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# Seasonal rainfall patterns affect rainfed maize production more than management of soil moisture and different plant densities on sandy soils of semi-arid regions

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ABSTRACT

In semi-arid regions, erratic rainfall and water losses through percolation are causing low yields of rainfed maize (*Zea mays L.*) grown on sandy soils. This study evaluated the effects of soil moisture management and different plant densities across four cropping seasons on rainfed maize performance. The study was conducted on a smallholder farm with sandy soils in a semi-arid district of Mutare, Zimbabwe. In a split-plot experimental design, low-density polyethylene membranes installed below the root growth zone known as sub-surface water retention technology (SWRT) and the control were main treatments and three different plant densities were sub-treatments. Maize performance including plant height, leaf chlorophyll, biomass and grain yields and rainwater use efficiency (RWUE) were monitored. Results showed that, while SWRT significantly increased maize grain yield by 21 % and total biomass yield by 13 % across seasons, this effect was smaller than that caused by the seasonal rainfall variation. In wet years, maize grain yield ranged from 3.0 to 5.8 t ha$^{-1}$, while in dry years, it ranged from 0.7 to 1.2 t ha$^{-1}$. RWUE of the maize increased significantly with plant density and was higher in dry (305 mm) compared to wet (780 mm) seasons. This study provides evidence of the need to optimize available water resources to increase maize grain yields under semi-arid conditions through integrated soil moisture management and optimised maize planting densities. It also highlights the need to invest in water harvesting and irrigation infrastructure to improve control over water resources and facilitate higher yields and yield stability.

## 1. Introduction

In semi-arid regions of Zimbabwe, maize grain yield gaps on low fertile sandy soils are exacerbated by disruptive changes in temporal rainfall distribution, prolonged mid-season droughts and extremely high temperatures (Jiri and Mafongoya, 2018; Mavhura et al., 2022). Another challenge is that low nutrients and water retention characterise the predominantly sandy soils. As a result, under rainfed crop production systems, applied nutrients not taken up by the growing crops are vulnerable to loss through processes such as leaching (Osman, 2018). Previous studies have shown that under the semi-arid climatic conditions in Zimbabwe, there is a 30–40 % risk of crop failure due to prolonged mid-season moisture stress (Thierfelder et al., 2015). The impacts of poor inherent soil fertility and erratic rains are partly evident in poor smallholder maize yields of less than 0.8 t ha$^{-1}$ (Madamombe et al., 2024; Nyagumbo et al., 2019). Therefore, closing the maize grain yield gaps will require technological and management options that mitigate the risks associated with poorly distributed rainfall.

Climate-smart agriculture (CSA), an integrated approach to land management and crop production, aims to increase farmer productivity

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and incomes and improve adaptation and resilience to climate change while reducing greenhouse gas emissions (Hussain et al., 2022). If adopted, CSA practices can reduce the negative impacts of climate change-related weather events on crop production (Mujeyi, 2021). The CSA approach includes a broad range of practices, such as rainwater harvesting (RWH), sustainable soil management, improved crop varieties, agroforestry, crop diversification, integrated pest management, crop-livestock integration, improved irrigation systems, and other soil and water conservation methods (Dubey et al., 2020; Palsaniya et al., 2023). Several CSA approaches have been explored in the past with varying levels of success. However, the persistent maize grain yield gaps imply a need for innovations that effectively tackle the root cause of low crop productivity.

Subsurface water retention technology (SWRT) is a new practice designed to mitigate the effects of short- and long-term droughts on field crops and horticultural crops grown on sandy soils (Guber et al., 2015; Lahbouki et al., 2022a). The technology involves the installation of polyethylene membranes below the root growth zone to minimise water losses, improve the retention of plant nutrients and support improved crop production (Guber et al., 2015; Abedalrahman et al., 2020). Previous experimental studies conducted in other regions have shown that SWRT significantly improves vegetable and cereal production (Churchman and Landa, 2014; Almasraf and Salim, 2018; Smucker et al., 2018; Aoda et al., 2021). A modelling study on the potential of SWRT indicated that the most promising diffusion scenarios would increase maize production in South and East Africa by 15–50 million tons per season after 20 years of widespread adoption (Nkurunziza et al., 2019). However, experimental research with SWRT conducted on smallholder farms under rainfed and semi-arid conditions is limited, and to our knowledge, none has been conducted in Zimbabwe. Under a semi-arid climate in Kenya, an experimental study comparing maize productivity with and without SWRT observed a 50, 100, 150 and 170 % increase in maize grain yield, cob numbers, cob weight and maize stover biomass, respectively (Nkurunziza et al., 2022). However, the study conducted in Kenya did not consider seasonal variability.

Low plant density of maize is recommended in drought-prone environments where the available water resources are too low to support high plant densities (Sinapidou et al., 2020). The introduction of SWRT and associated soil water conservation could enable the manipulation of plant density to optimise yield in drier environments. In the drylands of Zimbabwe, maize plant densities of between 33,000 and 44,000 plants $ha^{-1}$ are advised (Nyamuzenda, 2000). However, Thierfelder et al. (2015) suggested that plant density and maize grain yields could be increased with improved soil moisture associated with long-term conservation agriculture. Plant densities of 55,000–80,000 plants $ha^{-1}$ have been achieved under irrigation (Machethe et al., 2004; Moswetsi et al., 2017) and high rainfall (Nyakudya and Stroosnijder, 2014). Maize productivity depends on plant population density (Tokatlidis, 2013), water availability, soil fertility and row spacing (Jia et al., 2017; Haarhoff and Swanepoel, 2018). Therefore, an increase in plant density might presumably be required to optimise the benefits of water-saving technology (SWRT). Ascertaining this assumption requires a robust on-farm evaluation of the benefits of SWRT under semi-arid climatic conditions with multiple seasons and different plant densities.

This study examined the effect of SWRT on rainfed maize performance and rainwater use efficiency at different plant densities on sandy soil under semi-arid farming conditions. Specific objectives were to (i) evaluate the effects of seasonal variation in rainfall on plant growth parameters, (ii) determine maize grain and total above-ground biomass yield, and (iii) quantify rainwater use efficiency (RWUE) of maize under different plant densities with and without SWRT.

## 2. Material and methods

### 2.1. Study site

A four years on-farm experiment was established in the 2019/20 summer cropping season (Nov 2019) in a smallholder farmer's field at Mt. Zonwe (19°1′30″S, 32°3′28″E; 835 m above sea level), Mutare district, Manicaland province, Zimbabwe (Fig. 1). The field is located in Agro-ecological region IV, with a long-term average rainfall of 380 mm and a mean maximum air temperature of 28 °C (Manatsa et al., 2020). The rainfall pattern in the region is unimodal, with the growing season running from October to March, and mid-season dry spells and periods of heavy rainfall are common during the crop-growing period. Agro-ecological region IV is suitable for drought-tolerant crops such as cowpeas (*Vigna unguiculata L.*), sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet (*Eleusine coracana* L.) and maize varieties requiring 105–120 days to maturity, extensive cattle ranching, rearing small livestock such as goats, and wildlife (Manatsa et al., 2020).

### 2.2. Field and soil characteristics

The experimental field is on a slope of 3 % (Kubiku et al., 2022). Contour ridges are positioned across the slope at 15 m intervals to control runoff and erosion. Contour ridges are mandatory structures (Hagmann and Murwira, 1996) and are common on smallholder fields throughout Zimbabwe (Nyakudya and Stroosnijder, 2015; Wuta et al., 2018).

