moisture values were consistently observed under the conservation treatments (HM, PPB, and M), whereas the control treatment maintained the lowest moisture levels across seasons and growth stages.

At individual growth stages, half-moon pits (HM) generally recorded the highest soil moisture (Table 2), followed by permanent planting basins (PPB) and straw mulch (M), all of which were significantly greater than the control according to Tukey's HSD test ($p \leq 0.05$). The differences were particularly evident during tasseling and silking, which represent periods of high crop water demand (Table 2). These findings indicate that CSWMPs enhanced soil water retention and buffering capacity during critical reproductive growth stages.

Seasonal variation in soil moisture reflected not only total rainfall amounts but also rainfall timing, intensity, antecedent soil water conditions, and the capacity of CSWMPs to retain water within the root zone. Although Season 2 experienced a prolonged dry period during the latter part of the growing season, substantial rainfall received during the earlier vegetative and reproductive stages likely contributed to relatively high soil moisture observed at the phenological measurement dates. The conservation treatments further enhanced retention of this stored water, thereby reducing short-term moisture depletion.

### 3.2. Soil moisture by treatment across growth stages and depths

Soil moisture varied significantly across soil depths, growth stages, and CSWMPs ($p \leq 0.05$), with clear vertical and temporal patterns (Fig. 3).

Across all the treatments, soil moisture increased with depth, with maximum values in the 30-40 cm layer and minimum values in the 0-10 cm layer. The surface layer exhibited the highest variability, reflecting evaporation and surface water losses. Soil moisture increased from planting to reproductive stages and declined slightly toward maturity in upper layers (Fig. 3).

The CSWMPs (HM, M, PPB) consistently maintained higher median soil moisture than control (C), particularly in the 20-30 cm and 30-40 cm layers. Two-way ANOVA confirmed significant effects of treatment, depth, and growth stage ($p < 0.05$), with significant treatment x depth interactions indicating depth-dependent effectiveness of management (Fig. 3). Seasonal variability (S1-S3) influenced dispersion but did not alter overall treatment ranking, indicating consistent treatment effects across seasons.

### 3.3. Soil moisture dynamics in seasons and soil depths

Across seasons and depth, soil moisture showed a consistent temporal pattern from planting to the vegetative stage, declining at tasseling, peaking at silking, and decreasing towards maturity (Fig. 4). This pattern was strongly supported by a highly significant effect of growth stage (Wald $\chi^2 = 21.26$, df = 4, $p < 0.001$). In Season 1, surface layers (0-20 cm) responds rapidly to rainfall with CSWMPs maintaining 0.02-0.04 $cm^3\ cm^{-3}$ higher moisture than the control. At 30-40 cm depth, soil moisture was generally lower but more stable than in surface layers, reflecting depth-dependent water redistribution, reduced evaporative influence, and interactions between soil hydraulic properties and root water uptake. In Season 2, overall moisture increased across depths, with peaks at silking exceeding 0.45-0.55 $cm^3\ cm^{-3}$ at 0-20 cm (Fig. 4). Differences among CSWMPs remained statistically significant ($\chi^2 = 25.77$, df = 3, $p < 0.001$), while deeper layers showed delayed but sustained moisture peaks (Fig. 4).

In Season 3, variability increased, but the treatment ranking remained consistent. The CSWMPs buffered moisture fluctuations, particularly at 30-40 cm, supporting late-season crop water demand. The Stage × Practice interaction was not significant ($\chi^2 = 15.16$, df = 12, $p = 0.23$), indicating similar temporal trajectories across treatments (Fig. 4).

### 3.5. Effects of crop growth stage and soil water variables on soil moisture

Soil moisture (θnow) was strongly influenced by growth stage and soil water storage, both showing highly significant effects ($p < 0.001$; Table 3). Soil water storage was the dominant predictor of θnow, as indicated by the large $\chi^2$ value.

Soil water deficit (Dr) showed not significant main effect, indicating limited explanatory power alone. However, Stage × DeficitFC interaction was highly significant ($p < 0.001$), indicating phenology-dependent deficit effects. Similarly, Stage × Water stored interaction was significant ($p < 0.001$), reflecting stage-dependent sensitivity. Available soil

**Table 2**
Mean seasonal and phenological variation in soil moisture under different CSWMPs.

| Season | CSWMPs | Planting | Vegetative | Tasseling | Silking | Maturity |
|---|---|---|---|---|---|---|
| **Season 1** | C | 0.29 c | 0.31 c | 0.33 b | 0.35 b | 0.32 b |
| | M | 0.32 b | 0.36 b | 0.38 a | 0.41 a | 0.39 a |
| | HM | 0.34 a | 0.38 a | 0.40 a | 0.43 a | 0.41 a |
| | PPB | 0.33 ab | 0.37 ab | 0.39 a | 0.42 a | 0.40 a |
| **Season 2** | C | 0.27 c | 0.30 c | 0.32 b | 0.34 b | 0.31 b |
| | M | 0.30 b | 0.35 b | 0.37 a | 0.40 a | 0.38 a |
| | HM | 0.32 a | 0.37 a | 0.39 a | 0.42 a | 0.40 a |
| | PPB | 0.31 ab | 0.36 ab | 0.38 a | 0.41 a | 0.39 a |
| **Season 3** | C | 0.28 c | 0.30 c | 0.31 b | 0.33 b | 0.30 b |
| | M | 0.31 b | 0.34 b | 0.36 a | 0.39 a | 0.37 a |
| | HM | 0.33 a | 0.36 a | 0.38 a | 0.41 a | 0.39 a |
| | PPB | 0.32 ab | 0.35 ab | 0.37 a | 0.40 a | 0.38 a |

**Note:** Values are least-square means (LSMeans). Within each season × growth stage (column), means followed by different letters are significantly different at $p \leq 0.05$ according to Tukey's HSD test. C, control or conventional, HM, Half-moon pits, M, straw mulch, and PPB, Permanent Planting Basin.