The soil in the study field was sandy, with 95 % sand, 3 % silt and 2 % clay (Chiturike et al., 2023). Soil samples were collected from different layers (0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm) prior to setting up the experiment. Five sub-samples were taken from each layer in each experimental block (n = 3) and pooled into a composite sample. The composite soil samples were air-dried, sieved (<0.002 m) and analysed at the Chemistry and Soil Research Institute (Department of Research and Specialist Services in Zimbabwe) for pH (0.01 M $CaCl_2$), exchangeable bases, soil organic carbon (SOC), mineral nitrogen (N) and available phosphorus (P). Briefly, the soil pH was determined using the 0.01 M $CaCl_2$ method (Anderson and Ingram, 1993), and pH readings were made using a standard pH meter (Hanna, H18424). Exchangeable bases were extracted using 1 M ammonium acetate (Anderson and Ingram, 1993). Soil organic carbon (SOC) was measured using a modified Walkley-Black method (Okalebo et al., 2002). Mineral N was measured as ammonium-nitrogen ($NH_4^+$-N) and nitrate-nitrogen ($NO_3^-$-N) using 0.5 M $H_2SO_4$ for extraction method, followed by colorimetric methods (Okalebo et al., 2002). Available P was extracted using 0.5 M $NaHCO_3$ and measured using inductively coupled plasma optical omission spectrometry (Agilent 5100 ICP-OES) (Okalebo et al., 2002). Soils in the fields used for this study had low organic carbon contents (0.55–0.72 %) and moderately acidic pH (5.7) within the plough layer (Table 1). Mineral N, available P and SOC content and soil pH decreased with depth (Table 1).

### 2.3. Seasonal rainfall variation across cropping seasons

During the experimental seasons, rainfall was measured using a mini-weather station ATMOS-41 (Metagroup, USA), which was installed on the experimental farm. The total seasonal rainfall varied over the four seasons (Fig. 2). Season 1 received 313 mm of rainfall, primarily within six rainfall events of at least 20 mm $day^{-1}$. During the first season there were three short dry spell periods, lasting 11–15 days, during the periods December-January, January-February and March-April, and a prolonged dry spell lasting 31 days during the period February-March. In season 2, the total rainfall received was 780 mm, with 17 rainfall events of more than 20 mm $day^{-1}$. Season 2 also had a few short dry periods, lasting 10 days at most, and about 228 mm of rain was received from

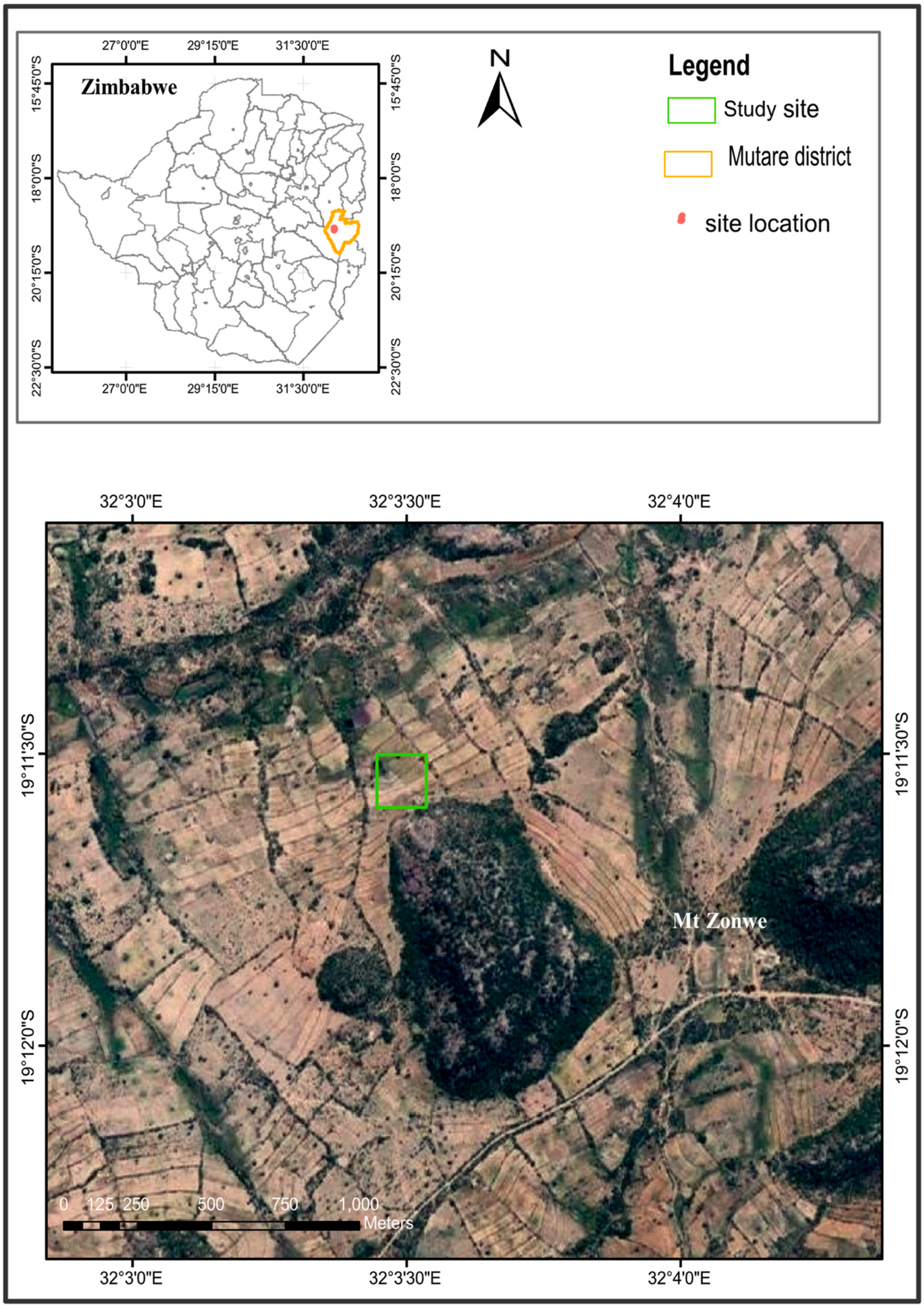


**Fig. 1.** Location of the study site at Mount Zonwe, Mutare district, Zimbabwe. Edited from Kubiku et al. (2022).

**Table 1**
Characteristics of the soil profile at the experimental site. Mean ± standard error for composite samples from blocks (n = 3) analysed for soil pH ($CaCl_2$), mineral nitrogen ($NH_4^+$-N + $NO_3^-$-N), available phosphorus (P, resin extract) , organic carbon and exchangeable cations.