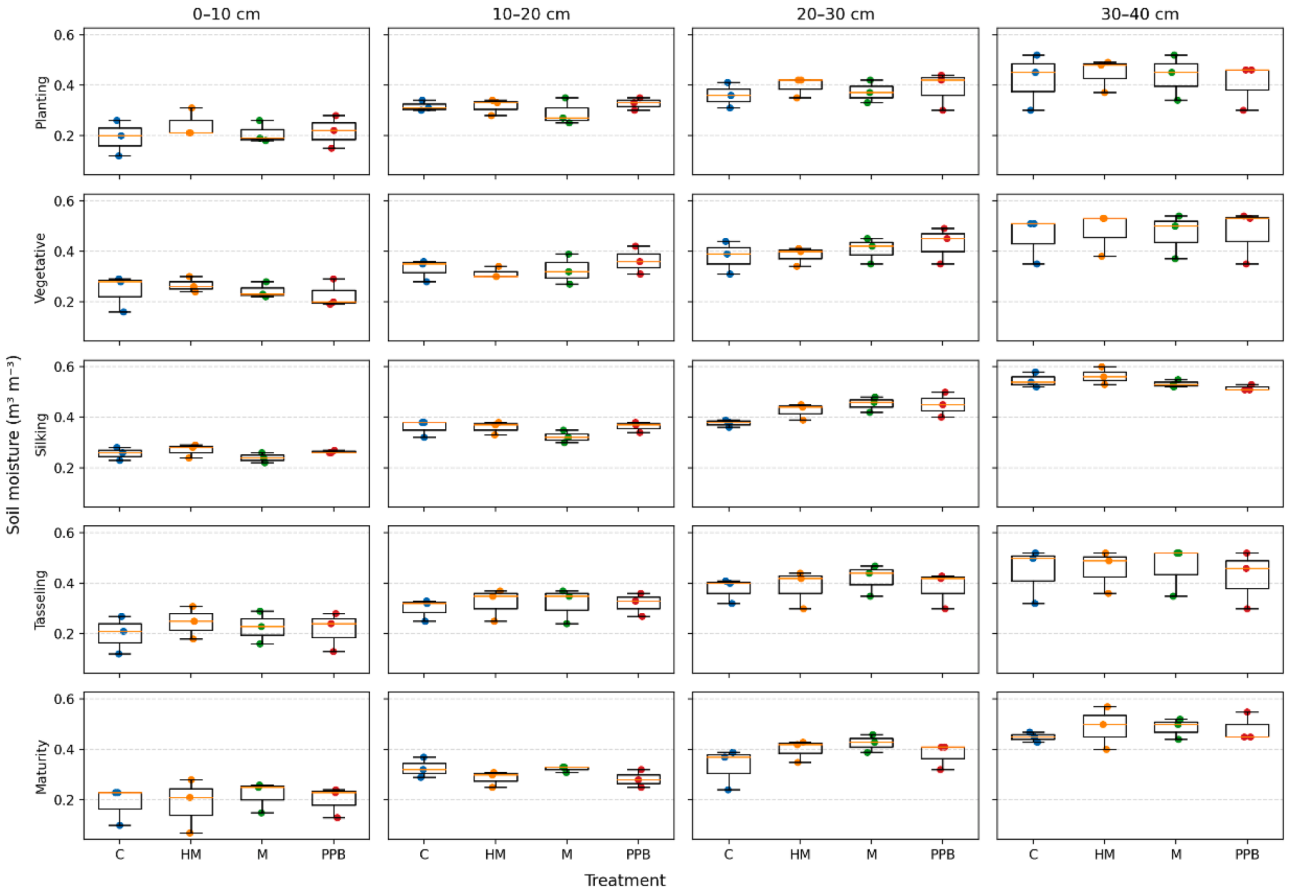



**Fig. 3.** Distribution of soil moisture ($m^3\ m^{-3}$) across four soil depths (0-10, 10-20, 20-30, and 30-40 cm) under treatments (CSWMPs) of C=control, HM=half moon pits, M=straw mulch, and PPB=permanent planting basin) during maize growth stages (planting, vegetative, silking, tasseling, and maturity). Boxplots represent seasonal variability of seasons (S1-S3), where the central line indicates the median, boxes represent the interquartile range, whiskers show the range, and points represent individual seasonal observations.