| | | | | | Exchangeable cations me (100 g)$^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|
| Soil depth (cm) | Soil pH ($CaCl_2$) | Mineral N mg kg$^{-1}$ | Available P mg kg$^{-1}$ | SOC % | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ |
| 0–10 | 5.7 ± 0.2 | 76.5 ± 4.5 | 10.2 ± 1.5 | 0.72 ± 0.04 | 0.22 ± 0.09 | 2.34 ± 0.02 | 0.83 ± 0.03 | 0.58 ± 0.02 |
| 10–20 | 5.7 ± 0.03 | 30.0 ± 5.5 | 5.2 ± 0.4 | 0.55 ± 0.07 | 0.26 ± 0.01 | 2.35 ± 0.09 | 0.89 ± 0.15 | 0.62 ± 0.02 |
| 20–40 | 5.1 ± 0.2 | 29.3 ± 3.8 | 2.7 ± 1.2 | 0.63 ± 0.16 | 0.24 ± 0.02 | 2.15 ± 0.12 | 0.82 ± 0.05 | 0.61 ± 0.03 |
| 40–60 | 5.0 ± 0.3 | 36.7 ± 6.2 | 2.2 ± 0.9 | 0.41 ± 0.4 | 0.24 ± 0.03 | 1.98 ± 0.14 | 0.78 ± 0.34 | 0.59 ± 0.03 |
| 60–80 | 5.2 ± 0.6 | 44.0 ± 3.6 | 5.9 ± 3.8 | 0.41 ± 0.09 | 0.23 ± 0.02 | 2.08 ± 0.18 | 0.75 ± 0.04 | 0.59 ± 0.05 |

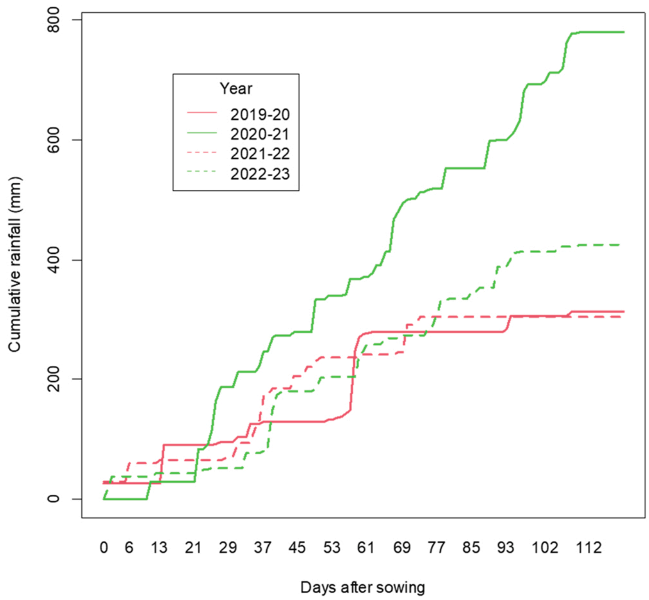


**Fig. 2.** Cumulative seasonal rainfall distribution during the experiment period from planting at Marange, Zimbabwe. Planting dates were 15 December, 12 November, 21 November and 27 November in the 2019–20, 2020–21, 2021–22 and 2022–23 seasons, respectively.

day 89 up to day 110 after sowing. Season 3 received a total cumulative rainfall of 305 mm with seven rainfall events of over 20 mm day$^{-1}$ and had a prolonged dry spell of 56 days from the end of January to the end of March. The maize crop suffered induced senescence during this dry period, which affected crop growth, mainly grain filling and cob setting. During season 4, about 424 mm of cumulative and evenly distributed rainfall was received from planting to harvesting. The dry spells during season 4 did not exceed 10 days (Fig. 2).

### 2.4. Experimental design, treatments and crop management

A split-plot design was used, with SWRT and control (no-SWRT) as main plots in three blocks and different maize planting densities in the sub-plots. The first year the main plots measured 40 m × 15 m and the sub-plots (40 m × 5 m) (Fig. 4). However, from the second year onwards the length of the main and subplots were reduced to 20 m. In the first year, SWRT membranes were manually installed within the soil profile at 40 and 60 cm depths (Fig. 3) and ran along the full plot length (40 m). The experiment ran for four years, including 2019–20 (season 1), 2020–21 (season 2), 2021–22 (season 3) and 2022/23 (season 4).

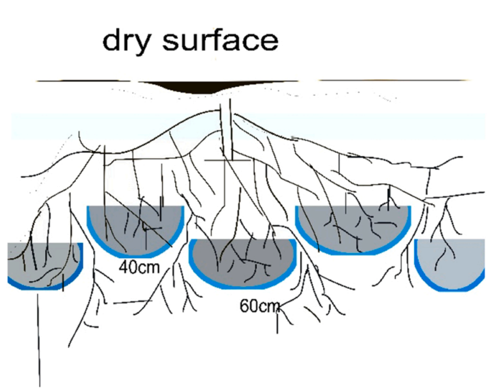


**Fig. 3.** Sub-surface water retention technology (SWRT) system, consisting of U-shaped polyethylene membranes installed at two depths (40 cm and 60 cm) below the root growth zone to create an artificial water table, increasing water and nutrient availability and reducing leaching losses.

Three plant densities were assigned to subplots: high (111,111 plants ha$^{-1}$, spacing 60 cm × 15 cm), medium (74,000 plants ha$^{-1}$, spacing 90 cm × 15 cm) and low (37,000 plants ha$^{-1}$, spacing 90 cm × 30 cm). The low plant density (37,000 plants ha$^{-1}$) is recommended by the extension, and it is the farmer practice in the area. In the medium and high plant densities, we doubled and tripled the low density to well cover the optimum densities used in irrigated and high rainfall areas. Medium-maturity commercial maize hybrid PHB 30G19 was planted manually at the beginning of each season, in November-December. Basal fertiliser NPK (7 % N, 14 % $P_2O_5$, 7 % $K_2O$; 6 g per planting station) was applied at planting, and about 5 g of ammonium nitrate topdressing was applied at 36–44 days after planting (DAP) and at 54–67 DAP, depending on soil moisture availability (Table 2).

### 2.5. Field measurements

#### 2.5.1. Leaf chlorophyll content and plant height

Leaf chlorophyll and plant height were monitored. Leaf chlorophyll was measured using a Soil-Plant Analyser Development (SPAD-502) meter (Minolta, Japan) to monitor water and nutrient use by the crop. Six, three, two and six chlorophyll measurements were conducted during seasons 1, 2,3 and 4, respectively. Leaf chlorophyll readings were measured on the uppermost fully developed leaf of multiple maize plants within a plot. Plant height was measured at the same time as chlorophyll except in season 1 when the SPAD meter was only available after four height measurements. These measurements considered the height from the ground to the apex of the uppermost leaf.

#### 2.5.2. Maize yield assessment

To measure maize biomass and grain yield in season 1, a net area of 8 m (within the row) × 3 rows was harvested in each plot. In seasons 2, 3 and 4, three harvested plots of 2.7 m long × 3 rows wide (8 m linear length harvested per plot) were randomly located in each treatment plot. The width of the harvested rows was measured three times along the harvest plot to obtain the average width of the three rows at different plant densities. Above-ground biomass, including cobs and stover from each check plot, was sampled and weighed using a digital balance after counting the number of plants and cobs. The number of plants in the harvested plots was used to estimate the final population standing at harvest per hectare. Harvested cobs and approximately 500 g of biomass sub-sample were taken from each harvested plot for further analysis. Maize cobs and biomass sub-samples were then air-dried and re-weighed, and grain moisture content was measured after two-three weeks with a mini GAC® moisture tester (DICKEY-John, USA). The maize cobs were shelled, and grain yields were adjusted to a 12.5 % standard moisture content. Maize grain yield in kg ha$^{-1}$ was divided by final plant population to determine maize grain yield per plant. Harvest index (HI) was calculated as the ratio of maize grain yield to total above-ground biomass.