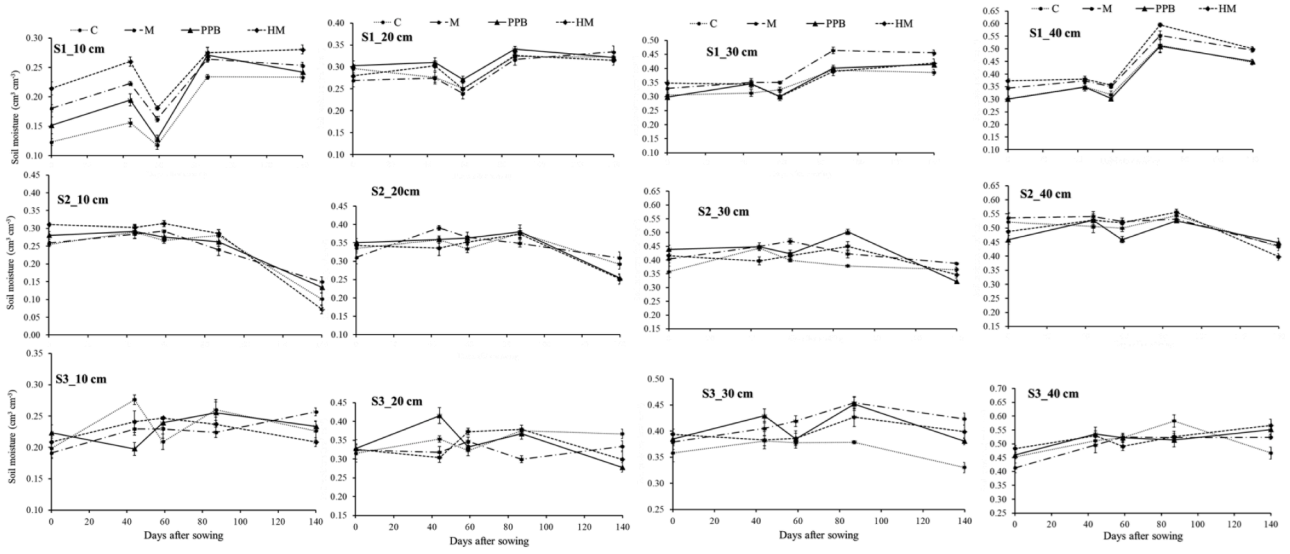



**Fig. 4.** Seasonal and depth-wise variation in soil moisture ($cm^3\ cm^{-3}$) across maize growth stages under different CSWMPs (C, control or conventional, HM, Half-moon pits, M, straw mulch, and PPB, Permanent Planting Basin). Soil moisture dynamics at 10, 20, 30, and 40 cm are illustrated with soil depths for Season 1 (S1_10-S1_40 cm), Season 2 (S2_10-S2_40 cm), and Season 3 (S3_10-S3_40 cm).

**Table 3**
Effects of crop growth stage and soil water variables on soil moisture (θnow).

| Effect | $\chi^2$ | Df | p-value | Significance |
|---|---|---|---|---|
| Stage | 50.65 | 4 | $2.64 \times 10^{-10}$ | *** |
| Water stored | $1.40 \times 10^{21}$ | 1 | $< 2.2 \times 10^{-16}$ | *** |
| Deficit to field capacity (Dr) | 1.59 | 1 | 0.207 | ns |
| Available water now | 2.91 | 1 | 0.088 | . |
| Stage × Water stored | 22.48 | 4 | 0.00016 | *** |
| Stage × DeficitFC (Dr) | 19.06 | 4 | 0.00077 | *** |
| Water stored × DeficitFC | 0.26 | 1 | 0.611 | ns |
| Stage × Available water | 10.69 | 4 | 0.030 | * |
| Water stored × Available water | 1.32 | 1 | 0.251 | ns |
| DeficitFC × Available water | 0.13 | 1 | 0.723 | ns |
| Stage × Water stored × DeficitFC | 1.43 | 4 | 0.839 | ns |
| Stage × Water stored × Available water | 4.80 | 4 | 0.309 | ns |
| Stage × DeficitFC × Available water | 2.49 | 4 | 0.647 | ns |
| Water stored × DeficitFC × Available water | 0.42 | 1 | 0.518 | ns |
| Stage × Water stored × DeficitFC × Available water | 5.71 | 4 | 0.222 | ns |

**Significance codes:** *** $p < 0.001$; * $p < 0.05$;. $p < 0.1$; ns = not significant. $\chi^2$ (chi-square) and df (degrees of freedom).

water showed a marginal main effect ($p < 0.1$), and a significant interaction with growth stage ($p < 0.05$). Higher-order interactions were not significant, indicating that soil moisture dynamics were primarily governed by first and second-order processes.

### 3.6. Effects of soil CWMPs, growth stage, and soil water variables

Soil moisture (θnow) was significantly affected by CSWMPs, growth stage, and soil water storage ($p < 0.001$; Table 4). Soil profile water retention remained the dominant physical control. CSWMPs significantly influence soil moisture with strong CSWMPs × Stage interaction ($p < 0.001$), indicating stage dependent effectiveness. Stage × Water stored interaction was also significant ($p < 0.05$), reflecting dynamic soil-plant coupling (Table 4). Deficit to field capacity (Dr) alone was not significant, but higher-order interactions with growth stage and soil practice were significant ($p < 0.001$), indicating context dependency. Overall, soil moisture dynamics were governed mainly by first- and second-order interactions.

**Table 4**
Effects of CWMPs, crop growth stage, and soil water variables on soil moisture (θnow).

| Effect | $\chi^2$ | df | p-value | Significance |
|---|---|---|---|---|
| CSWMPs | 28.32 | 3 | $3.11 \times 10^{-6}$ | *** |
| Stage | 59.68 | 4 | $3.38 \times 10^{-12}$ | *** |
| Water stored | $1.64 \times 10^{21}$ | 1 | $< 2.2 \times 10^{-16}$ | *** |
| Deficit to field capacity (Dr) | 0.66 | 1 | 0.416 | ns |
| Available water now | 2.09 | 1 | 0.148 | ns |
| CSWMPs × Stage | 129.48 | 12 | $< 2.2 \times 10^{-16}$ | *** |
| CSWMPs × Water stored | 7.42 | 3 | 0.060 | . |
| Stage × Water stored | 10.93 | 4 | 0.027 | * |
| CSWMPs × DeficitFC | 1.55 | 3 | 0.671 | ns |
| Stage × DeficitFC | 9.01 | 4 | 0.061 | . |
| CSWMPs × Available water | 11.99 | 3 | 0.007 | ** |
| Stage × Available water | 7.79 | 4 | 0.099 | . |
| CSWMPs × Stage × Water stored | 98.06 | 12 | $1.34 \times 10^{-15}$ | *** |
| CSWMPs × Stage × DeficitFC | 79.50 | 12 | $5.15 \times 10^{-12}$ | *** |
| CSWMPs × Stage × Available water | 67.40 | 12 | $9.78 \times 10^{-10}$ | *** |
| CSWMPs × Stage × Water stored × Available water | 32.03 | 12 | 0.00137 | ** |