#### 2.5.3. Rainwater use efficiency

Rainwater use efficiency (RWUE) was calculated based on total rainfall received between sowing and harvesting of maize and grain

**Table 2**
Application rates of basal compound D fertiliser (7 % N, 14 % $P_2O_5$, 7 % $K_2O$) and ammonium nitrate (AN) (34.5 %) topdressing at different plant densities: Low (37,000 plants ha$^{-1}$, spacing 90 cm × 30 cm), medium (74,000 plants ha$^{-1}$, spacing 90 cm × 15 cm) and high (111,111 plants ha$^{-1}$, spacing 60 cm × 15 cm).

| | Basal fertiliser | | | Ammonium nitrate |
|---|---|---|---|---|
| Plant density | N kg ha$^{-1}$ | P kg ha$^{-1}$ | K kg ha$^{-1}$ | N kg ha$^{-1}$ |
| Low | 15.5 | 13.6 | 12.9 | 127.6 |
| Medium | 31.1 | 27.1 | 25.8 | 255.3 |
| High | 46.7 | 40.7 | 38.7 | 383.3 |


**Fig. 4.** Experimental layout of main-plots and sub-plots. A 40 m plot length was used in season 1, while 20 m was used in seasons 2,3 and 4.

yield at 12.5 % grain moisture content, recorded for each plant density with and without SWRT (Mupangwa et al., 2016):

$$RWUE(kgha^{-1}mm^{-1}) = \frac{Grain\ yield(kgha^{-1})}{Total\ rainfall(mm)} \quad \text{(i)}$$

### 2.6. Data analyses

Data from all four seasons were combined to evaluate the effects of SWRT and plant density under varying seasonal conditions. Variables analysed included maize grain yield, total biomass, individual crop yield (per plant), final plant density stand (percentage at harvest), harvest index, and RWUE. Prior to statistical modeling, Q-Q plots and residual plots were used to assess the assumptions of normality and homogeneity of variance. Where deviations from the assumptions were observed log transformation was applied. Maize grain yield data lacked homogeneity of variance thus log transformation was perfomed. The transformed and untransformed combined data were subjected to a linear mixed-effects model to determine the effect of SWRT on maize performance and RWUE at different plant densities across seasons. The fitted model comprised fixed effects of SWRT, plant density, season (year) and all interactions between SWRT, plant density and season (year). Random effects of blocks, blocks within the season and SWRT treatment within blocks were included in the model using the *lmer* function from the statistical package *lmerTest* (Kuznetsova et al., 2017) in R statistical software version 4.3.0 (R Core Team, 2023). To compute the p-values for the treatments and interactive effects of SWRT × plant density, SWRT × season, plant density × season and SWRT × plant density × season on yield parameters and RWUE, the fitted linear mixed effect model was further subjected to analysis of variance (ANOVA) of type III with Kenward-Roger degrees of freedom, found in the package *pbkrtest* (Halekoh and Højsgaard, 2014). The computation of estimated marginal means (emmeans) was used to determine the averages of yield parameters and RWUE for each treatment and their interactions in the fitted model using the *emmeans* package (Lenth, 2022). Where ANOVA of the fitted model showed significant ($p < 0.05$) treatment and interactive effects, emmeans separation was performed using Tukey's HSD test at alpha = 0.05. Data on leaf chlorophyll and plant height were analysed for each season using a linear mixed-effects model. Chlorophyll levels and plant heights were analysed against DAP for each season. The fitted model for the growth parameters included fixed effects of SWRT, plant density and their interactions, and random effects of blocks.

## 3. Results

### 3.1. Effect of seasonal variation in rainfall on maize crop growth

In general, maize height reached at least 200 cm by harvest time in all four seasons, and SPAD values of between 50 and 60 were common after applying topdressing. During season 1, the main effects of SWRT on maize height were generally insignificant, but there were some tendencies for higher values in SWRT plots compared with the control. In the early days of maize growth (15–44 DAP), average height was similar at all three plant densities (Fig. 5). Plant density significantly affected maize height at 51, 59, 67 and 79 DAP ($p < 0.05$), in the order high < medium < low plant density. SWRT and plant density interactions significantly affected maize height at 51, 59 and 79 DAP (Fig. 5). Maize height increased with SWRT at the different plant densities but decreased with increasing plant density. The SPAD values generally decreased from the first sampling date towards physiological maturity at different plant densities in both SWRT and control plots (Fig. 5). SWRT had no significant effect on SPAD values, although there were some tendencies for SPAD values to increase with the use of SWRT at all sampling times. Significant differences in SPAD values were observed between plant densities at 74 DAP ($p = 0.035$), with higher SPAD values (~56 SPAD units) being recorded at the highest plant density compared to the medium and low plant densities (53 and 52 SPAD units, respectively).

In season 2, there was no significant difference in maize height between SWRT and control plots. Average maize height differed significantly between plant densities at 54 and 74 DAP, with height increasing from low to high plant density (Fig. 5). There were no significant interactions between SWRT and plant density throughout the season. Initially, the leaf chlorophyll (SPAD) values were not significantly different for SWRT plots or different plant densities, but significant differences were observed later (at 74 and 105 DAP). At 74 DAP, SPAD values were higher (~55 SPAD units) at high plant density, followed by medium (53 SPAD units) and low (49 SPAD units) plant density (Fig. 5).

In season 3, at 33 DAP, SWRT, plant density and their interaction significantly affected maize height. Maize height increased with SWRT use and plant density in the following order: low < high < medium (Fig. 5). SPAD values were generally below 50 in all treatments at 33 DAP, with some further decrease by 60 DAP (Fig. 5). Due to wilting and crop failure, no SPAD values were recorded at 88 DAP.

In season 4, maize height at each sampling day after planting was similar across plant densities under SWRT and the control. Average SPAD values decreased with crop growth and increased after applying