**Significance codes:** *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$;. $p < 0.1$; ns = not significant. $\chi^2$ (chi-square) and df (degrees of freedom)

### 3.7. Effects of soil management, crop growth stage, and soil physical properties on soil moisture (θnow)

Soil moisture (θnow) was strongly regulated by growth stage ($\chi^2 = 86.23$, $p < 0.001$), confirming strong phenological control (Table 5). Soil physical condition emerged as a critical control, with both bulk density and saturated hydraulic conductivity (Ksat) significantly effecting soil moisture ($p < 0.001$). Lower bulk density and higher Ksat under CSWMPs improved soil water retention and transmission, mechanistically explaining higher θnow and reduced Dr.

The CSWMPs significantly influenced soil moisture ($p < 0.05$), with strong CSWMPs × Stage interaction ($p < 0.001$). Static water retention parameters (field capacity, saturation, permanent wilting point) were less explanatory than dynamic hydraulic properties.

### 3.8. Soil moisture-depth relationships across seasons and treatments

Soil moisture showed significant positive relationship with soil depth across seasons and treatments ($p < 0.001$; Fig. 5).

In season 1 (S1), moderate relationships were observed ($R^2 = 0.55$-$0.65$). In Season 2, relationships strengthened ($R^2$ up to 0.87) and also the, strongest relationships occurred, especially under HM ($R^2 = 0.95$) and PPB ($R^2 = 0.91$). CSWMPs improved vertical redistribution and stabilized soil water storage (Fig. 5).

### 3.9. Seasonal effects of CSWMPs on crop yield, water use efficiency, and evapotranspiration

Across the three seasons, CSWMPs significantly influenced crop growth, water use, and yield formation, with clear treatment differences shown in Fig. 6(a-c). Crop yield (t $ha^{-1}$) increased significantly ($p \leq 0.05$) under CSWMPs relative to the control in all seasons, M and PPB consistently achieving the highest yields. In Season 1, yield increased to 8.23 t $ha^{-1}$ for PPB, while in Season 3, M and PPB reached 7.13 and 7.09 t $ha^{-1}$, respectively (Fig. 6a). These yield gains correspond directly with significantly higher water use efficiency (WUE) ($p \leq 0.05$), where M and PPB recorded peak values of 17.65 and 17.50 kg $ha^{-1}$ $mm^{-1}$ in Season 3 compared to 11.18 kg $ha^{-1}$ $mm^{-1}$ in the C treatment (Fig. 6b). Notably, evapotranspiration (ET) remained statistically similar across treatments

**Table 5**
Type II Wald $\chi^2$ tests from a mixed-effects model. Response variable: volumetric soil moisture (θnow, $m^3$ $m^{-3}$).

| Source of variation | $\chi^2$ | df | p-value | Significance |
|---|---|---|---|---|
| CSWMPs | 8.84 | 3 | 0.0316 | * |
| Crop growth stage | 86.23 | 4 | $< 2.2 \times 10^{-16}$ | *** |
| Bulk density | 12.53 | 1 | $3.99 \times 10^{-4}$ | *** |
| Saturated hydraulic conductivity (Ksat) | 10.89 | 1 | $9.66 \times 10^{-4}$ | *** |
| Field capacity | 1.59 | 1 | 0.208 | ns |
| Saturation | – | – | – | ns |
| Permanent wilting point | – | – | – | ns |
| CSWMPs × Stage | 34.63 | 12 | $5.37 \times 10^{-4}$ | *** |
| CSWMPs × Bulk density | 4.70 | 3 | 0.195 | ns |
| Stage × Bulk density | 3.42 | 4 | 0.490 | ns |
| CSWMPs × Ksat | 4.10 | 3 | 0.250 | ns |
| Stage × Ksat | 2.93 | 4 | 0.570 | ns |
| CSWMPs × Field capacity | 4.63 | 3 | 0.201 | ns |
| Stage × Field capacity | 1.75 | 1 | 0.185 | ns |

Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; $p < 0.1$; ns = not significant. Note: Higher-order interactions involving saturation and permanent wilting point were not estimable ($\chi^2 = 0$), indicating limited additional explanatory power beyond bulk density and Ksat.

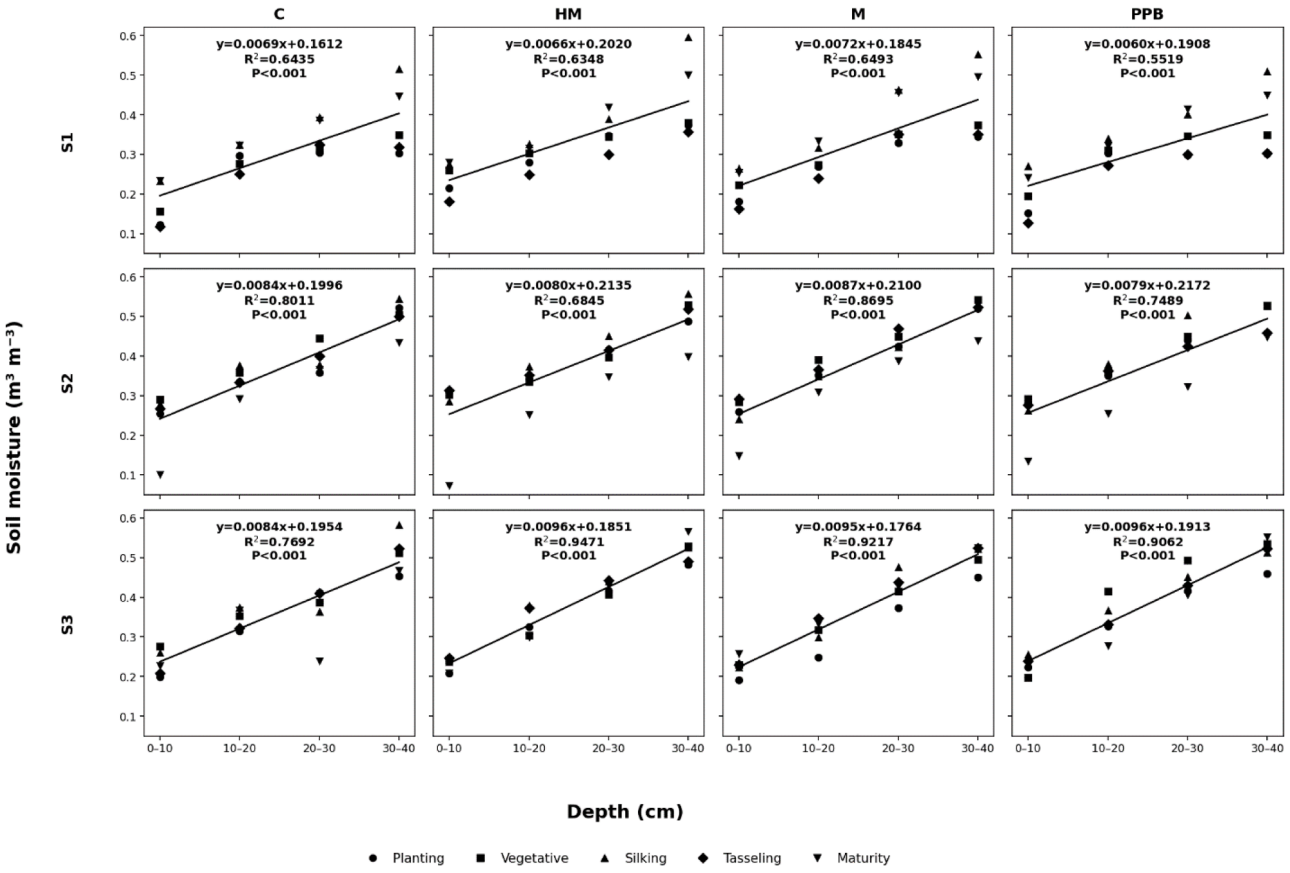



**Fig. 5.** Relationship between soil moisture content ($m^3\ m^{-3}$) and soil depth (0-40 cm) under different CSWMPs across three cropping seasons (S1-S3). Panels represent treatments: Control (C), Half moon pits (HM), Straw mulch (M), and Permanent planting basin (PPB), while rows correspond to the different seasons. Data points indicate soil moisture measured at different maize growth stages (Planting, Vegetative, Silking, Tasseling, and Maturity). Solid lines represent linear regression relationships between soil depth and soil moisture for each CSWMP and season.

in Seasons 2 and 3 ($p > 0.05$), while only slight differences were observed in Season 1 (Fig. 6c), indicating that yield improvements were not driven by increased water consumption but by improved water use efficiency. Mechanistically, straw mulch reduced soil evaporation and conserved surface moisture, while half-moon pits (HM) and PPB enhanced infiltration and root-zone water storage, ensuring sustained water availability during critical growth stages.

## 4. Discussion

### 4.1. Seasonal and phenological control of soil moisture dynamics

The observed soil moisture dynamics were consistent with the combined influence of rainfall occurrence, soil water infiltration, crop phenology, root water uptake, and atmospheric evaporative demand. The persistence of these temporal patterns across three consecutive growing seasons indicates robust seasonal regulation of root-zone soil moisture and agrees with previous studies demonstrating that soil moisture variability is primarily controlled by interactions among climatic conditions, soil hydraulic processes, and crop water use (Baroni et al., 2013; Jägermeyr & Frieler, 2018; Yang et al., 2020). These findings further underscore the importance of the synchronization between rainfall distribution and crop phenological development in determining soil water availability in rainfed maize systems, consistent with observations by Vivek et al. (2016).

Conservation Soil Water Management Practices (CSWMPs) maintained their effectiveness under contrasting rainfall conditions, suggesting their potential to enhance the resilience of rainfed production systems through improved soil water retention and sustained root-zone water availability (Vadez et al., 2024). While absolute soil moisture levels varied among seasons, with Season 1 recording higher values than Seasons 2 and 3 as a consequence of greater rainfall, the relative ranking of the CSWMPs remained stable. This consistency demonstrates that the benefits of the management practices were robust across varying climatic conditions, underscoring their potential to buffer seasonal fluctuations in soil water availability. Such characteristics are particularly valuable in smallholder rainfed systems, where inter-annual rainfall variability is a major limitation to crop productivity and yield stability (Ho et al., 2017).