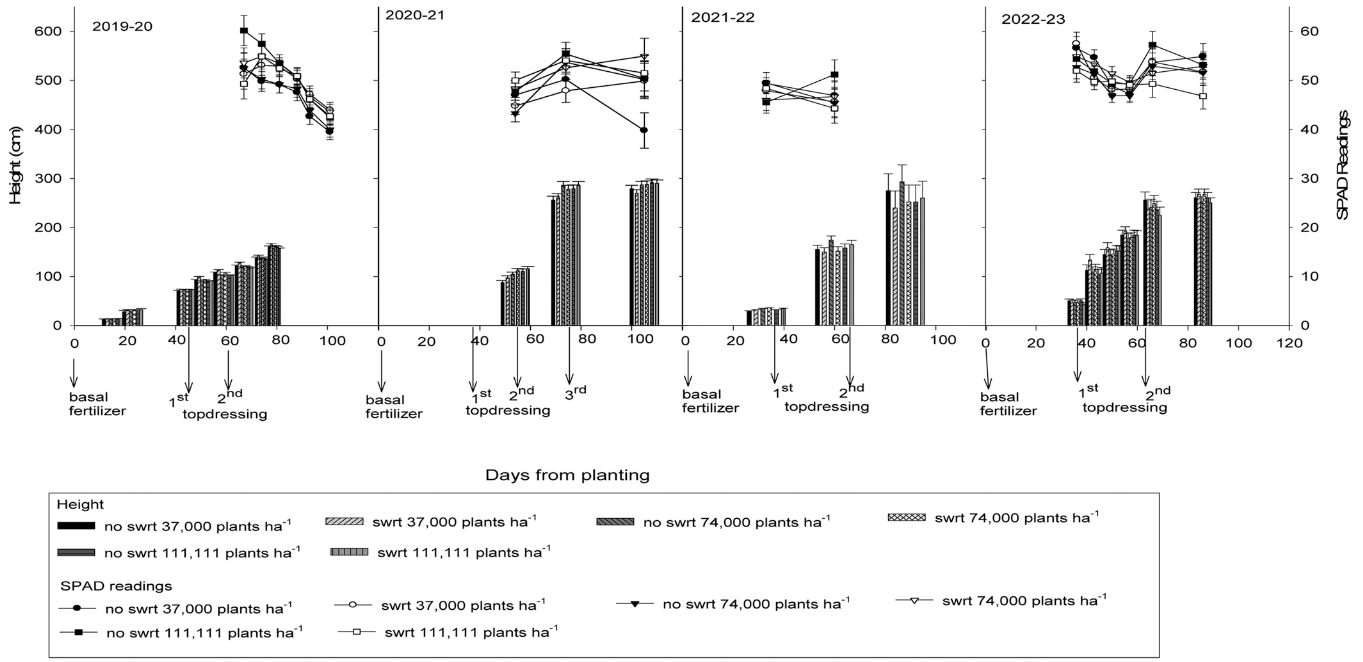


**Fig. 5.** Maize plant height and SPAD values recorded for different plant densities (low: 37,000 plants ha$^{-1}$; medium: 74,000 plants ha$^{-1}$; high: 111,111 plants ha$^{-1}$) in plots with sub-surface water retention technology (SWRT) and control plots (no SWRT). Error bars represent standard errors. In season 1 (2019–20), a SPAD meter was only available during the mid-and late season.

top-dressing fertiliser. The SPAD values decreased towards physiological maturity.

### 3.2. *Effect of SWRT and plant density on maize yield parameters*

#### 3.2.1. *Grain yield*

Grain yields were significantly higher (21 %) in plots with SWRT than in control plots (without SWRT) (Table 3). The plant density treatments also showed significant grain yield differences, with medium density giving significantly higher grain yield than low plant density (Table 3). However, grain yields in the high-density plots were not significantly different from those in the medium and low-density plots.

The cropping season had significant effects on maize grain yield. Specifically, maize grain yields in seasons 1 and 3 were significantly lower than in seasons 2 and 4 (Table 3).

SWRT × plant density × season had no significant interactive effects on maize grain yield. There were also no significant interactive effects of SWRT × season and SWRT × plant density on maize grain yield (Table 3). However, season and plant density significantly interacted with maize grain yield (Table 3, Fig. 6). Maize grain yield increased from low to medium plant density, then decreased at high plant density in cropping seasons 1, 3 and 4. Significantly higher grain yield was recorded in season 2 than in the other three seasons, with the yield increase following the order low < medium < high plant density. A yield

**Table 3**
Effects of sub-surface water retention technology (SWRT), plant density (low: 37,000 plants ha$^{-1}$; medium: 74,000 plants ha$^{-1}$; high:111,111 plants ha$^{-1}$), and season on four-year average maize grain yield, total biomass, final plant density stand at harvest and harvest index.

| Treatment | Grain yield (t ha$^{-1}$) | Total biomass yield (t ha$^{-1}$) | Grain yield kg plant$^{-1}$ | Final plant density stand at harvest (%) | Harvest Index |
|---|---|---|---|---|---|
| **SWRT (water management)** | | | | | |
| SWRT | 2.06 (7.63*)$^{b}$ | 8.01$^{b}$ | 0.049 (−3.01)$^{b}$ | 67$^{a}$ | 0.31$^{a}$ |
| Control | 1.70 (7.44)$^{a}$ | 7.10$^{a}$ | 0.041 (−3.19)$^{a}$ | 67$^{a}$ | 0.30$^{a}$ |
| **Plant density** | | | | | |
| 37,000 plants ha$^{-1}$ (90 × 30) cm | 1.72 (7.45)$^{a}$ | 6.34$^{a}$ | 0.056 (−2.88)$^{b}$ | 84$^{b}$ | 0.32$^{b}$ |
| 74,000 plants ha$^{-1}$ (90 × 15) cm | 2.04 (7.62)$^{b}$ | 7.65$^{b}$ | 0.049 (−3.01)$^{b}$ | 58$^{a}$ | 0.32$^{b}$ |
| 111,111 plants ha$^{-1}$ (60 × 15) cm | 1.86 (7.53)$^{ab}$ | 8.66$^{c}$ | 0033 (−3.41)$^{a}$ | 59$^{a}$ | 0.27$^{a}$ |
| **Season** | | | | | |
| 1 (2019–20) | 0.98 (6.89)$^{a}$ | 6.48$^{a}$ | 0.029 (−3.53)$^{a}$ | 55$^{a}$ | 0.16$^{a}$ |
| 2 (2020–21) | 4.68 (8.45)$^{b}$ | 10.53$^{b}$ | 0.102 (−2.28)$^{b}$ | 87$^{b}$ | 0.46$^{c}$ |
| 3 (2021–22) | 0.81 (6.70)$^{a}$ | 3.83$^{a}$ | 0.024 (−3.73)$^{a}$ | 53$^{a}$ | 0.22$^{a}$ |
| 4 (2022–23) | 3.29 (8.10)$^{b}$ | 9.37$^{b}$ | 0.070 (−2.66)$^{b}$ | 74$^{b}$ | 0.37$^{b}$ |
| ***p-value significance*** | | | | | |
| Season | (<0.001) | < 0.001 | (0.005) | < 0.001 | < 0.001 |
| SWRT | (0.026) | 0.026 | (0.024) | 0.945 | 0.557 |
| Plant density | (0.022) | < 0.001 | (<0.001) | < 0.001 | < 0.001 |
| **Interactions** | | | | | |
| Season × SWRT | (0.920) | 0.560 | (0.875) | 0.865 | 0.892 |
| SWRT × plant density | (0.496) | 0.992 | (0.446) | 0.980 | 0.333 |
| Season × plant density | (0.004) | 0.002 | (0.034) | < 0.001 | 0.004 |
| Season × SWRT × plant density | (0.829) | 0.957 | (0.201) | 0.019 | 0.365 |

* Numbers in brackets denote *log* transformed emmeans of grain yield ($x$) as log ($x$) and the p-values in brackets represent the significance of the transformed emmeans. Means within columns followed by different letters are significantly different at $p < 0.05$.