### 4.2. Effectiveness of soil water conservation practices

Across all seasons and growth stages, CSWMPs namely; half-moon pits (HM), straw mulching (M), and permanent planting basins (PPB), consistently maintained higher soil moisture than the control treatment. The significant main effect of CSWMPs and the highly significant CSWMPs × Stage interaction indicate that the benefits of these practices are stage-specific rather than uniform. The enhanced soil moisture conservation under CSWMPs can be attributed to improved rainfall capture, reduced runoff, and greater infiltration opportunity time. Half-moon pits primarily promote water harvesting and this is consistent with previous studies (Gedle et al., 2025; Li et al., 2026; Su et al., 2026), whereas straw mulch reduces soil evaporation and moderates soil temperature (Lin et al., 2016; Wang et al., 2011; Wanga et al., 2026; Zhang et al., 2014; Zizinga et al., 2026) and permanent planting basins enhance localized storage within the root zone (Ullah et al., 2019; Zizinga et al., 2022). These mechanisms collectively improve soil water availability during periods of high crop water demand and are consistent with

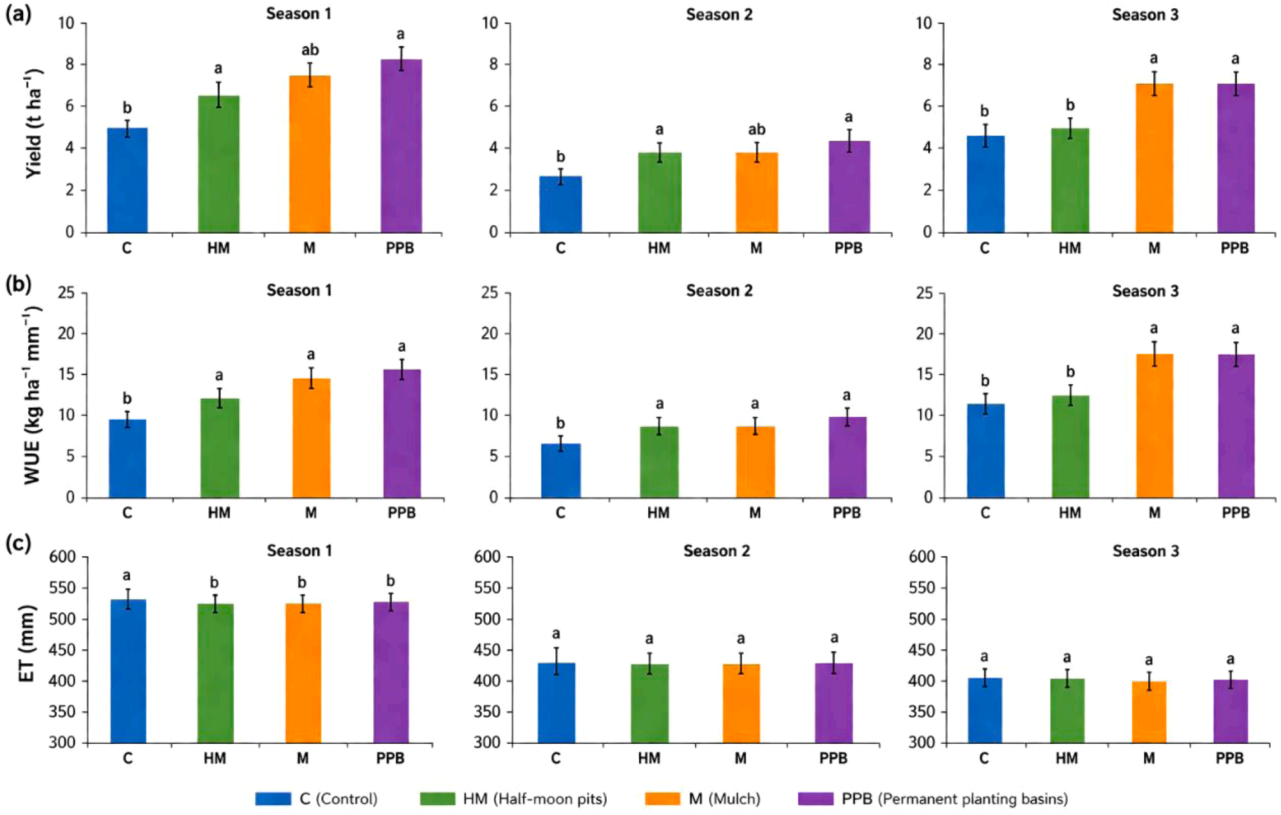



**Fig. 6.** Effects of CSWMPs on (a) crop yield (t ha$^{-1}$), (b) water use efficiency (WUE; kg ha$^{-1}$ mm$^{-1}$), and (c) evapotranspiration (ETmm) across three seasons. Treatments include control (C), half-moon pits (HM), straw mulch (M), and permanent planting basins (PPB). Bars represent means ± standard error (SE). Different lowercase letters within each season indicate significant differences among treatments according to Tukey's HSD test ($p \leq 0.05$).

findings reported in similar rainfed systems.