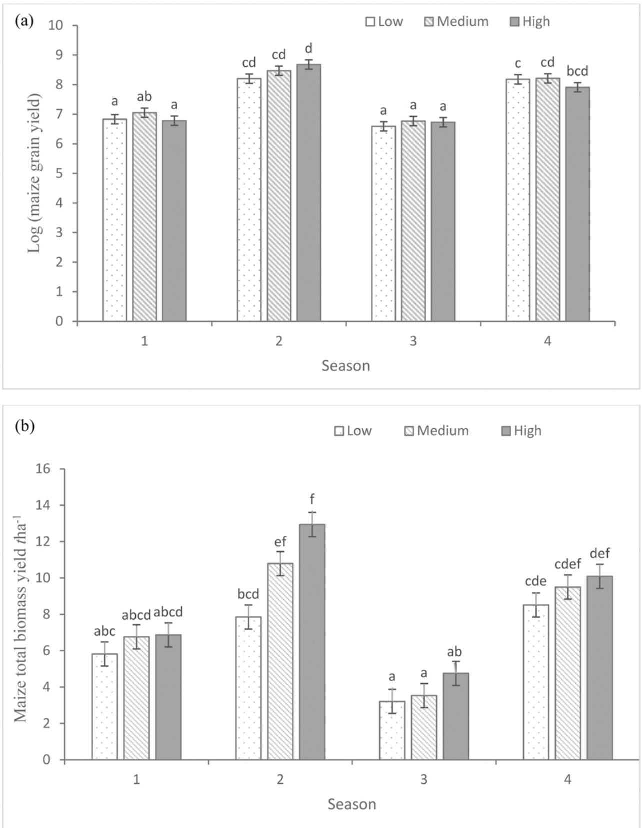


**Fig. 6.** Maize yield at different plant densities (low: 37,000 plants $ha^{-1}$; medium: 74,000 plants $ha^{-1}$; high:111,111 plants $ha^{-1}$) in the four seasons studied: 1 (2019–20), 2 (2020–21), 3 (2021–22) and 4 (2022–23). Plot (a) shows log transformed grain yield (x) as log(x).

of about 5.9 t $ha^{-1}$ was recorded in season 2 under high plant density, whereas in cropping seasons 1 and 3, low yields (about 0.8 and 0.9 t $ha^{-1}$) were recorded. In cropping seasons 1, 3 and 4, the grain yields recorded at the low plant densities were not significantly different from those at medium and high plant densities (Fig. 6).

### 3.2.2. Biomass yield

The SWRT plots had a 13 % higher biomass yield than control plots (Table 3). Total biomass yield was significantly higher in seasons 2 and 4 than in seasons 1 and 3 (Table 3). There were no significant interactive effects of SWRT × plant density × season, SWRT × season or SWRT × plant density on total above-ground biomass yield of maize (Table 3). There was a significant interactive effect of plant density × season (Table 3, Fig. 6). Generally, total biomass increased with increasing plant density within seasons and varied across seasons. Total biomass yield recorded in cropping seasons 2 and 4 for medium and high plant density was significantly higher than at the same plant densities recorded in seasons 1 and 3. Low plant density gave lower biomass yield in all four seasons, and biomass yield varied with seasons (Fig. 6).

Plots with low plant density had the highest final plant densities (~84 % of initial plant density. The high and medium plant density plots had significantly lower plant populations standing at harvest, 58–59 % of the initial plant population (Table 3). The final plant population at harvest also varied with season. The two dry seasons (1 and 3) had lower crop populations than seasons 2 and 4. On average, the harvest index (HI) over the four years was generally below 0.5 for all plant densities, although low plant density gave significantly higher HI than high plant density (Table 3). The HI value varied across seasons and plant densities; seasons 1 and 3 were 0.16–0.22, while seasons 2 and 4 were 0.37–0.47.

## 3.3. Effect of SWRT on rainwater use efficiency of maize

The RWUE of maize followed the same pattern as maize yield in all cropping seasons, i.e. it was significantly higher in seasons 2 and 4 than in seasons 1 and 3 (Table 4). The SWRT increased RWUE by about 17 % compared to the control. The RWUE of maize was significantly higher (5.48 kg $ha^{-1}$ $mm^{-1}$) at medium compared with low plant density (4.69 kg $ha^{-1}$ $mm^{-1}$) (Table 4). The season and plant density interactions significantly affected the RWUE of maize (Fig. 7).

# 4. Discussion

## 4.1. Effects of seasonal variation on maize growth and yield

The intra- and inter-seasonal variations in rainfall patterns observed over the four cropping seasons (2019/20–2022/23) were major maize productivity drivers. This importance of rainfall is further evidenced by the fact that maize productivity was generally high in a season with either above-average rainfall (season 2) or well-distributed rainfall (season 4). Moreover, during the drier seasons 1 and 2, the long dry spells coincided with the reproductive stages of maize, which negatively impacted maize productivity (Mbanyele et al., 2021; Bal et al., 2022; Adimassu et al., 2023). This finding corroborates several previous studies, which have also reported a decrease in maize yields with precipitation (Mushore et al., 2017; Mugiyo et al., 2018; Feng and Hao, 2020; Sah et al., 2020).

The seasonal variations also affected crop growth and yields under different treatments. A comparison of the different seasons showed that the interactive effects of SWRT and plant density on plant height depend on the growth stage. For example, in the dry season 1, there was a significant plant height increase in the SWRT-low plant density treatment, based on measurements taken after a 15-day dry spell at 51 DAP onward. A study by Fassih et al. (2024) in Morocco reported that SWRT increased the height of agar seedlings. In the driest season (season 3), plant density increased from low to high, and maize height increased at 33 DAP only, but maize height did not differ during the greater part of the maize growth period. These examples suggest that plant heights and density variations depend on the growth stage. Djaman et al. (2022)

**Table 4**
Four-year average rainwater use efficiency (RWUE) of maize crops with and without sub-surface water retention technology (SWRT) at low (37,000 plants $ha^{-1}$), medium (74,000 plants $ha^{-1}$) and high (111,111 plants $ha^{-1}$) plant density.

| Treatment | RWUE kg $ha^{-1}mm^{-1}$ | RWUE kg $plant^{-1}mm^{-1}$ |
|---|---|---|
| **SWRT (water management)** | | |
| SWRT | $5.5 \pm 0.35^{a}$ | $0.011 \pm 0.0002^{a}$ |
| Control | $4.7 \pm 0.35^{a}$ | $0.011 \pm 0.0002^{a}$ |
| **Plant density** | | |
| Low | $4.69 \pm 0.32^{a}$ | $0.014 \pm 0.0003^{c}$ |
| Medium | $5.48 \pm 0.32^{b}$ | $0.010 \pm 0.0003^{b}$ |
| High | $5.13 \pm 0.32^{ab}$ | $0.008 \pm 0.0003^{a}$ |
| **Season** | | |
| 1 (2019–20) | $3.42 \pm 0.57^{a}$ | $0.01 \pm 0.0004^{a}$ |
| 2 (2020–21) | $6.21 \pm 0.57^{b}$ | $0.02 \pm 0.0004^{b}$ |
| 3 (2021–22) | $2.74 \pm 0.57^{a}$ | $0.01 \pm 0.0004^{a}$ |
| 4 (2022–23) | $8.03 \pm 0.57^{b}$ | $0.01 \pm 0.0004^{a}$ |
| ***p-value significance*** | | |
| season | 0.002 | 0.0001 |
| SWRT | 0.084 | 0.951 |
| plant density | 0.017 | < 2.2e−16 |
| **Interactions** | | |
| SWRT × season | 0.930 | 0.982 |
| SWRT × plant density | 0.447 | 0.990 |
| plant density × season | 3.105e−05 | 3.484e−10 |
| SWRT × plant density × season | 0.892 | 0.014 |

Means ± SE within columns followed by different letters are significantly different at $p < 0.05$.