Although some soil moisture values approached or slightly exceeded the estimated field capacity, these measurements represent discrete observations collected at specific phenological stages and may have coincided with recent rainfall events. Field capacity is not a fixed threshold but rather a dynamic soil hydraulic condition that varies with soil texture, structure, antecedent moisture status, and spatial heterogeneity (Phogat et al., 2024; Yu et al., 2023). Consequently, the observed values likely reflect transient near-saturation conditions rather than prolonged soil saturation. Furthermore, sustained waterlogging typically impairs root respiration, nutrient uptake, and crop productivity through reduced soil aeration (Bodner et al., 2021). The absence of yield reductions under the conservation treatments therefore suggests that any temporary exceedance of field capacity was unlikely to have caused severe or persistent aeration stress during the study period. Nevertheless, the discrete measurement schedule did not allow continuous assessment of drainage dynamics, and future studies incorporating continuous soil moisture monitoring are recommended to better characterize short-term fluctuations around field capacity. Additionally, the persistence of these effects across seasons underscores that structural and surface-based soil water conservation measures can mitigate rainfall variability, rather than merely responding to favorable seasons.

### 4.3. *Depth-wise soil moisture redistribution and rooting zone buffering*

Depth-resolved analyses further explain the mechanisms underlying improved soil moisture under CSWMPs as in previous studies (Fan et al., 2026; Gelebo et al., 2026; Xu et al., 2026) where soil moisture redistribution affected the crop rooting zone. Soil moisture declined with depth across all seasons, reflecting reduced rainfall penetration and increasing dependence on cumulative infiltration. However, CSWMPs consistently maintained higher and more stable moisture within the root-active zone (10 cm-30 cm), particularly during vegetative and silking stages. Depth-wise moisture patterns reflect the combined effects of infiltration, redistribution, evaporation, and root water uptake. The greater persistence of moisture within deeper layers under CSWMPs suggests improved buffering of the rooting zone against short-term dry spells. Such buffering is particularly important during reproductive growth stages when maize is highly sensitive to water stress (Ahmad et al., 2026; Andima et al., 2026; Lorraine et al., 2025; Madembo et al., 2025).

The non-significant Stage × CSWMP interaction in the depth-wise model indicates that while absolute moisture levels differ among CSWMPs, the overall temporal shape of moisture dynamics with depth remains consistent, suggesting that conservation soil water management practices amplify rather than fundamentally alter soil water flow processes.

### 4.4. *Role of soil water storage and deficit in regulating θnow*

Across all models, the results indicate that root-zone water storage plays a more important role in determining soil moisture availability than static moisture thresholds alone. The dependence of soil moisture responses on crop growth stage further emphasizes the dynamic nature of soil–plant–water interactions and the need to evaluate soil water availability within a phenological context. This finding confirms that the amount of water retained within the soil profile, rather than instantaneous deficits alone, governs observed soil moisture conditions and this is in relation with past studies (Ma et al., 2026; Xing et al., 2025). In contrast, deficit to field capacity (Dr) did not show a significant main effect on θnow, indicating that soil water deficit alone is insufficient to explain in-season moisture variability. However, the significant Stage × DeficitFC interaction demonstrates that the impact of water deficit is strongly phenology-dependent. During stages of high water demand,

particularly silking, relatively small deficits translate into pronounced reductions in soil moisture, whereas similar deficits at earlier stages have weaker effects.

Similarly, the significant Stage × Water stored interaction highlights that the contribution of soil water storage to θnow varies across growth stages, reflecting dynamic changes in root uptake, canopy development, and evapotranspiration demand. These findings reinforce that soil moisture dynamics are governed primarily by first- and second-order interactions, rather than complex higher-order feedbacks.

### 4.5. Influence of soil physical properties on soil moisture

The strong and independent effects of bulk density and saturated hydraulic conductivity (Ksat) provide mechanistic insight into how soil management modifies soil moisture regimes (Christine et al., 2023; Evangelista et al., 2023). Bulk density and saturated hydraulic conductivity were significant predictors of soil moisture dynamics. However, because these properties were measured only as baseline site characteristics, the present study cannot solely attribute changes in soil moisture directly to management-induced modifications of soil physical properties. Future studies should quantify treatment-specific changes in soil structure and hydraulic functioning over time. These soil properties can also be attributed to the nature of tropical soils having dynamic physical properties such as pore connectivity, hydraulic conductivity, and evolving soil structure, which may not adequately capture in situ temporal variability across seasons (Luciana et al., 2023). This further indicates that soil structure and hydraulic functioning, rather than fixed moisture limits, govern in-season water availability. Therefore, these results emphasize that improving soil physical quality is more effective for climate resilience than focusing solely on soil water holding thresholds.

### 4.6. Implications for climate-resilient maize production

Collectively, these results also demonstrate that soil moisture dynamics in rainfed maize systems are controlled by the interaction of crop phenology, soil physical condition, and management-driven water storage, rather than by water deficit alone. Conservation soil water management practices (CSWMPs) enhance soil moisture most effectively during critical growth stages, particularly tasseling and silking, when maize is most sensitive to water stress (Vennam et al., 2023). By improving infiltration, reducing evaporative losses, and stabilizing moisture in the root zone, CSWMPs buffer crops against both intra-seasonal dry spells and inter-seasonal rainfall variability. This mechanistic understanding provides strong evidence that soil water conservation interventions represent a viable and scalable adaptation strategy for smallholder maize systems under increasing climate variability.

### 4.7. Soil water use and crop productivity dynamics

The CSWMPs do not solely improve soil moisture, but it also enhances the efficiency of soil water use in crops and adds agronomic value. Several studies (Zhang et al., 2017; Zhang et al., 2021a; Zhang et al., 2022; Zhang et al., 2021b), have demonstrated that improved soil moisture retention does not automatically translate into higher productivity unless it is effectively converted into transpiration and biomass accumulation. CSWMPs such as straw mulch likely reduced non-productive water losses, leading to higher water use efficiency (WUE) and grain yield in rainfed maize. Similarly, Bhattacharya, (2021) and Passioura, (2004), demonstrated that treatments maintaining moderate soil moisture depletion often produced higher yields because they reflected active crop water uptake rather than water limitation, hence lower soil moisture under certain treatments can be associated with better crop performance.

The significantly higher WUE observed under CSWMPs (M, PPB and HM) in this study corroborates findings by Hatfield & Dold, (2019), who emphasized that yield improvement under water-limited conditions is primarily driven by increasing the proportion of water used in transpiration relative to evaporation. In agreement, (Makurira et al., 2011; Rockström & Barron, 2007; Rockström & Karlberg, 2009; Temesgen et al., 2012), highlighted that soil water conservation practices may have increased the proportion of water available for productive crop use, particularly in rainfed systems of Sub-Saharan Africa. This mechanism explains why, despite relatively similar evapotranspiration (ET) across treatments in the present study, significant differences in yield and WUE were observed.

Although half-moon pits consistently maintained the highest soil moisture across growth stages, this did not translate into the highest grain yield or apparent water productivity. This suggests that soil moisture availability alone was not the sole determinant of crop performance. Excessive moisture retention may reduce soil aeration and root oxygen availability, particularly following intense rainfall events, while favorable crop growth depends on a balance between water availability, aeration, nutrient accessibility, and root activity and this related to past studies of (Blum, 2009; Passioura, 2004). Therefore, the relationship between soil moisture and crop productivity is not necessarily linear, and higher soil moisture does not always result in greater yield.

Furthermore, the superior performance of straw mulch (M) and permanent planting basins (PPB) is consistent with studies showing that these practices improve soil hydraulic properties, infiltration, and root-zone moisture retention, thereby sustaining crop water uptake during critical growth stages. Also, studies of Ullah et al. (2022) and Xiao et al. (2023), reported that, mulching reduces soil temperature fluctuations and evaporation losses, while basin-based systems enhance water capture and storage, resulting in improved crop growth and yield stability. The moderate response under half-moon pits (HM) further agrees with findings that infiltration-focused practices alone may not maximize productivity unless combined with evaporation control measures.

The higher yields and apparent water productivity observed under straw mulch and permanent planting basins compared with half-moon pits may be attributed to a more favorable root-zone environment. Straw mulch likely moderated soil temperature fluctuations and reduced evaporative losses, while permanent planting basins improved water capture and retention without prolonged saturation. In contrast, the greater soil moisture retained by half-moon pits may not have been entirely available for productive crop use because periods of elevated moisture can limit aeration, alter nutrient dynamics, and constrain root function. These findings indicate that optimal maize productivity depends on effective regulation of the soil–water–air balance rather than maximizing soil moisture alone.

All these studies corroborate the conclusion that CSWMPs enhance crop growth and production by improving soil water availability, uptake, and conversion efficiency into biomass and yield, rather than by simply increasing soil moisture levels. This reinforces the need to interpret soil moisture within the broader soil–plant–water continuum, where crop water use and productivity outcomes provide a more meaningful assessment of treatment effectiveness.

## 5. Conclusions

This study demonstrated that soil moisture dynamics were governed by the interaction between rainfall distribution, conservation soil water management practices (CSWMPs), crop development, and soil hydraulic processes. Across three seasons, soil moisture followed consistent

temporal patterns increasing from planting to the vegetative stage, peaked during tasseling and silking, and declined towards maturity. This seasonal behaviour reflects the combined influence of rainfall recharge, soil hydraulic processes, and crop water extraction, highlighting the importance of synchronizing soil water availability with crop water demand during critical developmental stages.

Conservation soil water management practices consistently enhanced soil moisture across growth stages and seasons, demonstrating their capacity to buffer root-zone water availability under variable rainfall conditions. Although half-moon pits maintained the highest soil moisture, particularly during the reproductive stages, straw mulch and permanent planting basins produced the greatest grain yield and water use efficiency without significantly increasing seasonal evapotranspiration. These findings indicate that improved crop performance under CSWMPs was associated primarily by more efficient utilization of available soil water rather than by greater crop water consumption.

Regression analyses further showed that soil water storage and soil physical properties, particularly bulk density and saturated hydraulic conductivity, exerted stronger control over soil moisture dynamics than water deficit alone. This demonstrates that soil moisture is governed by dynamic interactions among crop phenology, soil hydraulic functioning, and management practices rather than by static soil water thresholds.

The findings provide new evidence that effective conservation soil water management should prioritize improving the capture, storage, and productive use of rainfall within the root zone instead of maximizing soil water storage alone. By enhancing root-zone water availability and increasing water productivity under variable rainfall conditions, these practices offer practical climate adaptation strategies for improving the resilience and sustainability of rainfed maize production in sub-humid tropical environments.

A limitation of this study is that soil moisture measurements were collected at discrete phenological stages within the upper 0 – 40 cm soil profile, while deep percolation was not directly quantified. Future studies integrating continuous soil moisture monitoring and whole profile water balance measurements, would provide a more comprehensive understanding of the mechanisms through which conservation soil water management practices enhance crop productivity and climate resilience.

## CRediT authorship contribution statement

**Alex Zizinga:** Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization. **Jackson-Gilbert Majaliwa Mwanjalolo:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Himanshu Pathak:** Writing – review & editing, Supervision, Methodology. **Juliet Katusiime:** Writing – review & editing, Project administration. **Bobe Bedadi:** Writing – review & editing, Methodology, Data curation. **Britta Tietjen:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

T1he authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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