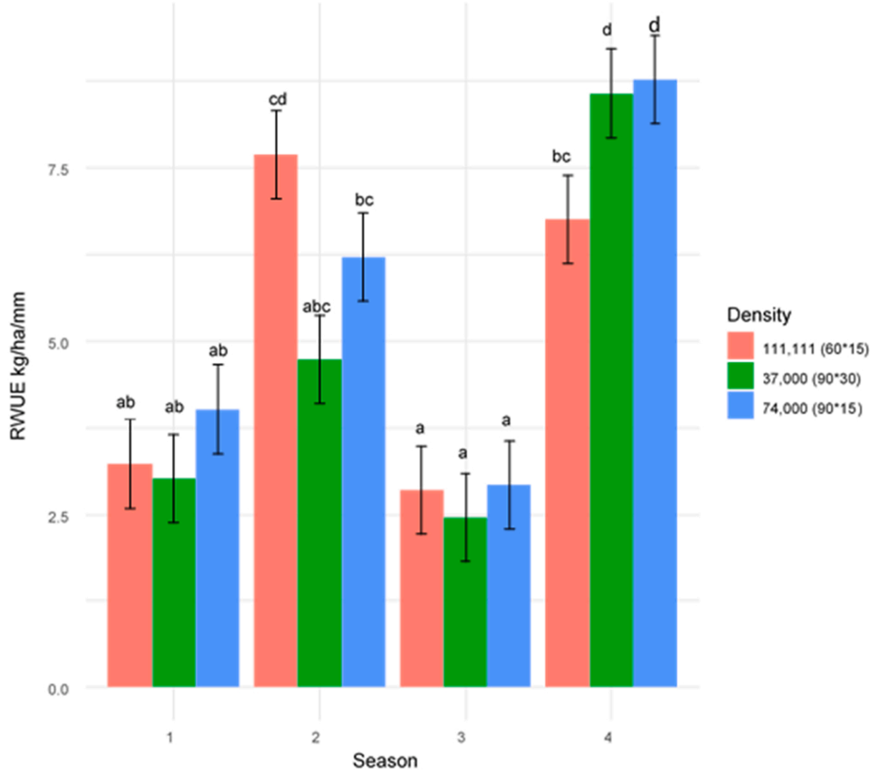


**Fig. 7.** Rainwater use efficiency (RWUE) per hectare of maize at different plant densities: low (37,000 plants ha$^{-1}$), medium (74,000 plants ha$^{-1}$) and high (111,111 plants ha$^{-1}$) in seasons 1 (2019–20), 2 (2020–21), 3 (2021–22) and 4 (2022–23). Cumulative rainfall was 313, 780, 305 and 424 mm in seasons 1, 2, 3 and 4, respectively. Error bars denote standard error. Different lower-case letters indicate significant differences ($p < 0.05$) between plant densities across seasons.

reported that plant density alone does not significantly affect maize height. Wilting of plants, which probably negatively affected biomass accumulation and thus plant height, was visible during the extremely long dry periods in season 3 in plant density treatments in both SWRT and control plots (in-field visual observation). The observed wilting was likely explained by the limited water supply and evapotranspiration leading to stomatal closure (Zhao et al., 2022).

There was no interactive effect of SWRT and season on maize grain and biomass yield, so it was impossible to show how SWRT affected yield during seasons with different rainfall patterns. Since SWRT acts to retain water within root depth, the dry seasons (1 and 3) could have shown a positive response of SWRT, but the mid-season dry spells were too prolonged, which probably resulted in all the retained water being exhausted and not being adequate to support crop development during the critical reproductive stages. Therefore, even though SWRT adds resilience to crop growth, irrigation is required during drought periods (Hommadi et al., 2023), especially during grain-filling, to maximise maize production (Comas et al., 2019).

### 4.2. Effect of SWRT and plant density on maize yield parameters

The increase in maize grain yield (21 %) and total biomass yield (13 %) observed in SWRT plots can be attributed to the ability of the technology to add resilience to climate conditions by retaining reserves of soil moisture and nutrients in the crop root zone. A previous one-year study by Nkurunziza et al. (2022) found that SWRT increased maize grain yield by 50 % and biomass yield by 150 % on coarse-textured sandy soils in Kenya. Other one-year studies with SWRT have observed yield increases of 6.5–38 % in rainfed and irrigated wheat in Iraq (Hommadi et al., 2021), irrigated field tomatoes in Morocco (Lahbouki et al., 2022b) and irrigated tomato and spicy pepper in Iraq (Aoda et al., 2021), and irrigated chilli pepper in Iraq (AL-Rawi, 2017). Other water management options complementary to SWRT, such as contour-based water harvesting techniques, have been studied in similar soil and environmental conditions and improved productivity (Nyagumbo et al., 2019; Gumbo et al., 2021). For example, a three-year study by Chiturike et al. (2024) showed that maize yield increased by 88 % using tied contours and by 52 % using infiltration pits on sandy soils. Contour-based water management options improve plant water availability by intercepting and capturing runoff water at the field edges, increasing in-field groundwater recharge (Nyamadzawo et al., 2013). On the other hand, SWRT is based on a more direct approach that focuses on retaining water and nutrients within the root zone. Our study contributes to the application of SWRT in rainfed systems over multiple seasons and its effects on field crops such as maize compared to previous studies where supplementary irrigation or full irrigation was used. Our study's lack of interactive effects between SWRT and plant density implies that SWRT did not influence the maize yield responses for the different plant densities. The lack of yield responses was possibly because the main treatments' yield difference was too small to reveal any interactions with the sub-plot treatments of plant densities. Environmental conditions determine the optimum plant density (Tokatlidis, 2013), which is more apparent under rainfed conditions. In the present study, maize productivity in grain yield per hectare was greater at medium plant density than at low and high plant density. The reduction in grain yield at high plant density was due to fewer cobs and lower grain weight, presumably owing to limitations in photosynthetic resources for cob and grain development (Al-Naggar et al., 2015; Haarhoff and Swanepoel, 2022). However, high plant density can increase grain yield under optimum water and nutrient supply (Lai et al., 2022). Accordingly, in the wettest season (season 2, 780 mm rainfall), we observed higher grain yield (5.88 t ha$^{-1}$) at high plant density compared with medium (4.77 t ha$^{-1}$) and low (3.64 t ha$^{-1}$) low plant density. However, productivity in grain yield per plant was significantly higher at low and medium plant density compared with high (Table 3). This finding corroborates with previous studies that observed that individual plant yield of maize decreases with increasing plant density in rainfed agriculture (Qian et al., 2016; Zhang et al., 2019). Individual plant productivity shows the efficiency of the plant in partitioning resources for growth and reproduction. Evolutionary agroecology theory suggests that individual and population productivity are inconsistent and that the variation increases with plant density (Weiner et al., 2010). Agronomic yield per hectare is a characteristic of plant density and field and environmental conditions and is not limited to individual plant yield (Friedman, 2024). Therefore, the most important parameter of maize productivity for farmers is yield per hectare, not per plant. The findings in this study can help maize breeders decide whether to increase individual plant grain yield, tolerance to high plant density, or both. For agronomists, the maize productivity findings in this study can help optimise plant density for improved crop production management.

While medium plant density (74,000 plants $ha^{-1}$) gave a higher yield than other plant populations, only 58 % of the initial plant population contributed to grain yield at harvest. This means that 42 % of the plants failed, but the final plant population at harvest was still higher (42,920 plants $ha^{-1}$) than that at low density (37,000 plants $ha^{-1}$), hence the higher yield. Thus, the higher number of plants per hectare compensated for the reduction in productivity of individual plants at the medium plant density. Plant failure was minimal at the low plant density since the final plant density stand at harvest was 84 % (31,080 plants $ha^{-1}$) of the initial plant density. This small maize density explains why the yield was lower at low plant density despite having a good crop stand at harvest and higher crop productivity than the other plant densities. At high plant density (111,111 plants $ha^{-1}$), only 59 % of the initial plant density remained at harvest, but the plant density was still the highest. However, this higher number of plants did not compensate for low individual plant productivity in final maize grain yield per hectare. Instead, that treatment gave the highest biomass yield and significantly low HI, meaning more biomass than grain was produced. Thus, the high plant density of maize would be ideal for smallholder farmers interested in fodder rather than grain production, as demonstrated during the two lowest rainfall seasons (seasons 1 and 3) in the rainfed semi-arid system in this study. Thus, the final plant density stand at harvest affected yield, confirming previous findings (Vijayaprabhakar et al., 2021). The reduction in plant density from the initial population could be explained by the non-uniform germination of the maize in the rainfed system. Correction for germination percentage by gap-filling at the medium and high plant densities was ineffective, suggesting non-uniform crop establishment and competitive growth between early and late establishing plants.

Diseases and pests can also be responsible for crop failure, reducing the final plant density stand (Sharma et al., 2017). In the study area and throughout southern Africa, fall armyworm poses a threat throughout the season (Banson et al., 2020; Bengyella et al., 2021; Matova et al., 2022). Another possible reason is that plants in the high-density plots grew excessively tall and thin (field observations), indicating that photosynthetic resources were apportioned to vegetative growth rather than reproductive structures. Tall, thin maize plants are susceptible to lodging and some self-thinning (Postma et al., 2021), which might have been one of the reasons for the crop losses at medium and high plant density. High plant densities also require more water, sunlight, and nutrients (Boomsma et al., 2009). Water was limited in our study since the system was rainfed, and mid-season droughts were observed. Competition for other photosynthetic resources can be high at higher plant densities, and limitations in these resources can cause crop failure.

The HI was generally below 0.5 in both SWRT and plant density treatments. SWRT plots had low (0.31) HI, which was not significantly different from the control, which means that SWRT did not improve the physiological efficiency of maize. The HI values were generally very low (range 0.27–0.32) for all plant densities, suggesting the low physiological efficiency of maize crops grown in semi-arid areas. The low and medium plant densities had similar HI, whereas high plant density decreased HI. Maize HI can remain stable across plant densities until it reaches a threshold, beyond which it decreases with increasing plant density (Li et al., 2015). The high rainfall season (season 2) had the highest HI of all seasons. This finding suggests that the physiological efficiency of maize grain development increased at higher rainfall levels. Factors such as extreme temperatures, limited available water, diseases and pests affect the reproductive development of crops, resulting in low HI (Hütsch and Schubert, 2017).

### *4.3. Effect of SWRT on rainwater water use efficiency*

Rainwater use efficiency tended to be higher in SWRT than in the control. Technologies to improve soil moisture retention, such as mulching, rainwater harvesting and plastic mulching, have been shown to enhance RWUE in semi-arid areas (Zheng et al., 2020; Mbanyele et al., 2021; Chiturike et al., 2023). SWRT, which can perform similarly to these technologies, did not enhance RWUE in the present study. In a season with a long dry spell, SWRT can reach a limit in its water retention capacity, while in a season with abundant rainfall, the effect of SWRT can be masked. In this study, RWUE increased with the rainfall received during the individual season. Maize yield is responsive to water availability, and rainfall is important in evaluating water management options (Bekuma Abdisa et al., 2022). A single-season study on wheat by Hommadi et al. (2021) found that water use efficiency increased with SWRT in plots where irrigation was supplemented by rainfall. In our study, individual maize plants with low plant density had higher RWUE, which explains the higher grain yield per plant than other plant densities. The RWUE increased as plant density increased from low to medium but decreased again at the high density. A study on maize in semi-arid areas by Jia et al. (2018) also found that moderate plant densities increased RWUE. The uniform rainfall distribution in season 4 allowed crops to have a higher RWUE than in seasons 1 and 3, indicating that the crop in season 4 efficiently utilized water. There may thus be an optimum water level for crop productivity. On the other hand, high rainfall, such as that received in season 2, may reduce the RWUE because not all water (in excess) can be utilised by the crop. The RWUE results explain why the final plant population standing at harvest under medium plant density performed better than that at other plant densities.

The maize variety used in this study, PHB30G19, is a medium-maturing variety, and it performed well in seasons characterised by average or above-average rainfall (2 and 4). Although recommended across many environments, including rainfall stress areas, it could not withstand the long durations of intra-season dry spells experienced in season 3. Maybe short-season varieties should be considered during low rainfall forecasted seasons.

### *4.4. Smallholder farmer considerations regarding SWRT use*

Adopting SWRT requires a high level of labour and financial investment of about USD 0.05 per square meter (Nkurunziza et al., 2019). In terms of labour, manual SWRT installations were done in this study, and installing a hectare of land would require 72 labour days for 20 working individuals.

The return on investment in terms of increased crop yield and soil health improvements can be realized over time, as shown in a study by Nkurunziza et al. (2019). However, the frequent droughts experienced in semi-arid areas limit the positive benefits of SWRT. The seasonal variations experienced in this study suggest the need for supplementary irrigation during the long intra-seasonal dry spells. Also, previous studies on SWRT complemented the technology with supplementary or full irrigation (Abedalrahman et al., 2020; Hommadi et al., 2021). However, due to socio-economic challenges such as labour shortages and financial limitations, smallholder farmers rely on rainfed agriculture instead of supplementary irrigation for the field crops (Makate et al., 2019; Madamombe et al., 2024). Nonetheless, since irrigation and SWRT installations require high capital investment, resource-constrained smallholder farmers may not have the financial capacity to adopt them.

## 5. Conclusions

This study evaluated the effects of SWRT on maize performance and RWUE at different plant densities on sandy soils under rainfed semi-arid smallholder farming in Zimbabwe and arrived at two main conclusions. Firstly, it indicated that SWRT and optimised plant density improved maize production in the smallholder system. Maize grain increased by 21 % and biomass yield by 13 % on average over four years when using SWRT. Seasonal variations in rainfall patterns significantly impacted maize yield more than the experimental treatments SWRT and planting density. Overall, medium plant density (74,000 plants $ha^{-1}$) performed better than the low and high density.

Secondly, differences caused by seasonal variations indicate a need to invest in supplementary irrigation to reduce the impacts of prolonged droughts and during dry cropping seasons. Based on studies conducted in other regions, we postulate that this should improve the performance of SWRT. Soil moisture can also be improved with other management practices, such as surface mulching. Further work is needed to determine the best water balance in SWRT systems in rainfed maize production and complementary management options.

## Author contribution

Madamombe Sandra collected, analysed the data, interpreted the results and prepared the manuscript. Nyamadzawo George, Öborn Ingrid, Smucker Alvin, Chirinda Ngonidzashe, Kihara Job and Nkurunziza Libère contributed to the synthesising of results and reviewing the manuscript.

## CRediT authorship contribution statement

**Nkurunziza Libère:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Smucker Alvin:** Writing – review & editing, Resources, Methodology, Conceptualization. **Öborn Ingrid:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Kihara Job:** Writing – review & editing, Supervision. **Chirinda Ngonidzashe:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Nyamadzawo George:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Madamombe Sandra Makaita:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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## Declaration of Competing Interest

The 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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## Data Availability

Data will be made available on request.

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